Assessing the level of adaptation to heat waves in Parisian housing

Letizia Roccamena*[1], Jean-Marie Alessandrini[1], Pierrick Gervasi[1], Julien Guilhot[1], Georgios Kyriakodis[1], Simon Molesin[2], Maeva Sabre[1], Wenjuan Wei[1]

1 Centre Scientifique et Technique du Bâtiment (CSTB)
84 Av. Jean Jaurès,
77420, Champs-sur-Marne, France
**Corresponding author: letizia.roccamena@cstb.fr*

2 Régie Immobilière de la Ville de Paris (RIVP)
13, Av. de la Porte d'Italie,
75621, Paris CEDEX 13, France

ABSTRACT

The paper introduces an approach for assessing the resilience of buildings to both current heat waves and their recurrence in the future under the impact of climate change. The method, applied to the 60,000 dwellings of the RIVP (Régie Immobilière de la Ville de Paris), the second-largest social landlord in Paris, aims to provide reliable information to enable the buildings' owner to assess the heat-related health risk for the tenants and the actions to be taken to decrease it. To this end, it provides them with a quantifiable indicator, the probability of risk occurrence, to enable them to decide which adaptation pathways are suitable based on a cost-benefit balance.
Upon defining the study's scope, the method defines faultless performance criteria for dwellings, set here at operative temperatures below 27°C and 30°C at night-time and daytime respectively. Subsequently, it identifies the climatic sequences that make the dwellings faulty and finally quantifies their recurrence across present, near-future (2040), and distant-future (2080) scenarios.
By applying the method, dwellings are classified into three categories based on the number of times the climatic sequences that deteriorate the apartments' thermal performance are exceeded over a given period: those in which these boundary conditions are exceeded once every ten years or less, less than once a year, and more than once a year.
In addition to this classification, the study highlights the substantial benefits of thermal insulation and window solar protection and emphasizes the critical importance of opening windows at night to reduce indoor temperature. Despite the significant impact of employing passive solutions, the results indicate that maintaining nighttime temperature thresholds remains challenging due to difficulties in heat evacuation exacerbated by rising outdoor temperatures caused by global warming. Looking ahead, this method may find application in diverse contexts and urban settings.

KEYWORDS

Social housing, Climate change, Resilience assessment, Refurbishment

1 INTRODUCTION

Under the altered oceanic climate characteristic of Paris, the presence of warm days and cool nights historically maintained a moderate indoor thermal environment in dwellings obviating the need for air conditioning systems. Over the last two decades, the combined effect of climate change and the urban heat island (UHI), has increasingly strained the efficacy of night ventilation to maintain indoor thermal comfort in Parisian dwellings (Daniel et al., 2018). While installing air conditioning systems within residential dwellings may be an effective solution amidst the escalating frequency of heatwaves, it is important to consider that this system is highly energy-consuming, emits greenhouse gases, contributing to the heating of the outside environment, particularly in densely populated areas (Tremeac et al., 2012).

In the context of social housing, landlords are faced with the challenge of wanting to protect the health of their dwellings' occupants in the face of climate change, without systematically resorting to the installation of air conditioning systems.

Recognizing the protective capacity of the building stock as a prerequisite, the challenge is to provide these owners with the necessary information to assess the effectiveness of climate change adaptation of their building stock. In cases where adaptation levels prove insufficient, refurbishment measures can be devised. Evaluating these actions under current and future climates enables building owners to establish adaptation pathways and minimize cooling requirements over time and space.

To address this objective, the reliability of dwellings is assessed based on three points:

1. Establishing the limits of the thermal environment that must not be exceeded to ensure fault-free operation.
2. Identifying the climatic conditions that must not be surpassed to comply with the operating limits.
3. Determining the probability of exceeding these climatic thresholds.

This paper presents the method developed as part of a study carried out in collaboration with the RIVP (Régie Immobilière de la Ville de Paris), the second-largest social landlord in Paris, and subsequently applies it to the RIVP building stock, both in its current state and post-refurbishment. This process involves calculating criteria and thresholds for fault-free operation (1), defining alert conditions for each dwelling (2), and determining their probability of occurrence (3) under the current climate, as well as projections for the 2040 and 2080 horizons.

2 METHOD

The risk is a danger whose occurrence is more or less predictable. Risk analysis involves defining the hazard and quantifying the probability of it occurring. To build an adaptation pathway for their dwellings, the building owners need to assess the risk using quantifiable criteria. The definition and method to calculate it were constructed in close collaboration between the stakeholders in a five-step method introduced afterward.

2.1 Description and quantification of comfort and health risk criteria

In an ideal indoor thermal environment, occupants' health and safety are preserved. To define the limits of this "flawless" thermal environment, we aim to identify the maximum indoor temperature and relative humidity (RH) values, known as "heat stress", that meet this requirement. Heat stress can be predicted by carefully selecting indicators and the related thresholds. Indicators must be understandable by stakeholders and easily measurable, while related threshold(s) must be set according to the action to be taken if it is exceeded and the time required to implement it. A margin for the threshold must therefore be provided to ensure that the risk does not become a danger.

Given the varying levels of sensitivity to heat among different population groups (such as disabled persons, the elderly, infants, pregnant women, athletes, etc.) (Alessandrini et al., 2018; Brücker, 2003), the selection of indicators and thresholds follows a structured approach:

1. Definition of the target population based on the priorities outlined by the building owner.
2. Identification of indicators and their thresholds in official literature (regulations or recommendation guides).
3. Calculation of the faultless thermal environment for the target population. A body thermo-physiological template is used to calculate the heat stress limits for the heat

strain indicator (the core temperature) at the threshold for which human health is not affected (Alessandrini et al., 2022).
4. Selection of the indicator to describe the heat stress aligning with the preferences of the building owner.
5. Realisation of a sensitivity analysis of the heat stress indicator to the thermo-physical characteristics of the environment to set its threshold (Alessandrini et al., 2023).

2.2 Buildings and dwellings sampling

The heat stress is assessed for a homogeneous indoor environment. Assuming its environment is homogeneous, the dwelling is the spatial scale chosen in this study. To streamline the study, a building typology is built. Then, for each typical building, the dwellings to be studied are sampled.
The typology is the result of a compromise between two objectives:
1. To retain the representative buildings according to the building owner,
2. To select the buildings most exposed to heat.

Once the representative buildings are selected, for each of them the flat sampling is realised according to the same logic:
- Selection of the most common flat in size, number of rooms, and floor ("typical" dwelling);
- Selection of the flat most exposed to heat ("vulnerable" dwelling).

The aim is to simulate their thermal behaviour with an hourly timestep and assessing their climate change adaptation level at different time horizons. In addition, a refurbishment program made of a combination of common passive technical solutions for the envelope is defined with the building owner for all dwellings.

2.3 Selection of climatic sequences

The process of identifying climatic conditions that must not be surpassed to comply with the dwellings' operating limits, and determining the probability of exceeding these thresholds consists of three steps:
1. Selection of past heatwaves based on their correlation with estimated excess mortality during summertime.
2. Characterization of each sequence in terms of duration and intensity.
3. Selection of the hottest sequences based on the calculation of a criterion for each sequence (e.g. daily minimum temperature averaged over its duration).

2.4 Running required conditions

The required conditions are determined by the activity inside the building (internal conditions) and the climate (external conditions).
The occupancy scenario is established to maintain a good balance between:
- The most heat-protective conditions of use;
- Recommendations easily accessible to as many people as possible, so that the landlord can spread them to tenants to encourage them to adopt protective measures.

The required climate conditions are selected thanks to a sensitive study. The thermal behaviour of each flat modeled at §2.2 is simulated using the previously selected climatic sequences (see §2.3). For each flat, the climatic sequence defined as the outside limit required condition, is the one that leads to exceeding during more than a given time (defined based on the building

owner's requirements) the heat stress threshold. The outside limit required conditions are defined for each dwelling in its current state and after refurbishment.
Therefore, depending on whether or not a climate sequence leads to compliance with the previously established indoor exposure thresholds (outlined in §2.1), the functional or dysfunctional perimeter of the dwelling is defined.

2.5 Risk analysis (Calculation of occurrence probability)

The following steps are followed to carry out the risk analysis:

1. The characteristic criterion (see §2.3) of each climatic sequence selected as the running required conditions for a given dwelling (as explained in §2.4), is calculated for current, near-future, and distant-future climates.
2. For a given period (present, near future, and distant future) the criterion values previously calculated are ranked in ascending order.
3. The probability of each climatic sequence being exceeded (according to the criterion previously defined) for the present, near future, and distant future is quantified.

As a result, the number of times the flat under study malfunctions is known for each given period. Based on this probability of occurrence, the building owner can assess the vulnerability to heat of each dwelling in the present, the near future, and the distant future. Depending on the results obtained with the renovation measures, they can identify the most suitable option for guaranteeing the health of the occupants.

3 RESULTS

The method described hereinabove was applied to the 60000 dwellings of the RIVP. The results obtained for each phase of the method are illustrated in the following paragraphs.

3.1 Definition of the health risk thresholds

In this study, the fault-free operating limit was defined by an operating temperature of 27°C at night (from 10 PM to 7 AM) and 30°C during the day.

This threshold was defined based on:
- World Health Organization (WHO) recommendations (not to exceed a thermometer temperature - equivalent to air temperature - of 24°C at night and 32°C during the day) (WHO, 2018)
- the use of a thermophysiological model (Kurazumi, 2008), which compares the thermal stress (characteristics of the indoor environment) and thermal strain (core temperature).

The daytime threshold of 32°C proposed by the WHO has been lowered to an operative temperature of 30°C to take account of the sensitivity of the elderly. Indeed, with an air temperature of 32°C, their body temperature exceeded 38°C, the maximum threshold tolerated for health reasons. Even with an air speed of 0.4 m/s, obtained using a fan, for example, the threshold is exceeded under the RH of 50%.
The nighttime threshold of 27°C for the operative temperature is the weighted average of wall and air temperatures. Considering that the 30°C daily threshold is not exceeded during the day, the wall temperature is supposed to be at the maximum of 30°C at 10 PM, while the air temperature is set at 24°C, the WHO night threshold.

The results of our thermophysiological study show that an operating temperature of 27°C causes a sharp rise in occupants' body temperature (close to 38°C) with an air velocity of 0,1 m/s and a RH of 60% (Alessandrini et al., 2023).

After several exchanges with the RIVP, the number of hours during each day/night that these health risk thresholds (30°C during the day and 27°C at night) are exceeded was chosen as the heat stress indicator. To avoid short breaks, it was decided to consider as indicative only the exceedances that last at least 5 hours during the heatwave.

3.2 Dwellings selection

Many buildings' characteristics depend on their periods of construction, such as the level of thermal insulation of the opaque and transparent envelope, the type of envelope and its geometric characteristics, the efficiency of the technological systems, etc. (Mutani et al. 2020). This is the information used to subdivide the RIVP building stock into five categories:

1. Buildings constructed between 1851 and 1917
2. Buildings constructed between 1918 and 1955
3. Buildings constructed between 1960 and 1974
4. Buildings constructed between 1975 and 1999
5. Buildings constructed after 2000

The choice of a representative building for each of these categories was made following two actions:

1. A satisfaction questionnaire was sent to all the buildings' caretakers, to understand which buildings had the worst behaviour in the summertime based on the percentage of dissatisfied occupants.
2. A discussion was held with RIVP to ask them which of the less-performing buildings was the most representative and the most deserving to be used as a 'type' building.

The chosen buildings are shown in Figure 1.

Figure 1 - Typology of RIVP buildings and selected buildings

It is important to note that the period 1955-1960 is a transition period for which it is difficult to give a clear "construction profile". Therefore a gap period does exist between 1955 and 1960, for which we are not proposing any standard buildings.

Once the buildings had been identified, two dwelling samples had to be selected for each building to be used for the modelling phase. The selection was based on two criteria: representativeness (criterion for choosing the "typical" dwelling) and exposure to heat in summer (criterion for choosing the "vulnerable" dwelling).

Typical dwellings were always those that were the most representative of the building in terms of size (two-bedroom flats), always at the intermediate level. The selection of vulnerable dwellings was more complex, but in general, the dwellings most exposed to heat are those on the top floor, small, with a single orientation, and that are not floor-through. The dwellings selected cannot cover all the dwellings in the stock; our objective was rather to cover three-quarters of the situations.

For each dwelling, several packages of passive solutions (different thicknesses and types of internal/external thermal insulation, installation of solar protection) were studied, based on their intrinsic characteristics. These packages of solutions were evaluated to find the optimum solution for each type of dwelling in terms of thermal performance (see §3.4).

3.3 Selection of climatic sequences

The climate data collected by the weather station located in the heart of Paris in a park called Montsouris in the summer period from 1981 to 2019 and the number of deaths caused by the heatwaves over the same period (reported by Santé Publique France, the French national public health agency) were analysed to select 8 summers that have had the most deadly impact (see table below).
For each of these summers, the daily minimal temperatures were ranked in descending order. Considering the number of consecutive hottest nights, 12 climatic sequences lasting from 3 to 12 successive days with a minimum temperature of 18.7°C to 21.2°C averaged over their duration, were selected as the hottest sequences. The minimum daily temperature averaged over the duration of each sequence represents the criterion used for characterizing it.

3.4 Implementation of required conditions

A realistic occupancy scenario was defined by determining repetitive behaviours that could be easily performed by the occupants (concerning the windows opening and the use of solar protection) and analysed the impact of this scenario on the thermal performance of all the dwellings by carrying out a numerical simulation campaign utilizing the COMETH simulation engine (Alessandrini et al., 2019; Mazza et al., 2017). In this model, the air change rate is calculated according to the EN 15242 airflow model through large openings (AFNOR, 2007).
For each of them, the operative internal temperature was calculated during the 12 previously selected climatic sequences (see §3.3). The studied occupancy scenario considered all the windows of the dwelling to be open every night at 10 PM and keep them open all night until 7 AM (according to WHO recommendations), and the use of solar protection throughout the day, keeping 80% of glazed surfaces occluded. If this scenario is not applied, the dwellings' operating limits would be permanently exceeded, as the windows opening has a crucial role in heat evacuation.
To define the outside limit required conditions, a numerical simulation campaign was carried out, to check the thermal behaviour of each dwelling in the face of the 12 previously selected climatic sequences (see §3.3) in order to find which one would lead to the threshold for the previously selected indicator (see §3.1) being exceeded.
After carrying out many simulations of the dwellings' thermal behavior, it was noted that when the daytime thresholds are exceeded, the night-time thresholds are systematically exceeded, whereas the reverse is not true. Considering, moreover, that during the day people are less isolated and have more freedom of action (going out, looking for air-conditioned places, etc.), the criterion for defining fault-free operation has been set at a maximum of five hours above 27°C during the heatwave.

Each dwelling was tested in its current state and after applying different packages of refurbishment solutions. The impact of applying passive solution packages was assessed to find the 'optimal' refurbishment package for each type of dwelling, enabling the number of heatwave sequences in which it fails to perform to be reduced.

3.5 Risk analysis

Once the outside limit required conditions defined for each dwelling, these sequences were analyzed and ranked in ascending order according to their characteristic criterion defined in §3.3. In the second step, the number of times they appeared or were exceeded in the time series of data observed from 1981 to 2019 at the Paris Montsouris station was calculated. Since many of the outside limit required conditions were common to several dwellings, only five out of the twelve climatic sequences obtained in §3.3 were retained.
The results are summarized in the table below:

Table 1 - Analysis of climatic sequences and frequency of exceedances

Sequence	Initial occurrence	Duration (in days)	Mean minimum temperature (in °C)	Number of times the sequence has been equaled/exceeded between 1983 and 2019
1983 - 2	26/07 to 28/07/1983	3	19,6	23
2006 - 1	03/07 to 05/07/2006	3	18,7	44
2015 - 1	01/07 to 04/07/2015	4	20,6	4
2017 - 1	20/06 to 22/06/2017	3	19,9	13
2017 - 2	06/07 to 09/07/2017	4	18,8	30

For example, as can be noted, the sequence “2015-1”, characterised by a duration of 4 days and an average minimum temperature of 20.6°C, was equaled/exceeded 4 times during the 39 summers spanning from 1983 and 2019.
The same analysis applied to the observed data was carried out on the modeled data of the summers between 2020 and 2058 (near future horizon) and between 2059 and 2097 (distant future horizon). These climate models were obtained using the RCP8.5 scenario and 9 models of the Eurocordex database debiased using the CDF-t method (Michelangeli et al., 2009; Vrac et al., 2012). The near future climate results indicate that the number of times the 12 sequences are exceeded increases. For example, the above-mentioned sequence “2015-1” was equaled or even exceeded from 15 to 60 times (depending on which of the 9 models from the Eurocordex was used), during the 39 summers. The results for the distant future indicate an explosion in the number of excesses, whichever model is considered. In this horizon, the “2015-1” sequence was equaled or even exceeded from 37 to 172 times, during the 39 summers.
Based on this information, we were able to create a table (Table 2) that can inform the building owner of the probability that the occupants of each of the dwellings (in its current state and after applying the 'optimal' refurbishment package of solutions) enter into the health risk zone currently, in the near future, and in the distant future for each of the studied climatic sequence, by reporting the number of times this will happen.

Table 2 - Number of times each type of dwelling exceeds its outside limit required conditions in the present, near future, and distant future

	Outside limit required conditions				
	2006 - 1	**2017 - 1**	**2015 - 1**	**1983 - 2**	**2017 - 2**
Type and period of construction of the dwellings becoming faulty	"Vulnerable" dwellings before refurbishment: – before 1918 – 1918-1955 – 1960-1974 – 1975-1999 "Vulnerable" dwellings after refurbishment: - 1918-1955	"Typical" dwellings before refurbishment: – 1918-1955 – 1960-1974 – 1975-1999 "Vulnerable" dwellings after refurbishment: - 1960-1974 "Vulnerable" dwelling built after 2000	"Typical" dwellings after refurbishment: – before 1918 – 1918-1955 – 1960-1974 – 1975-1999 "Typical" dwelling built after 2000	"Typical" dwelling before refurbishment: – Before 1918	"Vulnerable" dwellings after refurbishment: – before 1918 – 1975-1999
Number of times the climatic sequences are exceeded in the present	**More than once a year**	**Once every 3 years**	**Once every 10 years**	**Once every 2 years**	**More than once every 2 years**
Number of times the climatic sequences are exceeded in the near future	**More than twice a year**	**More than 4 times every 7 years**	**More than 4 times every 10 years**	**More than once a year**	**More than once a year**
Number of times the climatic sequences are exceeded in the distant future	**More than three times a year**	**Twice a year or more**	**Once a year or more**	**More than twice a year**	**More than twice a year**

Using a color code, dwellings were classified into three categories based on the number of times their outside limit required conditions are exceeded in the present, near future, and distant future: those in which these boundary conditions are exceeded once every ten years or less are indicated in green, those in which it occurs less than once a year in yellow, and those in which it occurs once a year or more in red.

4 DISCUSSION

In order to identify the dwellings' criteria with the greatest impact on the results, the characteristics of the dwellings constituting the 5 groups were analyzed. The results are summarised in the table below:

Table 3 - Characteristics of the 5 groups of dwellings sharing the same outside limit required conditions

Outside limit required conditions	**2006 - 1**	**2017 - 1**	**2015 – 1**	**1983 - 2**	**2017 - 2**
U value (in W/m²K) of the external walls	0,37 to 3,1	0,21 to 3,1	0,18 to 0,36	3,2	0,14 to 0,18
U value (in W/m²K) of the roof	0,3 to 3,6	0,16 to 0,22	-	-	0,13 to 0,16
Thermal capacity (in kJ/m²K) calculated according to ISO 13786 (AFNOR, 2017) for a period of 1 day and 14 days respectively	266 to 793; 348 to 864	383 to 849; 384 to 1212	434 to 662; 511 to 734	571; 656	419 to 434; 473 to 665
% of the glazed surface compared to the floor area	13 to 23	15 to 24	14 to 23	23	13 to 17

The risk analysis showed that not all the refurbished "vulnerable" dwellings share the same outside limit required condition (Table 2) even if they have similar heat gains (due to a similar U value obtained for the external walls/roof) and inertia. The differences in the results are essentially explained by the impact of the natural ventilation airflow, proportional to the size of their windows, which is a key factor in adaptation.
Concerning the refurbished "typical" dwellings, it was noted that at present, their limit climatic sequence is exceeded once every ten years. The validation of this adaptation score, the highest obtained in our study, is the responsibility of the building owner.

For non-renovated "vulnerable" dwellings, the outside limit required conditions were not found, as all the studied climatic sequences, starting from the less intense (2006-1), made them faulty throughout their duration. According to the more optimistic climatic model, the 2006-1 will be exceeded at least twice a year in the near future and three times a year in the distant one. A building should be usable during these episodes, especially given their frequency; this would require the use of an indicator capable of quantifying comfort, considering even lower operating thresholds, and not only health risk.

5 CONCLUSION

In this paper, an approach for assessing the resilience of buildings to both current heat waves and their recurrence in the future under the impact of climate change is described, as well as the results obtained applying it to the 60000 dwellings of the second-largest social landlord in Paris, the RIVP.

To succeed, the method developed requires close collaboration with the building owner, who must validate the key information that will be used to select reliable adaptation pathways and risk prevention plans:

- The thermal environment thresholds that must not be exceeded to ensure fault-free operation, adapted to the target population.
- The indicator that defines the outside limit required conditions that lead to exceeding during more than a given time the heat stress threshold.
- The level of adaptation required, set by the probability of occurrence or the return time of the hazard, in this case, the limiting climatic sequence.

For the housing stock studied, the size of the windows and the thermal insulation of the roofs are key elements in improving dwellings' level of adaptation. For the dwellings located on an intermediate floor and floor-through ("typical" dwellings), thermal insulation of the walls, integration of solar protection, and instructions on opening windows at night provide sufficient protection from hazards with an occurrence factor of 1/10. In the future, the level of protection will deteriorate, with operating limits being exceeded every two years, or even every year by 2080; this implies that the level of adaptation of these dwellings must be improved, considering cooling solutions primarily for bedrooms at night to preserve sleep quality, an essential condition for the occupants' health.

For the top-floor dwellings, in light of the results obtained in the present climate, the application of these solutions should already be taken into account.

To improve health risk prevention, the night-time threshold should be revisited in the future, with studies of the impact of heat on sleep and health. This work might be also complemented by an analysis of the urban ecosystem, where the urban heat island and nuisances, particularly noise pollution, associated with the density and diversity of activities, act as barriers to the dissipation of heat through ventilation.

To conclude, it is important to consider that the results of this work are based on simulations and would deserve to be corroborated by experimental work. Nevertheless, the major trends outlined here and the relative analysis, comparing one situation to another, make it possible to identify priority dwellings and the actions to be taken, and to open up new perspectives.

In future endeavors, this method holds promise for application across various contexts and urban environments.

6. ACKNOWLEDGEMENTS

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