A study of indoor environment and window use in French dwellings monitored during a summer with heatwaves

Mathilde Hostein*[1,2], Bassam Moujalled[1,3], Marjorie Musy[1,3], and Mohamed El Mankibi[2]

1 Cerema, BPE Research Team
46 rue Saint Théobald
38081, L'Isle d'Abeau, France
**Corresponding author:*
mathilde.hostein@cerema.fr

2 Univ. Lyon, ENTPE, Ecole Centrale de Lyon,
CNRS, LTDS, UMR 5513
3 Rue Maurice Audin
69518, Vaulx-en-Velin, France

3 Univ. Savoie Mont Blanc,
CNRS, LOCIE,UMR 5271
60 rue du lac Léman, Savoie Technolac
73376, Le Bourget-du-Lac, France

ABSTRACT

Heatwaves are extreme events that will become more frequent and intense with climate change. Maintaining a comfortable and healthy indoor environment becomes crucial during these periods. The occupants are not just passive individuals who undergo the evolution of their environment. They can act to ensure their thermal comfort, in particular by opening or closing windows in summer.

This article thus aims to examine the thermal environment and indoor air quality during the summer period in French dwellings. Window use is studied in order to identify the physical and contextual factors influencing the occupants' behaviour thanks to a feature selection algorithm.

Four dwellings, three in a multi-family building and one in a single-family house, were monitored between June and September 2022. Three heatwaves occurred during this summer in the French region Auvergne-Rhône-Alpes. In addition to measurements of the indoor and outdoor environments, occupant actions on windows, fans and air conditioners were recorded. Three types of surveys were conducted with the occupants to understand their perceptions, experiences, and overall use of the dwellings.

The results show that the four households have different window use behaviours. Analysis of the data revealed that the variables influencing occupants' window behaviour are indoor and outdoor air temperatures, indoor CO_2 and light VOC concentrations, global horizontal irradiation and time of day.

KEYWORDS

Occupant Behaviour, Window use, Monitoring, Heatwave, Summer

1 INTRODUCTION

Windows are a link between the indoor and outdoor environment that occupants can control (Carlucci et al., 2020) to ensure their thermal comfort (Rijal et al., 2018) and indoor air quality (Marchand et al., 2018). However, noise or pollution can be disincentives to window opening (Rijal et al., 2018). Occupants have to make a compromise in their search for thermal, visual or acoustic comfort, or indoor air quality. It is therefore understandable that window use is influenced by **physical variables** of the indoor and outdoor environment.

However, although opening them could help to cool the room, closed windows can be observed at night during hot weather. Indeed, **context** matters. Occupants are not only looking for good indoor environmental quality, but also for their needs for security and privacy, as the dwelling is a shelter (Marchand et al., 2018). Moreover, each person acts differently. In addition to social and cultural factors (Rijal et al., 2018), **individual** habits and preferences can be drivers to window openings or closings (Carlucci et al., 2020).

Many studies analyse window use based on field data. In 2012, Fabi et al. (Fabi et al., 2012) conducted a literature review about window opening behaviour. They divide factors influencing occupant behaviour into five categories: physiological, psychological, social, physical environmental and contextual. Since this review, several studies on the residential context have been published on this subject. Table 1 summarizes the results of these studies. It shows the physical and contextual variables influencing window openings and closings. Green ticks indicate a driver, and red crosses a non-driver. The presence of a tick and a cross means that the results are different for opening and closing, or between studies for the literature review.

Table 1. Variables influencing window openings and closings in residential buildings

Variables	**(Fabi et al., 2012)** *Review*	**(Calì et al., 2016)**	**(Barthelmes et al., 2017)**	**(Jones et al., 2017)**	**(Yao & Zhao, 2017)**	**(Rijal et al., 2018)**	**(Shi et al., 2020)**	**(Cho et al., 2021)**
T_{int}	✓		✓	✓	✓	✓		✓
T_{out}	✓	✓	✓	✓	✓	✓	✓	
RH_{int}		✓	✓	✓	✓			
RH_{out}			✗	✓ ✗	✓		✓	
$CO_{2,\ int}$ level	✓	✓	✓		✓			✓
$PM_{2.5,\ ext}$ level					✓		✓	
Solar radiation	✓ ✗		✓	✗				
Illuminance			✗ ✓					
Wind speed	✓ ✗		✗ ✓	✓	✓		✓	
Wind direction	✗				✓			
Rainfall	✗			✓				
Time of day	✓	✓	✓	✓	✓	✓		
Weekday	✗		✗		✓			
Season	✓			✓	✓	✓		
Others contextual drivers	✓ ✗	✓ ✗				✓	✓	

These studies aim to model window-related occupant behaviour. Logistic regression is used in five of these articles (Calì et al., 2016; Jones et al., 2017; Rijal et al., 2018; Shi et al., 2020; Yao & Zhao, 2017). Barthelmes et al. (Barthelmes et al., 2017) perform a variable selection with a Kolmogorov-Smirnov test, then model window use with Bayesian Network. Cho et al. (Cho et al., 2021) also conduct a feature selection before modelling, using a generalized additive model.

Feature selection methods can be used in data preparation for machine learning algorithms with predictive purposes (Brownlee, 2020). Speiser et al. (Speiser et al., 2019) compared 13 of these methods based on random forest thanks to 311 classification datasets from multiple scientific fields. To our knowledge, random forest variable selection has never been used for occupants' window-use behaviour.

This study aims to identify physical and contextual drivers influencing window opening and closing during summer in dwellings. A field measurement campaign was therefore conducted in four occupied French dwellings during summer 2022. A variable selection method based on random forests was used to analyse the measurement data.

2 METHODOLOGY

2.1 Data collection

A measurement campaign was conducted as part of the CREATIV project, which aims to analyse the relationship between **thermal comfort** and **indoor air quality** in dwellings during **heatwaves**. Therefore, four dwellings were monitored during summer 2022. Three of them are social housing of a multi-family building located in Lyon, and the fourth is a single-family house in Clermont-Ferrand. Both buildings are located in the South-Est of France. We will refer to dwellings A, B, C and D in the following. Their characteristics are detailed in Table 2.

Table 2. Dwellings monitored in the CREATIV project during summer 2022

Identifier	Dwelling A	Dwelling B	Dwelling C	Dwelling D
Location city	Lyon	Lyon	Lyon	Clermont-Ferrand
Dwelling type	Multi-family housing	Multi-family housing	Multi-family housing	Single-family home
Number of rooms	3	3	4	5
Living-room orientation	East	East	Southeast	South
Number of occupants	1	2	1	2
Household equipment	1 fan purchased during the summer thus not monitored	2 fans and 1 AC	-	1 fan
Start of monitoring	07/07/2022	17/06/2022	16/06/2022	13/06/2022 and 14/06/2022
End of monitoring	15/09/2022	15/09/2022	15/09/2022	07/09/2022 and 27/09/2022
Holidays	-	08/07/2022 to 19/07/2022	10/08/2022 to 27/08/2022	08/08/2022 to 17/08/2022

For the indoor environment variables, several types of sensors were used (Figure 1):

- **NEMO XT** monitoring stations measured air temperature (T_{int}), relative humidity (RH_{int}), CO_{2int}, light VOC_{int} and fine particles (PM_{1int}, $PM_{2.5int}$ and PM_{10int}) levels in the living room and master bedroom of each dwelling at a time step of 10 minutes.
- **HOBO U12-011** dataloggers measured air temperature and relative humidity at a 10-minute time step. They were placed in most of the rooms in each dwelling. The temperature and humidity measurements were therefore duplicated in the living room and the master bedroom.
- **HOBO UX90** change of state recorders captured the opening and closing of windows, French windows and some interior doors. Some openings in dwelling D were equipped with **HOBO U9** which operate similarly.
- For dwellings with fans or mobile air conditioners, **VOLTCRAFT Energy Logger 4000** wattmeters were installed ahead of the appliances to record power consumption at a time step of 1 minute.


Outdoor NEMO powered by a solar panel
Indoor NEMO XT
HOBO U12 installed on a VMC outlet
HOBO UX90
Voltcraft EL4000

Figure 1. Pictures of the sensors used during the measurement campaign

Two types of outdoor sensors were used:

- On both sites, a **NEMO Outdoor** monitoring station was installed: on the balcony of a second-floor apartment in Lyon and on the terrace of the house in Clermont-Ferrand. They measured outdoor air temperature, relative humidity, light VOC_{out} and fine particles (PM_{1out}, $PM_{2.5out}$ and PM_{10out}) at a 10-minute time step.
- At the Lyon site, a **HOBO U23-002** datalogger was placed on the 6th floor. It measured outdoor air temperature (T_{out}) and relative humidity (RH_{out}) at a time step of 10 minutes.

As the pitched roofs were not accessible, it was not possible to install weather station. Wind and solar radiation data were collected from nearby stations. For the Lyon site, the **ENTPE**

station (ENTPE, s. d.), located at about 10 km aerial distance from the monitored building, was used. Wind speed and direction (WS/WD), as well as global and diffuse horizontal irradiation (Ihg/Ihd) were extracted at a time step of 1 minute over the whole monitoring period, i.e. from 16/06/2022 at 16:00 to 15/09/2022 at 14:30. No stations were found for the Clermont-Ferrand site with the relevant variables and at a rather low time step, so these variables are not used for dwelling D.

In order to complete the measured data, three types of surveys were filled in with the occupants in order to find out how they used the dwelling and how they felt about it:

- **Logbook** was filled in by the occupants independently during a one-week period of heatwave during the summer. Occupants were called at the beginning of the week. This document recorded cooking practices, household chores, solar protection use, bathroom use, door use and occupation. Only the occupants of dwelling D completed this document from Friday 15/07/2022 to Thursday 21/07/2022.
- **Thermal comfort surveys** were completed by the occupants independently throughout the summer. At any time during the campaign, an occupant could fill in a page specifying the date and time, the perceived thermal ambience and personal parameters useful in thermal comfort study.
- **General questionnaires** were filled in with the occupant when the sensors were removed or afterwards by telephone if the first option was impossible. It concerns the use of the dwelling and the equipment during the summer, the general comfort as well as the differences identified during a heatwave.

2.2 Data processing and analysis

After extracting the data measured by each sensor, a code written in R is used to group the data by dwelling and by room. To ensure a **single time step**, the environmental measurements are interpolated, the ENTPE data are averaged, and the window status (open/closed) is filled in between the state changes. The choice of a 5-minute time step corresponds to a compromise between the dynamics of the thermal and aeraulic variables, and the windows openings. Openings of less than a minute are neglected because we noticed some openings of a few seconds which seem to be due to a sensor failure rather than a real opening/closing.

Cleaning steps are then performed manually, i.e. the consistency of the measured values is checked for each sensor. Some malfunctions were identified on some sensors used for the openings. They are due to the fall of one of the sensor parts. They were recovered separately and therefore recorded an open position since their fall. Data from these sensors is deleted from the end of the last closure, i.e. just before the opening due to the fall. Some sensors were dropped the day or the day after they were installed, and therefore no data is used for these sensors.

After processing the data, an **exploratory analysis** of the physical data is conducted. The indoor environments of the four dwellings are compared statistically. Occupant behaviour is then studied during the summer and heatwaves, through the measured data and surveys. A focus is made on dwelling B and D.

Finally, in order to identify the variables influencing the use of windows, a **feature selection** algorithm is applied for each room of each dwelling. We are interested here in the use of the windows (opening/closing) and not the state of the windows (open/closed). For this reason, at this stage, only the observations that correspond to a change of state are kept.

Libraries have been created in different programming languages to automate feature selection. In particular, the *VSURF* package on R, based on random forests, allows variables selection for interpretation or prediction purposes (Genuer et al., 2015). In the second case, the set of predictor variables will be smaller because the redundant variables among all those that influence the target variable are removed in order to maximise performance in terms of prediction. There are other libraries on R for random forest variable selection, such as *Boruta* (Kursa & Rudnicki, 2010) or *varSelRF* (Diaz-Uriarte, 2007). However, both are well suited to databases with more than 50 features according to Speiser et al. (Speiser et al., 2019).

The **VSURF** library (Genuer et al., 2015) is therefore used. This method is chosen because it is implemented in R, it is one of the two best random forest variable selection methods of all those compared by Speiser et al. (Speiser et al., 2019), and it provides a distinction between interpretation and prediction purposes. This former functionality is used. The objective is indeed to find all the influential variables even if they may be redundant among themselves.

In addition to the measured environmental variables, we add several contextual explanatory variables: the heatwave (HW) warning, the day of week and the time of day.

- **HW alert** is a binary categorical variable which allows to identify if a HW has been declared by *Santé Publique France*[1] at the time of the action. Indeed, during HW periods, awareness messages are broadcast in France to prevent health risks related to HW. According to *Santé Publique France*, three periods of HW occurred during summer 2022 for both locations. They were under orange vigilance from 15 to 22 June. The second HW occurred from 12 to 26 July, during which Lyon was under orange vigilance and Clermont-Ferrand under yellow vigilance. Finally, both locations were under orange vigilance from 31/07/2022 to 05/08/2022, with a HW extended to 13 August under yellow vigilance for Lyon (Santé Publique France, s. d.).
- **Weekday** is a categorical variable with seven factors.
- **Time of day** is a numeric variable that corresponds to the number of minutes since the beginning of each day. It represents the occupants' habits.

3 RESULTS

3.1 Indoor environment

Figure 2 shows the boxplots of the indoor temperature (T_{int}) in the different rooms of the dwellings. In the three monitored dwellings of the multi-family building, T_{int} values are above 28°C at least 44% of the time in the living room, and this value reaches 63% in dwelling C. Temperatures are much lower in dwelling D, with average values below 25°C for all rooms.

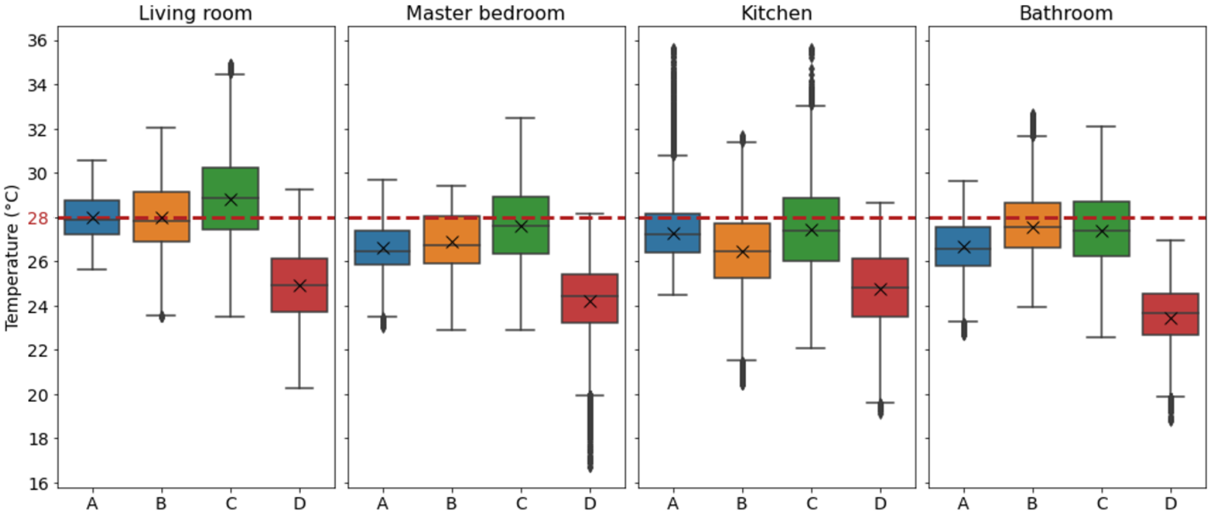

Figure 2. Comparison of T_{int} by room in the four dwellings using boxplot diagrams with means displayed

Dwelling D is a single-family house where the occupants are particularly active in keeping the temperature low, as we will see later. It is also the only dwelling where CO_2 level exceeds 1133 ppm half of the time at night in the main bedroom. Indeed, two occupants sleep in this room

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[1] *Santé Publique France* is the national public health agency in France.

with the door and window closed, unlike the other dwellings where the master bedroom is occupied by one person. Figure 3 is a violin plot showing the distributions of CO_2 measurements with coloured density curves, and quartiles and medians as dotted lines.

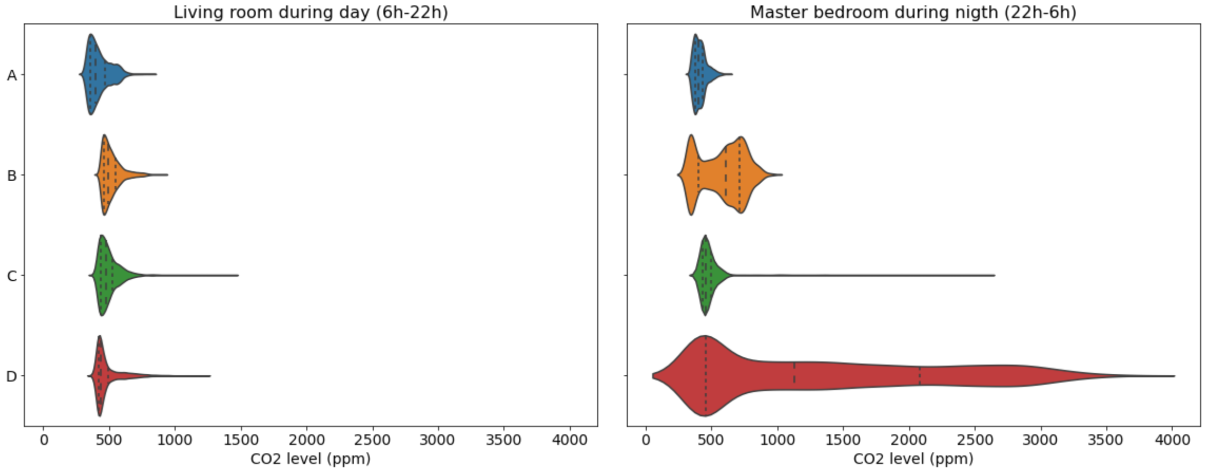


Figure 3. Distribution of CO_2 levels in the different dwellings using violin diagrams with quartiles displayed

In all monitored rooms of all dwellings, RH remains between 30 and 70% most of the time, and is outside this range less than 9% of the time. Dwelling C is the warmest and the most polluted, since it is the only one where the maximum daily average $PM_{2.5}$ concentration exceeds the exposure limit set to 25 µg/m^3 (Cony et al., 2017) in both monitored rooms. It is also the dwelling with the highest daily average concentration of light VOCs, up to 771 ppb in the living room and 308 ppb in the main bedroom.

3.2 Occupant behaviour

Household B is the only one with an air conditioner (AC). It also has two fans: one in the living room or bedroom 2 depending on the presence of the occupants, and one in the kitchen or master bedroom in the same way. Figure 4 shows the temporal evolution of the indoor air temperature and the CO_2 level in the living room during the third HW, highlighting the opening of the windows and the operation of AC and fan.

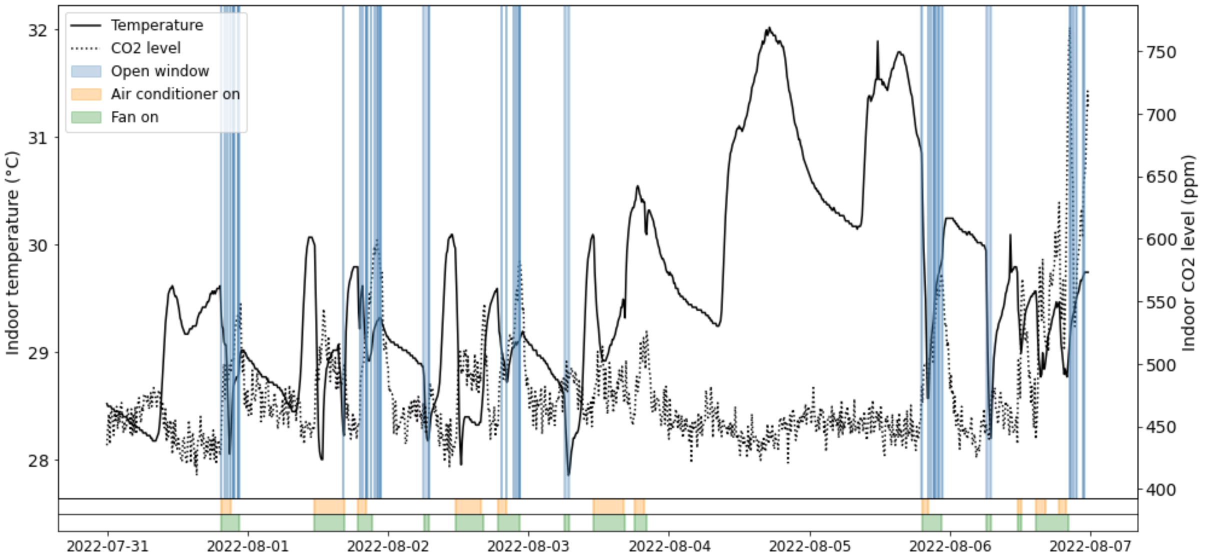


Figure 4. Evolution of the indoor environment with adaptation actions in the living room B during the 3rd HW

The window is opened mostly in the evening with some openings in the morning. The openings are short and frequent in the evening. This is a French window, so the openings can be a response to heat, a habit or simply a means of accessing the balcony. From the evening of Wednesday 3 August, the occupants leave the house for two days, and T_{int} rises sharply.

During morning openings, fan is turned on but not AC. Fan and AC are turned on in the afternoon and evening when temperatures are hottest and occupants are present. During the night, AC is turned off and fan moved to the bedroom, to be turned on during sleep. When the fan is on, the window is closed 92.59% of the time in the living room. When AC is on, the living room window is closed 98.67% of the time.

According to the interview, the occupants of dwelling B open the windows for aeration and out of habit. They close the shutters against glare and heat. They feel restricted in their adaptive actions by external noise. The thermal environment is considered very hot and unacceptable in all main rooms in summer, with unbearable discomfort in the master bedroom during heatwaves. They sometimes leave the house for the day when the discomfort becomes unbearable. They feel powerless against the heat during heatwaves.

Occupants of dwelling D are the only one to have completed the logbook, which gives us detailed information on the use of solar protections. They also have a fan in the living room. Figure 5 plots the temporal evolution of the indoor temperature and the CO_2 rate in the living room during the second heatwave, by highlighting the opening of the windows and shutters, and the fan operation.

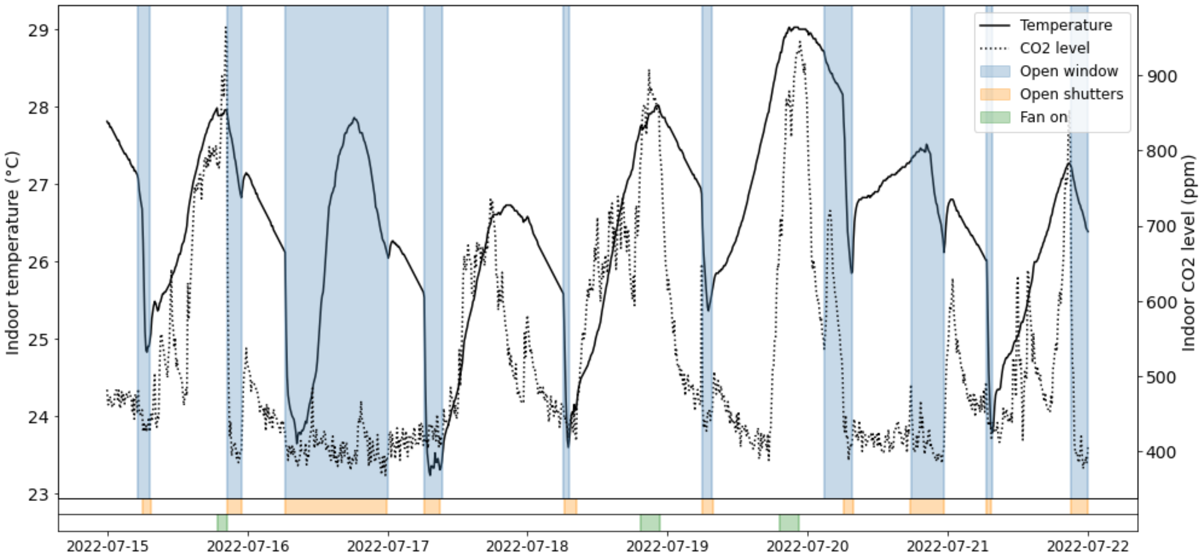


Figure 5. Evolution of the indoor environment with adaptation actions in the living room D during the 2nd HW

It can be observed that during this week, in all the rooms, the window is opened at the same time as the shutters. The window is always opened in the morning, which is the case during nearly the whole summer and for all the windows in the house. The opening durations are longer than in dwelling B. The fan is turned on in the evening. Compared to dwelling B, the occupants use the fan much less and it remains switched off 95.69% of the time. When the fan is on, the living room window is closed 64.58% of the time.

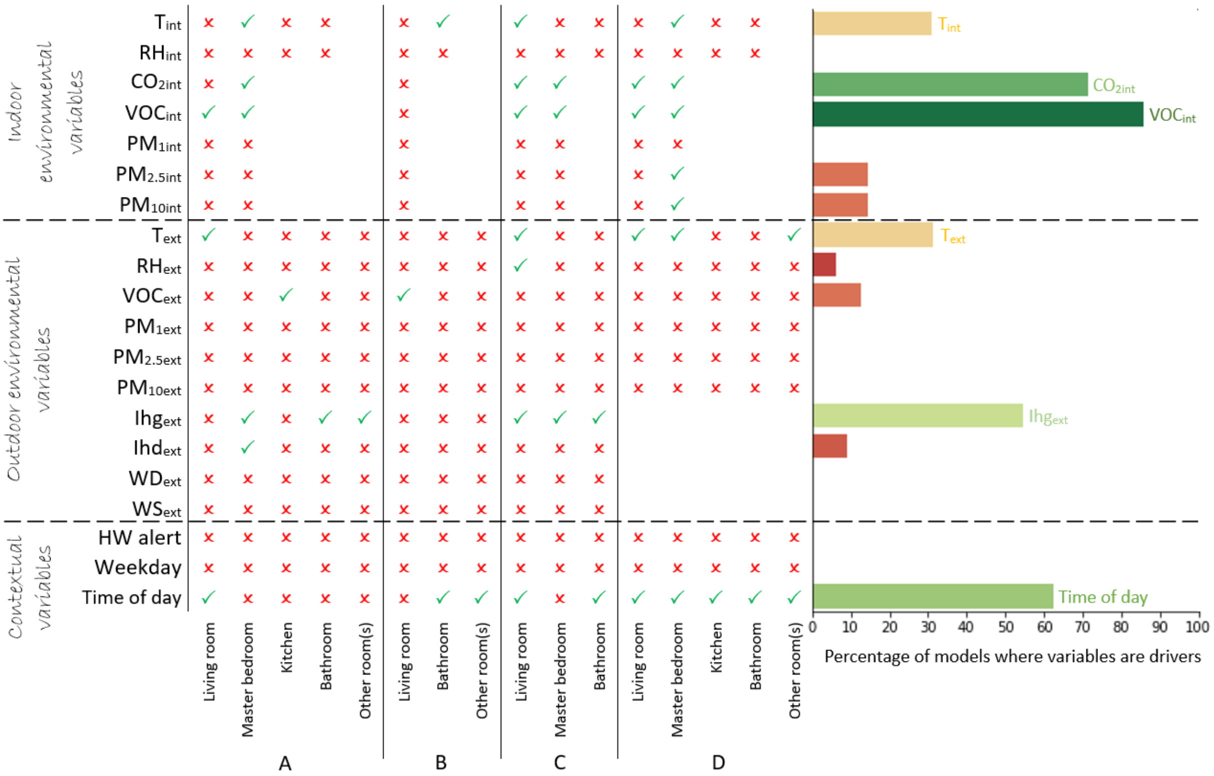
The interview revealed that the two occupants of dwelling D open the windows for aeration and close the shutters out of habit, for safety, and against glare and heat. The thermal environment is considered acceptable in all main rooms in summer, but unacceptable during heatwaves: very hot in the living room/kitchen and hot in the bedrooms and office. They mainly use windows and shutters to keep indoor temperatures low as shown in Figure 5. Fear of intrusion can limit their adaptive opportunities, because they live in a single-storey house. They feel that these adaptive actions are useful in summer, but that their effectiveness is limited during heatwaves, especially at night.

In order not to overload the article, we do not draw the same graphs for the other two dwellings but simply analyse the surveys. Dwelling A is a through apartment with two opposite orientations. It is located on the second floor. The occupant opens the windows for aeration and out of habit, and close the shutters against glare and heat. Her adaptive actions are restricted by the feeling of insecurity and the fear of intrusion. Thermal environment is perceived very hot throughout the summer in all the main rooms, hot during the night and extremely hot during the day during heatwave. Numerous adaptation actions are implemented: over-ventilation at night, solar protection lowered during the day, a fan in the living room, light clothing, cold drinks, a water spray and a shower in the evening.

Dwelling C is located on the sixth and top floor and has windows on three different orientations. The occupant opens the windows to ventilate, as a matter of habit, to get rid of odours and humidity, and against the heat. She cannot open them sometimes because of draughts, dust, and noise from outside. She closes the shutters against glare and heat, and opens them to access daylight and let in the sun's rays. When the heat becomes unacceptable, she can leave the dwelling for about a week. She does not have a fan or an air conditioner for economic reasons. During heatwaves, thermal environment is experienced in all the main rooms as slightly hot and acceptable during night, and extremely hot and unbearable during day. Indoor air quality is sometimes felt to be unacceptable during heatwaves.

3.3 Feature selection

For each room of each dwelling, Figure 6 shows the identified influencing variables with a green tick, according to *VSURF* library. On the right side of the figure, the percentage of rooms where the model finds these drivers is displayed. Some environmental variables are not measured in all rooms.



		A					B			C			D				
		Living room	Master bedroom	Kitchen	Bathroom	Other room(s)	Living room	Bathroom	Other room(s)	Living room	Master bedroom	Bathroom	Living room	Master bedroom	Kitchen	Bathroom	Other room(s)
Indoor environmental variables	T_{int}	×	✓	×	×		×	✓		✓	×	×	×	✓	×	×	
	RH_{int}	×	×	×	×		×	×		×	×	×	×	×	×	×	
	CO_{2int}	×	✓				×			✓	✓		✓	✓			
	VOC_{int}	✓	✓				×			✓	✓		✓	✓			
	PM_{1int}	×	×				×			×	×		×	×			
	$PM_{2.5int}$	×	×				×			×	×		×	✓			
	PM_{10int}	×	×				×			×	×		×	✓			
Outdoor environmental variables	T_{ext}	✓	×	×	×	×	×	×	×	✓	×	×	✓	✓	×	×	✓
	RH_{ext}	×	×	×	×	×	×	×	×	✓	×	×	×	×	×	×	×
	VOC_{ext}	×	×	✓	×	×	✓	×	×	×	×	×	×	×	×	×	×
	PM_{1ext}	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	$PM_{2.5ext}$	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	PM_{10ext}	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	Ihg_{ext}	×	✓	×	✓	✓	×	×	×	✓	✓	✓					
	Ihd_{ext}	×	✓	×	×	×	×	×	×	×	×	×					
	WD_{ext}	×	×	×	×	×	×	×	×	×	×	×					
	WS_{ext}	×	×	×	×	×	×	×	×	×	×	×					
Contextual variables	HW alert	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	Weekday	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	Time of day	✓	×	×	×	×	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓

Figure 6. Variables influencing window use

Indoor and outdoor humidity, indoor and outdoor fine particle concentrations, outdoor VOC level, diffuse solar radiation, wind speed and direction, heatwave context and day of week have very little or no influence on window use. These variables are indeed identified as drivers for maximum 1 room in all dwellings, except for the VOC_{out} which concerns 2 rooms out of all. We therefore find five variables that influence the opening of windows: VOC_{int}, $CO2_{int}$, Time of day, Ihg_{ext}, T_{int} and T_{ext}.

3.4 Discussions

In terms of environmental variables, our results show that indoor and outdoor temperatures, indoor CO_2 and light VOC concentrations, and global horizontal irradiation influence window use. These results are similar to the studies in Table 1. Solar radiation can be a driver or not depending on the article. However, we find that indoor and outdoor humidity, indoor and outdoor fine particle concentration, and wind speed and direction have no influence on window use. RH_{int} and $PM_{2.5, ext}$ were always found to be influential in Table 1 even though the second variable only concerns two studies. RH_{out}, WS and WD are controversial among the studies. It should be noted that in our case, WS and WD are not measured on site but at a nearby meteorological station. Draughts could have an impact.

To our knowledge, there are no residential studies that address the influence of indoor VOC concentration on window use. Fabi et al. (Fabi et al., 2014) address the issue for offices and find a small influence compared to other environmental factors. In our case, this factor is one of the most important, influencing window use in all living rooms and main bedrooms, the only rooms where it is measured, except in dwelling B. VOC_{int} may be one of the best indicators of perceived indoor air quality, as some of these pollutants have odours and may be associated with mucosal irritation (Fabi et al., 2014). However, the health impact depends very much on the VOC(s) considered, as this family includes many pollutants.

In terms of contextual variables, we only studied the HW alert, the day of week and the time of day. Only the last contextual variable is identified as a driver. These results are similar to those listed in Table 1 for time of day and day of week. Time of day variable represents the occupants' habits. We wanted to study the influence of HW on the use of windows, to see if the French government's message would have an impact. It does not seem to be important, and it is better to take into account directly the outside temperature.

4 CONCLUSIONS

Through a field measurement campaign in four French dwellings during the summer of 2022, this study seeks to identify the physical and contextual variables influencing window use, after looking at the indoor environment variations. Even if the indoor temperature distributions are different, surveys indicate that in all dwellings in Lyon, the thermal environment is perceived to be extremely hot during heatwave days. The house in Clermont-Ferrand is more thermally comfortable in the summer but the thermal environment is still considered unacceptable during heatwaves, especially at night.

Among the adaptive actions taken during heatwaves, all households reduce their calorific activities, open windows when the outside temperature drops and close solar protections during the hottest hours of the day. Some may also over-ventilate during night, use fans or air conditioners, leave or confine themselves to their homes, avoid some rooms, reduce their activity levels or adjust their clothing.

Using data analysis, we find that indoor and outdoor temperatures, indoor CO_2 and light VOC concentrations, global horizontal irradiation and time of day influence window use. Having identified the window use drivers using a feature selection method, we will be able to apply machine learning algorithms to model occupant behaviour. Future work will focus on assessing the indoor environment through indicators, and developing and evaluating behaviour models.

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