



HAL
open science

Towards Assessing Houses Resistance and Resilience Indicators At Inhabitants' Actions Using Temporal Sensitivity Analysis

Léa Gondian, Jeanne Goffart, Monika Woloszyn, Catherine Buhé, Philippe Marechal, Étienne Wurtz

► To cite this version:

Léa Gondian, Jeanne Goffart, Monika Woloszyn, Catherine Buhé, Philippe Marechal, et al.. Towards Assessing Houses Resistance and Resilience Indicators At Inhabitants' Actions Using Temporal Sensitivity Analysis. 2019 Building Simulation Conference (BS 2019), Sep 2019, Rome, Italy. pp.4149-4156, <10.26868/25222708.2019.210422>. <hal-02914110>

HAL Id: hal-02914110

<https://hal.science/hal-02914110v1>

Submitted on 11 Aug 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Towards Assessing Houses Resistance and Resilience Indicators At Inhabitants' Actions Using Temporal Sensitivity Analysis

Léa Gondian^{1,2}, Jeanne Goffart¹, Monika Woloszyn¹, Catherine Buhé¹, Philippe Maréchal², Étienne Wurtz²

¹Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, LOCIE, Chambéry, France.

²Univ. Grenoble Alpes, CEA, LITEN, INES, Le Bourget-du-Lac, France.

Abstract

This paper tends to evaluate the robustness of the summer building behaviour under inhabitants' actions. For that, two indicators are introduced: the *resilience* and the *resistance* of a building at the inhabitants' action. They evaluate by means of time-dependent sensitivity analyses how in amplitude and duration an inhabitants' action impacts the indoor operative temperature. The inhabitants' actions under the scope of the study are time-related and are: the opening of blinds and windows, the use of electrical appliances and the use of mechanical night ventilation. The evaluation of these indicators for two different designs of a low-energy house (with and without overhangs) reveals for both cases that the opening of windows in the morning is the action with the most influence during an heat-wave period in term of intensity and persistence in time.

Introduction

Occupant summer thermal comfort is and will be an issue when designing residential buildings. There are mainly two reasons for that: first, due to climate change, temperatures in summer will be higher, and longer periods of heat-waves i.e. abnormally high temperatures during several consecutive days are expected (IPCC, 2012), secondly, for environmental and energy savings purposes, it is beneficial to achieve thermal comfort in residential buildings without air-conditioning.

To assess the capability of future buildings to achieve summer thermal comfort, several indicators have been developed. Carlucci (2012) performed a review of these indices and Silva (2016) used 37 long-term thermal comfort indices to analyse them and divided them into percentage outside range of PMV and operative temperature; exceedance hours of PMV and operative temperature; degree-hour criterion of operative temperature; PPD-based; PPD weighted criterion; and operative temperature weighted criterion. Nevertheless, these approaches do not provide practical guidance for the designer to assist them in designing more summer efficient residential buildings.

Moreover, many studies have shown the influence of occupant behaviour on building summer thermal performance (Vorger, 2014; Silva, 2014) and it would be beneficial to exploit that knowledge to design building that are more efficient and robust i.e. better summer comfort even during occupancy. In addition, all these

studies have shown the possibility to use sensitivity analysis to assess the impacts of occupant behaviour on building summer thermal performance but none of them proposes to develop indicators using sensitivity analysis results to conduct a better design of residential building.

In this paper, two indicators that observe these specifications are introduced: the *resilience* and the *resistance* of the building at the occupant action. The first section of the paper describes the development of these indicators. In the second section, the two developed indicators are applied to a reference case (with overhangs) and to an alternative design (without overhangs) of a low-energy house to study the impact of the design on the robustness of the summer building behaviour.

Indicators development

The objectives of the two developed indicators seek to respond to two questions when one is interested in building thermal performance evaluation of a free-running residential building during the design phase. How intensely might an occupant action affect indoor temperature? And for how long? The first indicator, named the *resistance* of the building, reflects the impact of a precise action on the indoor operative temperature in a zone of the building during a heat-wave period. The second one, named *resilience* of the building, reflects the duration of the studied impact during the same heat-wave period. To compute the indicators, a temporal sensitivity analysis with time-related inputs is requested. The time-related inputs are inhabitants' actions and are introduced in the following subsection. Then the sensitivity analysis method used in this study is described and finally indicators' definitions are set.

Time-related occupants' actions

Occupant behaviours in building performance simulation (BPS) tools are traditionally described by static schedules (Yan, 2015; Saelens, 2011). As these static schedules are not able to reflect the stochastic nature of occupant behaviour, more complex occupant behaviour models were developed (Vorger, 2014). These stochastic models are based on monitoring campaigns or surveys that measure/indicate each targeted behaviour at the same time as contextual factors. By a statistical approach, relationship between these factors and behaviours are explained and at each time step, the probability of an action is assessed. With this more complex model, it is possible to obtain a variability of scenarios under the same environment and to produce scenarios that are more

realistic. However, with this approach, it is not possible to study the influence of occupant behaviour on building thermal performance using a sensitivity analysis as the sampling for the sensitivity analysis will be done on the inputs of the stochastic models i.e. on the contextual variables and not on the occupant actions. For this reason, stochastic model is not implemented in our study.

Moreover, in low-energy housing, it is expected in summer that inhabitants follow different recommendations at every moment of the day to achieve thermal comfort. The designer advises them to close the blinds during the day, to use night ventilation, to reduce internal heat gains and to close windows during the day to avoid warmer air to go inside and. Nevertheless, several feedbacks show that these recommendations are not always followed as inhabitants meet some constraints (noise, security, daylighting needs, feasibility...) to apply them (Brisepierre, 2015).

To study the impact of inhabitants' actions over time, the inhabitants' actions under scope of this study are:

- setting blinds position
- windows ratio of opening
- ratio of usage of electrical appliances
- use of mechanical night ventilation

and to get temporal information about the influence of these actions on the indoor temperature, some of them were differentiated for different moments of a day. By that means, 12 inputs actions are obtained:

- blinds position respectively between 8 a.m.-12 p.m., 12 p.m.-2p.m., 2 p.m.-6 p.m., 6 p.m.-9 p.m.
- windows ratio of opening between 7 a.m.-8 a.m., 12 p.m.-1 p.m., 8 p.m.-9 p.m.
- ratio of usage of electrical appliances between 7 a.m.-8 a.m., 12 p.m.-1 p.m., 8 p.m.-9 p.m., constant over time
- use of mechanical night ventilation between 10 p.m.-7 a.m.

The previous actions are intermittent and reproduced daily (except for constant plugs loads). The daily division for each action was settled so that it tends to represent variability of pseudo inhabitants' habits and mimic inhabitants that are actively using windows and electrical appliances in the morning, at lunch time and in the evening and that control blind position once for each period of the day. The possible values of the actions are randomly taken on consistent operating range that are introduced in next section.

This paper aims to use the results of a BPS tool [EnergyPlus] of a summer free evolution low-energy house to evaluate the influence of time-related occupant actions on indoor operative temperature using the presented static schedule-based behaviours and through a sensitivity analysis. In first study, there is no differentiation between the days of the week.

Sensitivity analysis

In this study, a global sensitivity analysis method is used. The random balance design-Fourier amplitude sensitivity test method (RBD-FAST), available on SALib

(Sensitivity Analysis Library) in Python has been selected as it is a robust and low-cost simulation sensitivity analysis method and it provides an accurate estimation of all the first-order sensitivity indices of inputs on a model output (Tarantola, 2006). It is a variance-based method and according to Sobol decomposition, the total variance V obtained of the output can be split into a sum of fractional variances:

$$V = \sum_{i=1}^m V_i + \sum_{j>1}^m V_{ij} + \dots + V_{1\dots m} \quad (1)$$

where V_i is the partial variance related to the input x_i alone among the m inputs and the other terms represent the variance explained by inputs interactions in the model. First-order sensitivity index S_i are obtained by dividing Equation (1) by the total variance and give:

$$1 = \sum_{i=1}^m S_i + \sum_{j>1}^m S_{ij} + \dots + S_{1\dots m} \quad (2)$$

with $S_i = V_i/V$ [-] and the other terms are the sensitivity index of order 2 to m . RBD-FAST is a frequency analysis, it computes the total and partial variance of the model output and gives access to the first-order sensitivity indices with only one dataset of simulation. The sampling method use in RBD-FAST is the well-know and efficient Latin Hypercube Sampling method with a permutations trick. More information and details about RBD-FAST applied on BPS tool can be found in Goffart (2015).

Indicators

The two indicators that are the focus of this study can be derived from the results of the temporal sensitivity analysis, i.e., sensitivity index at each time step for which the 12-presented actions are the inputs and the hourly zone operative temperature obtained by a BPS model is the output. The indicator of *resistance* [$^{\circ}\text{C}^2$] of the building for the i th-action is defined by:

$$resistance_i = \max_{t_0 \leq t \leq t_{max}} [V_i^*(t)] \quad (3)$$

Where V_i^* represents the signed partial variance related to the input x_i alone and the sign of the partial variance is determined by a linear regression process between the action i and the output, t_0 and t_{max} respectively represent the beginning and the end of the heat-wave period and within which the partial variance of each input is reassessed at each time step. In our study, the time step for the sensitivity analysis is fixed at one hour. The *resistance* to an action is therefore the maximal value of the variance of the operative temperature that can be assigned to the action alone for heat-wave period.

The indicator of *resilience* [h] of the building for the i th-action is defined by:

$$resilience_i = \max [t_p - t_k] \begin{cases} V_i^*(t) \neq 0 \forall t \in [t_k; t_p] \\ t_p, t_k \in [t_0; t_{max}] \\ p > k \end{cases} \quad (4)$$

The *resilience* of an action is therefore the longest duration in hours within the heat-wave period for which the partial variance never equal zero. That means that it is the longest period when an input continues to affect the operative temperature. In our study, the partial variances are set to zero in two cases. The first case is when $S_i(t)$, the first order sensitivity index at time step t of the input

x_i is less than 5%. The second is when $V(t)$ is less than $0,06^\circ\text{C}^2 \approx \sigma(t) < 0,25^\circ\text{C}$ with σ the standard deviation to ensure that relative impacts on the temperature are significant.

Case Study

This research has been carried out by using as case study a model of an already built house located in Paris area (France) that is part of a French research and development project named COMEPOS (www.comepos.fr), which aims to optimise the design of plus-energy houses.

Building description

The building is north-south oriented detached house. It is a low-energy building with a lounge/kitchen room in the first floor and three bedrooms in the second floor for a total living surface area of 80 m². The house is well insulated with interior insulation wall composed of glass wool layer ($R=1,2\text{m}^2\cdot\text{K}/\text{W}$) and polyurethane foam layer ($R=4,4\text{m}^2\cdot\text{K}/\text{W}$). The floor insulation is made of polyurethane layer ($R=4,7\text{m}^2\cdot\text{K}/\text{W}$). The roof is insulated with glass wool ($R=12,4\text{m}^2\cdot\text{K}/\text{W}$) and South facade has double-glazed windows while for North facade triple glaze windows were installed. The ventilation system is a double flow mechanical ventilation system with heat recovery and bypass. Figure 1 shows the reference case with 1-m depth solar overhangs and the alternative design without solar overhangs.

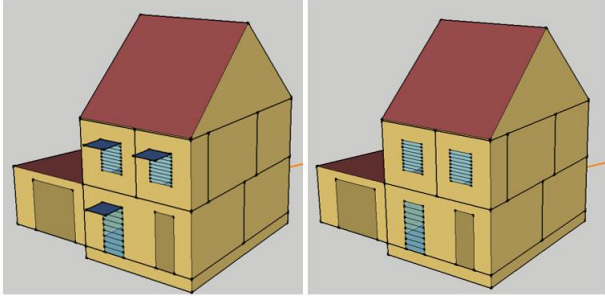


Figure 1: South facade of the case study modelled with OpenStudio SketchUp Plug-in: reference case (on the left) and alternative design (on the right)

Modelling and simulation

This study uses version 8.6.0 of the EnergyPlus software to compute operative temperature in each thermal zone of the building. Each room of the building has been described as a thermal zone for a total of 10 thermal zones. For this study, sensitivity analysis is run with 1000 simulations (convergence issues will be discussed later in the present paper). The time step of EnergyPlus computation is 10 minutes. Using LHS 1000 samples were created and propagated into EnergyPlus. In the next paragraphs is described how the four actions (12 inputs) of inhabitants under study are modelled in the software and detailed information about their range of variations are given. Table 1 summarizes the 12 inputs and their range of variation. The weather file used in this paper is a 2018-historical weather file from Melun (France) located at 20km from the house. That year, a hot summer with a 16-day period of heat-wave has been recorded in France from the 24th July to 8th August. It is the second warmest

summer, just after summer 2003 according to the French weather agency MétéoFrance.

1. Blind ratio

Designer recommend to totally close shading devices during the day to avoid solar irradiation to enter the local. However, inhabitants keep control the blind position. The blind can vary from totally open to totally closed position. As EnergyPlus does not permit to partially open/close blinds, each window of the building has been split in nine parts, as it can be seen in Figure 1 and a proper blind is attributed to each segment of the window. At the sampling phase, for this input, a number x between $[0;1]$ is obtained for each sample. If $x < 0,10$, all blinds are activated, for $0,10 \leq x < 0,20$ only the blind on the lowest segment of the window is not activated and that represents $\approx 11,1\%$ of opening of the blinds, for $0,20 \leq x < 0,30$, the blinds on the two lowest segments of the window are not air activated ($\approx 22,2\%$ of shading) until $0,90 \leq x \leq 1$ where all blinds of are totally opened. When generating the idf files i.e. input files of EnergyPlus, all shading devices of all the windows of the building follow the same position. Because blind position is differentiated at four different moments of the day, the presented process is repeated four times. Finally, for example, the blind position between 8 a.m. - 12 p.m. is the same for all the windows of the house and remains the same for all days in a same simulation.

2. Windows ratio of opening

It is recommended to keep windows closed when outside air temperature is warmer than indoor temperature and to open them when it is possible to use free cooling. In this study, a model of EnergyPlus, derived from Bernoulli equation, that relate natural ventilation flow rate Q_{nat_vent} [m³/s] by opening area with the local wind speed U_{wind} [m/s] and thermal stack effect has been used (Equation (5)). This model describes air movement in a simplest way than CFD (Computational Fluid Dynamic) so it less time consuming and it is possible with the model to specify the ratio of opening of the window R_{op} [-] that is one input of interest in this study:

$$Q_{nat_vent} = R_{op}A_{op} * \sqrt{C_1 U_{wind}^2 + 2C_2 g H \frac{|\Delta T|}{T_{zone}}} \quad (5)$$

where A_{op} [m²] is the area of the window, g is the acceleration due to gravity, H [m] is the height between the lowest and highest point of the openings and ΔT is the difference of air temperature in the zone (T_{zone} [K]) and the outdoor (T_{out} [K]). C_1 and C_2 are constant and are respectively the opening effectiveness and a discharge coefficient of the opening. C_1 depends on the angle between wind direction and the opening face orientation. C_2 is calculated according to:

$$C_2 = 0,40 + 0,0045|T_{zone} - T_{out}| \quad (6)$$

In each room, this model is applied when T_{out} is more than 10 °C and the ratio of opening is the same for every window of the house but is differentiated for the three periods of a day and the three values remain the same in one single simulation.

Table 1: List of inputs for the sensitivity analysis and variation range

Inhabitants' actions	Schedule time	Distribution	Mean	Interval	Min.	Max.
1-Blind_position_morning [%] (opening)	8 a.m.-12 p.m.	Uniform	50	+/-100 %	0	100
2-Blind_position_lunch [%] (opening)	12 p.m.- 2 p.m.	Uniform	50	+/-100 %	0	100
3-Blind_position_afternoon [%] (opening)	2 p.m.- 6 p.m.	Uniform	50	+/-100 %	0	100
4-Blind_position_evening [%] (opening)	6 p.m.- 9 p.m.	Uniform	50	+/-100 %	0	100
5-Window_ratio_morning [%] (opening)	7 a.m.- 8 a.m.	Uniform	50	+/-100 %	0	100
6-Window_ratio_lunch [%] (opening)	12 p.m.-1 p.m.	Uniform	50	+/-100 %	0	100
7-Window_ratio_evening [%] (opening)	8 p.m.- 9 p.m.	Uniform	50	+/-100 %	0	100
8-Plug_loads_morning [W]	7 a.m.- 8 a.m.	Uniform	368	+/-50 %	184	552
9-Plug_loads_lunch [W]	12 p.m.-1 p.m.	Uniform	368	+/-50 %	184	552
10-Plug_loads_evening [W]	8 p.m.- 9 p.m.	Uniform	368	+/-50 %	184	552
11-Plug_loads_stand_by [W]	24-hour	Uniform	88	+/-50 %	44	132
12-Night_control_ventilation_flow_rate [m ³ /h]	10 p.m.- 7 a.m.	Uniform	120	+/-25 %	90	150

3. Plug loads

Electrical equipment in a zone such as computers, televisions, and cooking equipment, also known as “plug loads” consume energy that might become a heat gain in the zone and affect indoor temperature. Therefore, it is recommended to limit (not to stop) the use of this equipment and the stand-by mode as far as possible in a period of heat-wave. Instead of listing and modelling every single equipment in the house, the choice was made to use the average ratios from the French thermal regulation that define a ratio per square meter of the average power uses during active phase of 4,6W/m² and a ratio per square meter of the average power uses in stand-by mode of 1,1W/m². These ratios were calculated by considering cooking, washing, refrigerating, audio-visual and computer equipment. As this equipment are mostly located in the lounge/kitchen zone, these ratios were applied to the total living surface area but the obtained power was only affected to this zone. As these ratios from regulation are average values, it is possible to define a range of variation +/-50% around these values to assess higher and lower level of household equipment. Finally, in this study, it was considered that 100% of energy use is converted into heat and scenario of usage are differentiated at three moments of the day.

4. Ventilation

At night, the use of a higher speed level of ventilation's fan is encouraged to dissipate heat that the building may have accumulated. According to the fan's documentation and to the topology of the case study ventilation rate can vary from 90m³/h (base level of 0,5ach) to 150m³/h (boost level of 0,9ach) according to the speed level. However, inhabitants keep control on the speed level and do have to reset speed fans every night. In this context, night ventilation rate can vary between the base speed level and the boost speed level. To ensure the consistency with the other inputs, continuous values between these two speeds are taken. In the model, a separate ventilation was dedicated for each zone and the ventilation rate of a single zone is proportional to the volume of the zone as previous values are given for the whole building.

Results

Presentation of the results

With 1000 simulations for each case, (=1000 combinations of actions) indicators are calculated in the lounge/kitchen. For that, sensitivity analysis is run for every hour of the heat-wave period i.e. 384 hours. The time calculation of 1000 simulations is around 180 minutes with 8 processors. Before presenting and comparing the computed indicators, intermediate results are shown for one case: a study of the behaviour of the variability of the output, the evolution of the computed sensitivity index and the partial variance due to each input over time.

Intermediate results for the reference case

All the results of a sensitivity analysis depend on either the observed dispersion of the output i.e. the hourly operative temperature in a zone is significant or not.

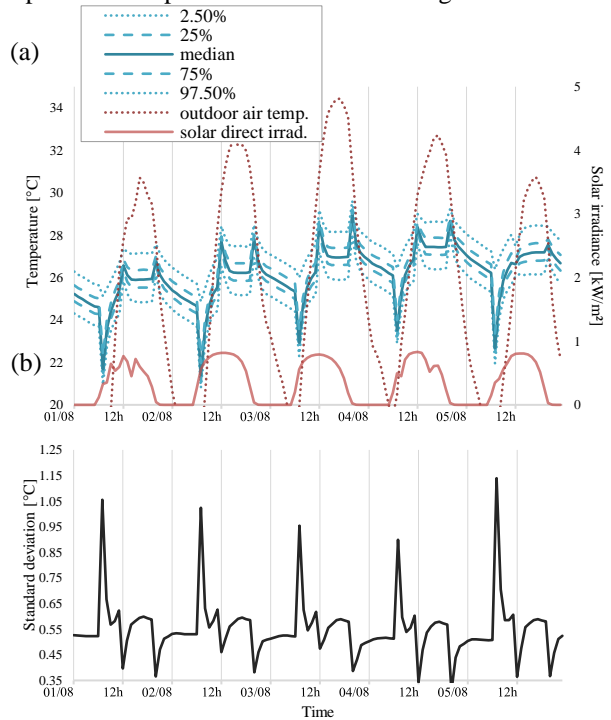


Figure 2: Time evolution of the variability of the operative temperature in the lounge/kitchen with (a) the median, the 50% (dashed line) and 95% (dotted line) confidence intervals and (b) the standard deviation

For that, Figure 2 shows the evolution of the variability of the indoor operative in the lounge/kitchen room during five days of the heat-wave period of the summer 2018.

In Figure 2(a), the median value, the standard deviation as well as the 50% and 95% confidence intervals of the operative temperature under the 1000 simulations have been plotted along with weather conditions. During the heat-wave period, the mean value of the mean operative temperature is about 26,1°C and the mean standard deviation is 0,56°C. During the same period, the maximum amplitude of the 95% interval confidence is 4,7°C and the operative temperature may reach 32,0°C. In Figure 2(b), it is possible to observe more clearly the behaviour of the variability of the operative temperature in the zone i.e. how the variability and the intermittency of the inhabitants' actions affect the variability of the output differently over time.

To quantify the influence of each input variability on the output variability, the first-order sensitivity indexes were computed for each hour and are represented in Figure 3 on a stacked area plot for five days of the heat-wave period. The indices give the relative influence, between 0 and 1, of each input on the output variability. On the bottom, the actions that have little influence all over time are plotted in grey colour. When the sum of all first-order indices is closed to 1 that means that there is no noticeable interaction between inputs on the operative temperature over time whereas a value significantly different reflects presence of interactions.

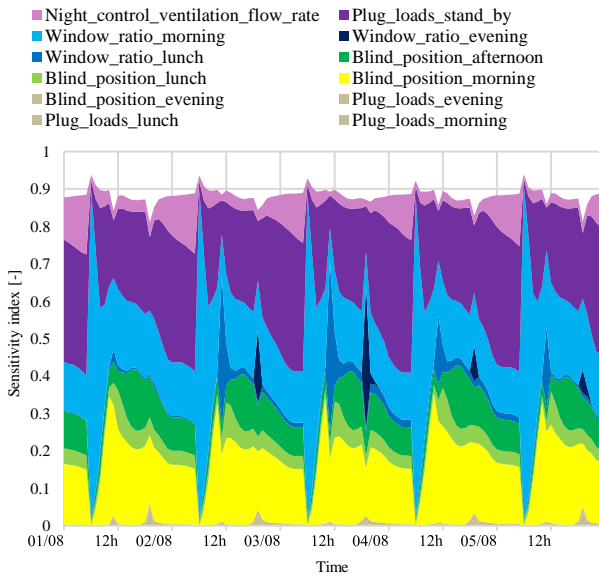


Figure 3: Stacked area plot of first-order sensitivity indices

The indices show that the use of electric equipment in stand-by mode, the ratio of opening of windows in the morning, the ratio of opening of blinds in the morning as well as in the afternoon are inhabitants' actions that have a high influence on the operative temperature in the lounge/kitchen. For example, the 01/08 at 11 a.m., the ratio of opening of blinds in the morning and the ratio of opening of windows represent, respectively, 30% and 19% of the total variance (0,39°C²) at that time.

Moreover, results also show that an inhabitant action affects the temperature in a zone not only when it took place but also several hours after it has finished. For example, the opening of blind in the morning happens at 8 a.m., lasts for four hours, and still have an influence on the variability of the operative temperature superior to 10% until 6 a.m. the next day.

It is also necessary to verify if 1000 simulations are sufficient for robust assessment of sensitivity. For that, a convergence analysis has been carried out. Figure 4 shows the convergence of the mean and the variance of the operative temperature in the lounge/kitchen for the 01/08 at 11 a.m., as well as the convergence of the sensitivity index of the most influential input at that time i.e. the ratio of opening of the blinds in the morning.

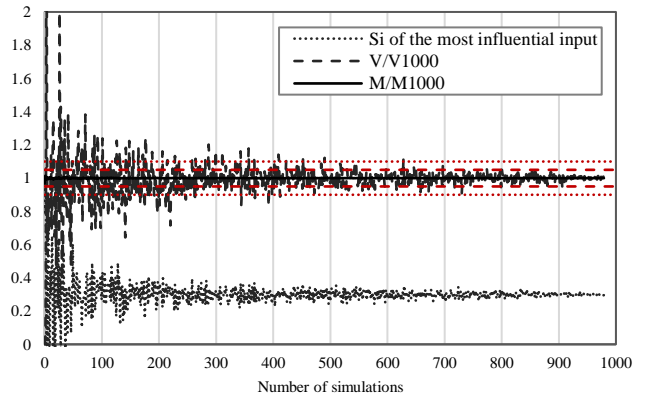


Figure 4: Convergence plot of the mean, the variance of the output and the first-order sensitivity index of the most influential input for one time step (01/08 11 a.m.)

With 800 simulations, the total variance is the interval of 5% of confidence (red dashed line) whereas with only 650 simulations (red dotted line), it is possible to obtain a confidence interval of 10%.

As it can be seen in Figure 2(b) that over time the variability of the output is not constant, it is therefore relevant to determine at each time step which input is influent and how intensely using absolute values and not only the relative influence at each time step as done by the classic sensitivity indexes represented in Figure 3. For that, partial variance values related to each input have to be determined at each time step. The respective partial variance related to each input was represented in Figure 5 on a stacked area plot for five days of the heat-wave period. It corresponds to the product between the pre-determined first-order sensitive indexes and the pre-determined total variance. The sum of the partial variances is equal to the total variance in accordance with Equation (1) and the variability over time of the total variance has already been visualised in Figure 2(b) as $\sigma(t) = \sqrt{V(t)}$. For the eight most influential inhabitants' actions, the respective partial variance has been plotted on a separated plot in Figure 6 for the whole period of the study. The ratio of opening of the windows in the morning is the action that affects the most the amplitude of the operative temperature in the lounge/kitchen. In Figure 5, it can be seen a peak of the total variance, when the action occurs, which is about

three times higher than the variance of the output observed at other moments.

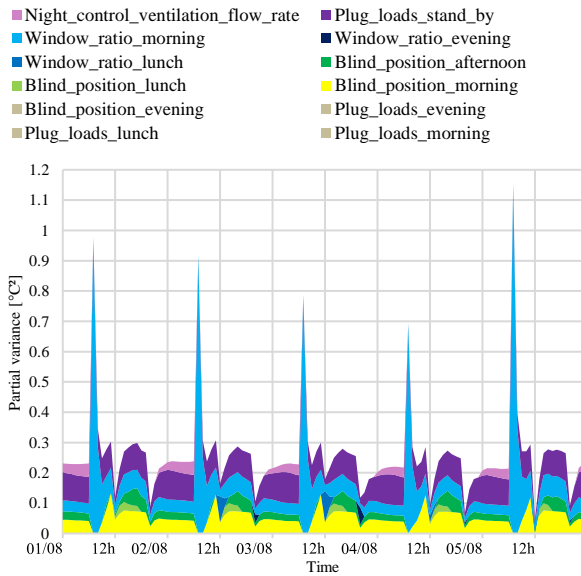


Figure 5: Stacked area plot of all partial variance values

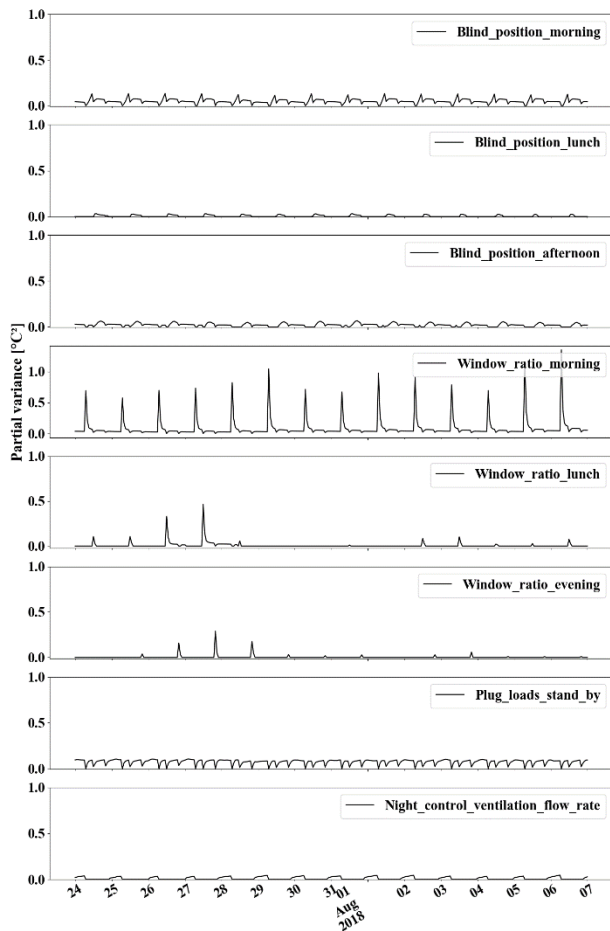


Figure 6: Partial variance evolution over time for the most influential inputs

Other inputs, as the ratio of opening of the blinds in the morning affect the temperature with less amplitude but for a long period over a day as its partial variance equals zero only a few times on the period (Figure 6).

To determine if the contribution of each input tends to obtain high or low temperatures in the zone, linear regression coefficients were computed for each input and for each time step along with the indoor temperature. Figure 7 shows one scatter plot with its linear regression curve. It represents the indoor temperature the 01/08 at 11 a.m. for the 1000 simulations respectively with the ratio of opening of the windows in the morning. As expected, for that parameter and at that time step, coefficient of regression is negative. The sign of partial variance of each parameter for every time step is determined similarly and partial variance values are then multiplied by -1 or 1 depending of the result.

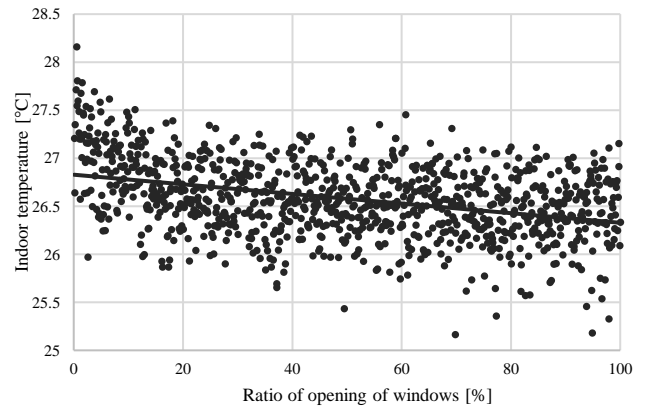


Figure 7: Scatter plot and linear regression curve between the indoor temperature and action n° 5

The Figure 8 shows the result of that analysis. On that figure, y-axis has been rescaled for each input to visualize the behaviour. It can be observed that there are two types of inputs. One categorie of inputs always impacts the temperature in the same way i.e. the related partial variance is always positive or negative and others for which the sign obtained by linear regression can vary between time steps. For example, it can be seen that the opening of windows in the morning is an inhabitant action that implies to obtain low temperature, whereas the opening of windows in the evening can either allow to obtain lower temperature as for example the 28/07 or also higher temperature like the 27/07, depending on the climate.

Computed indicators

Both the *resistance* and *resilience* indicators were determined for each inhabitant action and for the lounge/kitchen (South-Est oriented). In Figure 9, one example of the graphical display of the two indicators is represented for one input for the reference case. Finally and because of the significant quantity of information to visualise, it is relevant to evaluate the indicators that aggregate results rising from the signed partial variances curves analyses.

The results for the indicators of *resistance* and *resilience* for reference case are shown in Table 2. The results show that the opening of the windows at 12 p.m. or at 8p.m. are the two most “harmful” actions as the computed *resistance* for both of these actions are the highest.

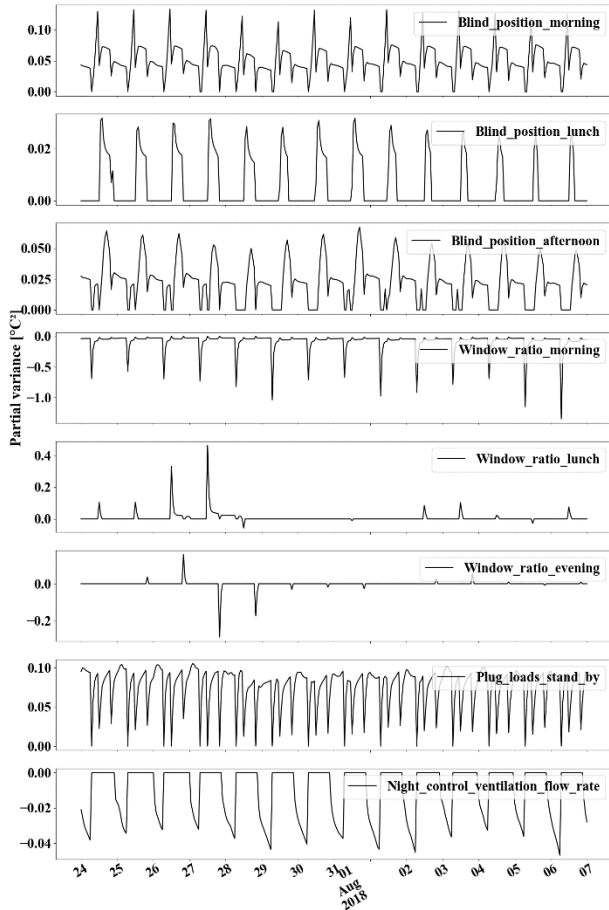


Figure 8: Signed partial variance evolution over time for the most influential inputs

Nevertheless, indicators reveal that the way the inhabitants employ blinds in the morning and in the afternoon have a lower impact in amplitude (lower *resistance*) than the opening of windows at lunch time or in the evening but their impact lasts for a longer period (higher *resilience*). Finally, it is important to notice that by definition, *resistance* indicators only highlight actions that can be harmful for the operative temperature. That's why indicator of *resistance* of the windows opening in the morning is found to be zero. The *resilience* indicator reveals that the opening of blinds is the only action that affects the operative temperature in the room for more than 1 day.

Table 2: Resistance and resilience indicators for reference case and alternative case studies

	<i>Resistance</i> [°C²]		<i>Resilience</i> [h]	
	Reference case	Alternative	Reference case	Alternative
1-Blind_position_morning	0,13	0,25	23	47
2-Blind_position_lunch	0,03	0,09	9	19
3-Blind_position_afternoon	0,07	0,12	19	23
4-Blind_position_evening	0,00	0,00	0	0
5-Window_ratio_morning	0,00	0,00	220	220
6-Window_ratio_lunch	0,46	0,40	10	10
7-Window_ratio_evening	0,16	0,12	2	2
8-Plug_loads_morning	0,00	0,00	0	0
9-Plug_loads_lunch	0,00	0,00	0	0
10-Plug_loads_evening	0,00	0,00	0	0
11-Plug_loads_stand_by	0,11	0,12	23	23
12-Night_control_ventilation_flow_rate	0,00	0,00	9	6

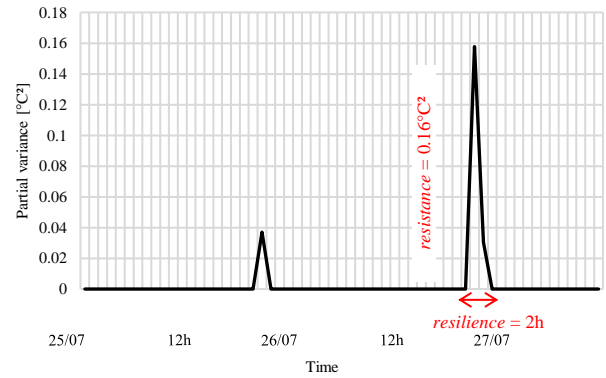


Figure 9: Computed resistance and resilience for the ratio of opening of windows in the evening

Comparison between the two variants

For the case without solar overhangs, a new sampling has been realised and 1000 new simulations have been launched with the proper EnergyPlus model. Consequently, the variability evolution over time of the operative temperature is different in this case in trend and in amplitude. The mean value of the mean temperature in this case for the same period is 26,5°C (+0,4°C compared to reference case) whereas the mean standard deviation is 0,66°C (+0,10°C), the maximum amplitude of the 95% interval confidence is 5,0°C (+0,3°C) and the maximum temperature is 32,3°C (+0,3°C). The output variability is slightly higher for this case and an analysis of the two indicators will help to understand which inhabitants' actions are responsible.

As the removal of the overhangs induces more solar irradiations at the windows, higher indicators of *resistance* and *resilience* for the blinds should be obtained for this simple case. The Table 2 gathers the computed indicators for the alternative case. As expected, it can be noticed higher values of *resistance* of the blinds in the morning, at lunch and in the afternoon, respectively +92%, +200% and +71%. According to the indicators, this constructive choice without solar overhangs necessitates much more caution on the part of inhabitants and advanced solutions of blind control can be proposed at the design phase. Interestingly, in both cases, the opening of windows at lunch remains the most influencing action.

Discussion and Conclusion

The study introduced two new indicators that allow assessing impact of inhabitants' actions in summer on thermal behaviour of a building. They are the *resilience* and the *resistance* of the building at the occupant action. Firstly, to develop these indicators, a set of 4 inhabitant's actions have been selected: opening of blinds, opening of windows, use of electrical appliances and use of mechanical night ventilation.

The calculation of the indicators requires temporal sensitivity analyses results. The methodology has been introduced and require one simulation by time step here 384 sensitivity analyses with only one dataset of 1000 simulations. Moreover, a convergence study has been conducted and the results show that 800 simulations i.e. a sample with a size of 800 would have been sufficient to estimate the indicators with a good accuracy (< 5%). The proposed *resistance* and *resilience* indicators allow to aggregate the results from the multiple sensitivity analyses and can be used to evaluate, compare different designs of a buildings and to be used for a design decision making process as they reflect how intensely might an occupant action affect indoor temperature and for which persistence. The purpose is to determine which design choice would make the building more robust, stable, to the variability of inhabitants' actions.

Applied to a reference case (with solar overhangs) and to a simple alternative (without solar overhangs) design of the same building, this simple illustration shows the potential of these indicators. The most important result of the study is that the indicators reveal that the inhabitants' action that have the most influence on the indoor operative temperature is the action related to the ratio of opening of windows between 7 a.m. and 8 a.m. This action affects the most both in amplitude and duration the temperature. An additional analysis has been done and revealed that the previous impact always induces lower operative temperature in the lounge/kitchen room. Nevertheless, the limit of the indicators has been reached as the *resistance* indicator only highlights actions that induce higher temperature. As the results show that actions can lower temperature in a building, a third indicator would be necessary in future studies to point them out.

Further investigations will focus on the relevance of this kind of indicators for characterizing the robustness of building summer performance of different design choices. More complex designs for which the dynamic of the building thermal response with respect to inhabitants' actions is more difficult to assess will be investigated as for example an alternative case with less inertia or with exterior insulation or with a different system of ventilation that coupled different building phenomena. It is also possible to use this methodology to provide the inhabitants with advices specific to summer conditions.

Nomenclature

- t time [h]
 S_i sensitivity index of the i th input [-]

- V output total variance
 V_i output partial variance associated with the i th input
 V_i^* output signed partial variance associated with the i th input
 x_i i th input

Acknowledgement

The authors would like to thank the French Agency for the Environment and Energy Management (ADEME) for funding this work through the COMEPOS research and development project.

References

- Brisepierre, G. (2013). Les conditions sociales et organisationnelles d'une performance énergétique in vivo dans les bâtiments neufs. Rapport de synthèse. *Les Chantiers Leroy Merlin Source*.
- Carlucci, S. and Pagliano, L. (2012). A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings. *Energy and Buildings* 53, 194–205.
- Goffart, J., Rabouille, M. and Mendes, N. (2015). Uncertainty and sensitivity analysis applied to hygrothermal simulation of a brick building in a hot and humid climate. *Journal of Building Performance Simulation* 10(1), 37–57.
- Intergovernmental Panel on Climate Change (2012): *Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge University Press.
- Saelens, D., Parys, W. and Baetens, R. (2011). Energy and comfort performance of thermally activated building systems including occupant behaviour. *Building and Environment* 46, 835-848.
- Silva, A.S. and Ghisi, E. (2014). Uncertainty analysis of user behaviour and physical parameters in residential building performance simulation. *Energy and Buildings* 76, 381–391.
- Silva, A.S., Ghisi, E. and Lamberts, R. (2016). Performance evaluation of long-term thermal comfort indices in building simulation according to ASHRAE Standard 55. *Building and Environment* 102, 95–115.
- Tarantola, S., Gatelli, D., and Mara, T.A. (2006). Random Balance Designs for the Estimation of First Order Global Sensitivity Indices. *Reliability Engineering & System Safety* 91 (6), 717–727.
- Vorger, E. (2014). Étude de l'influence du comportement des habitants sur la performance énergétique du bâtiment. *PhD thesis*.
- Yan, D., O'Brien, W., Hong, T., Feng, X., Burak Gunay, H., Tahmasebi, F. and Mahdavi, A. (2015). Occupant behavior modeling for building performance simulation: Current state and future challenges. *Energy and Buildings* 107, 264-278.