Cooling indicators for free floating buildings – quantifying the impact of inhabitants' actions using Temporal Sensitivity Analysis

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Abstract. In the coming years, heat waves will be more and more frequent and severe. New buildings must ensure thermal comfort to the occupants despite hot summer conditions, using passive elements, such as solar shadings, night ventilation, limitations of heat gains. The real performance of such systems is very sensitive to occupants' actions in the case of un-automated systems. In order to better understand and quantify the influence of different occupants' actions (window opening, solar shading closing, etc) on the building thermal response, novel cooling indicators are proposed based on building energy simulation and global temporal sensitivity analyses. Partial signed variances are used to quantify the impact of each action in terms of intensity and duration. In the present work two indicators are proposed and discussed: cooling indicator and global cooling indicator. They are applied on a case study of an energy efficient detached house constructed in France. 1000 simulations are run, with random selection of actions' parameters. Maximal temperatures in the main bedroom reach values between 27 and 33°C and are strongly impacted by night ventilation. The proposed cooling indicators aggregate the vast amount of information provided by the simulations and temporal sensitivity analyses and facilitate detailed investigations and comparative studies.

1 Introduction

In the coming years, heat waves will be more and more frequent and severe. New buildings must ensure thermal comfort to the occupants despite hot summer conditions, while limiting the use of air conditioning. For example, new residential buildings in France are mainly constructed without air cooling system. Then passive elements, such as solar shadings, night ventilation, limitations of heat gains from equipment and other solutions are needed. The real performance of such systems has strong limitations in terms of occupants' acceptance and ownership in case of automatic control, or is very sensitive to occupants' actions in the case of un-automated systems.

To study the influence of the inhabitants' behaviour on the performance of a building, whether it is energy use or comfort, the classical method consists in looking at the performances obtained for different occupation scenarios in the same building.

Using measurements, Andersen [1], gathered data from 290 identical houses, and was able to demonstrate the huge influence of occupants on energy consumption by looking at the dispersion of energy use. The characterization of the impact of the presence or action of the occupant on the building performance using experimental data is mainly done by searching for a trend line between action intensity and measured building performance ([2]). However, this type of experimental data is still rare, most work relies on Building Energy Models (BEM) - simulation tools dedicated to represent building response under varying boundary conditions, such as weather and occupants' actions. By modifying the behaviour of the inhabitants from one simulation to another, it is possible to calculate the energy consumption or the value of the comfort indicator retained for each scenario. The scenarios should correspond to behaviours close to reality in the type of building studied. Modelling of occupancy or corresponding activities is a very active research field, proposing methods from statistical tools [3] to machine learning techniques [4]. However most of these models are able to represent occupants' presence and activity, but not the impact of an individual action on building thermal response.

In the present work we aim to analyse and quantify the impact of actions that can contribute on passive cooling of a building during a heatwave. Selected actions of occupants, such as window opening, solar shading closing, etc, will be represented with an associated probability distribution. Then temporal sensitivity analyses will be used in order to quantify the relative importance of each action. Use of temporal analyses is very important in the case of summer overheating as the conditions in the building respond quickly to modifications of boundary conditions. Then, new cooling indicators will be proposed. Finally, the proposed method will be applied on a semi-detached energy efficient house located in France.

2 Methodology

2.1 Sensitivity analysis

To account for realistic variability in occupant actions, statistical approaches are needed and sensitivity analysis is the commonly used statistical tool [5]. Different studies in the literature highlighted the potential of sensitivity analysis. Even more precise than standard sensitivity analysis on aggregated outputs, the temporal sensitivity analysis allows to quantify the sensitivity of the thermal response of a building to different actions over time. In this way, it is possible to highlight the dynamics of the influence of actions on the thermal response, including the intensity and especially the persistence of the impact of an action on a model [6-7].

Here, one of the ANOVA (ANalysis Of VAriance) methods, the EASI RBD-FAST method, enabling for fast and robust computations of first order Sobol sensitivity indices, is used with Latin Hypercube Sampling (LHS), following the steps presented in [7].

Indeed, Sobol sensitivity indices S are the most popular measures of importance. These indices are based on the complete decomposition of the model's output variability V into a sum of fractional variances (see eq. (1) and (2)).

$$V = \sum_i V_i + \sum_{i<j} V_{ij} + \sum_{i<j<m} V_{ijm} + \cdots + V_{12\ldots k} \quad (1)$$

$$1 = \sum_i S_i + \sum_{i<j} S_{ij} + \sum_{i<j<m} S_{ijm} + \cdots + S_{12\ldots k} \quad (2)$$

where $S_i = V_i / V$ is the first-order sensitivity index that measures the amount of the response variance induced by each disturbed input X_i alone. The sensitivity indices evolve between 0 and 1.

2.2 Proposed cooling indicators

The general objective of the new indicators is to quantify more precisely the impact of an action on cooling down of a building, using the results of sensitivity analyses. Two indicators are proposed, one to describe the instantaneous reduction, and the second one to assess its persistence (duration in time). They are based on partial variances, and not on sensitivity indices, in order to represent the "room for manoeuvre" related to the real output variable, the free-floating operative temperature.

The *cooling* indicator is defined as the maximum negative partial variance $V_i^*(t)$, in absolute value, of an action calculated over the study period. The '*' indicates the signed (positive or negative) variance. The unit of this indicator is therefore °C². The higher the cooling indicator associated to an action is in absolute value, the more the building is able to benefit from the temperature decrease induced by this action. The cooling of action i is calculated from equation (3).

$$cooling(i) = \max_{t_0 \leq t \leq t_{end}} |V_i^*(t)| \{V_i^*(t) < 0 \quad (3)$$

The *global cooling* indicator is defined as the total negative partial variance of an integrated action over the study period. The unit of this indicator is therefore °C².h. The higher the global cooling indicator associated to an action is in absolute value, the more the building is able to benefit from the cooling induced by this action over the whole study period. The global cooling of action i is calculated from equation (4).

$$global\ cooling(i) = -\int_{t_0}^{t_{end}} |V_i^*(t)| dt \ \{V_i^*(t) < 0 \quad (4)$$

3 Case study

3.1 The building

The case study, an occupied house, is located near Paris (France) and presented in Figure 1. Large living space is located on the ground floor and three bedrooms on the first floor (surface area 80 m²). The house is well insulated on the inside with glass wool (R=1.2 m².K/W) and a layer of polyurethane foam (R=4.4 m².K/W). The floor is insulated with a layer of polyurethane foam (R=4.7 m².K/W) and the roof with glass wool (R=12.4 m².K/W). The windows are double-glazed (U=1.4 and 2 W/(m²K), and equipped with roller shutters as solar shadings. Moreover, the south façade has roof overhangs of one meter deep, to limit the solar radiation entering the house during the summer period. The ventilation system is a balanced mechanical ventilation system with heat recovery and a by-pass. The airflow rate can be modulated by the residents: the minimum corresponds to the basic flow rate value of 90 m^3/h in accordance with French regulations. The maximum corresponds to an air flow rate of 150 m^3/h for night-time mechanical ventilation in summer. The intermediate flow rate gives 120 m^3/h. Natural ventilation is possible by opening windows.

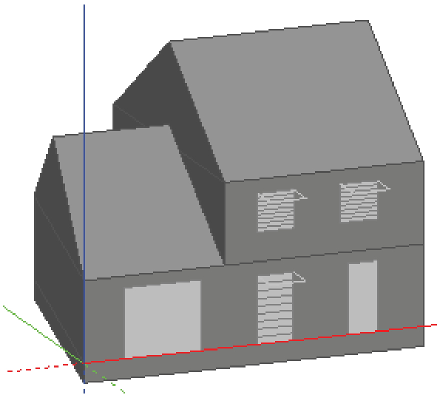

Fig. 1. Schematic view of the studied house.

The 2018 summer heat wave in France, and more specifically the period from July 24 to August 08 was selected for this study on summer comfort management in a free-floating building. The evolution of temperature and irradiance are given in Figure 2. The maximum daily temperatures are between 27.3°C and 36.4°C and the minimum temperatures between 19.0°C and 22.9°C.

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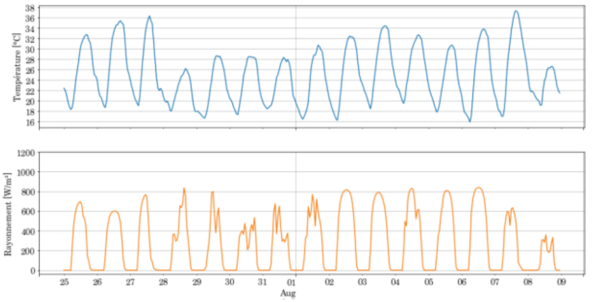

Fig. 2. Air temperature and direct solar irradiance recorded during the heatwave

3.2 Numerical simulation

The case study is modelled with EnergyPlus, a well-known and largely validated BEM. Here, the model is composed of 10 thermal zones, 8 for the living space, complemented with the attic and the crawl space. Natural ventilation via windows openings is modelled using buoyancy effect only and neglecting wind impact in order to represent extreme heatwave conditions. Occupancy schedule (a family of 4) is a typical deterministic schedule for France, except selected stochastic parameters for sensitivity analyses presented below. More details about the simulation assumption are presented in a previous paper by Gondian et al [8].

3.3 Variable parameters

The objective of the present work it to quantify, using the proposed cooling indices, the impact of occupant's actions on cooling down of a building with free-floating temperature during the heat wave. The main potentially impacting actions concern the ventilation (natural by opening of windows, or mechanical by controlling the airflow), operation of solar shadings, and the heat gains from the use of electrical equipment. As the impact of these actions may be different depending on the moment of the day, the corresponding parameters are divided into 3 or 4 periods (morning (8h-12h) / noon (12h-14h) / afternoon (14h-18h) / evening (18h-21h) / night (22h-7h)).

For sensitivity analysis all these parameters were given a uniform probability distribution, with minimum, average and maximal values reported in Table 1. As stated before, random selection using LHS was applied to generate 1000 input vectors. Then corresponding EnergyPlus simulations were run and the partial variances and sensitivity indices were computed for the operative temperature for each hourly time step.

4 Results and discussion

4.1 Temperature dispersion

At each hourly time step, the distribution profile of the operating temperatures can be plotted. The median value of the temperatures, the 50% confidence interval in which 500 of the 1000 calculated temperature values lie for each hour, and the 95% confidence interval containing 950 of the 1000 temperature values were determined. These curves are shown in Figure 3. The orange band corresponds to the envelope curve drawn from the minimum and maximum temperature values calculated for each time step and thus contains all the temperature values calculated at each time step.

As the actions are the only inputs to the model modified from one simulation to another, the variability between the 1000 temperatures obtained is then only due to the actions of the inhabitants. The amplitude between the different temperature values obtained highlights the existence of a possible 'room for manoeuvre' on the temperature induced by the actions of the inhabitants. Strong dispersions between the temperature values are obtained, at least 3.5°C depending on occupants' actions.

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

Action	Average	Interval	Min-Max
Windows opening / morning	50%	+/-100%	0 – 100%
Windows opening / noon	50%	+/-100%	0 – 100%
Windows opening / evening	50%	+/-100%	0 – 100%.
Shadings opening / morning	50%	+/-100%	0 – 100%
Shadings opening / noon	50%	+/-100%	0 – 100%
Shadings opening / afternoon	50%	+/-100%	0 – 100%
Shadings opening / evening	50%	+/-100%	0 – 100%
Elec. Equip use / morning	4.6 W/m²	+/-50%	2.3-6.9 W/m²
Elec. Equip use / noon	4.6 W/m²	+/-50%	2.3-6.9 W/m²
Elec. Equip use / evening	4.6 W/m²	+/-50%	2.3-6.9 W/m²
Constant Elec. Equip	1.1 W/m²	+/-50%	0.55-1.65 W/m²
Use of night mech. Ventil.	120 m^3/h	+/-25%	90-150 m^3/h

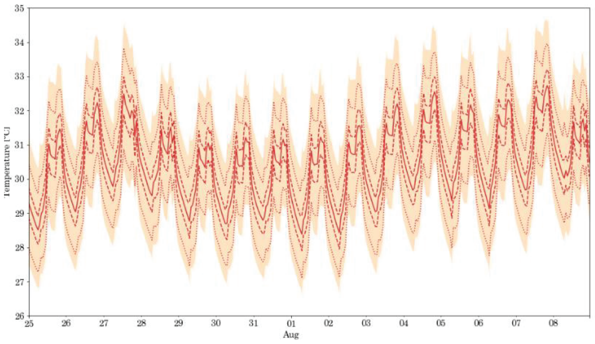

Fig. 3. Evolution of the median (solid line), the 50% confidence interval (dashed lines), the 95% confidence interval (dotted lines) and the min-max envelope curve (in orange) of the operating temperature in the living room during the heating wave

4.2 Study of sensitivity indices and partial variances

In order to identify which of the 12 actions influence the temperature dispersion obtained previously, the sensitivity of the operating temperature to the occupants' actions was evaluated.

As mentioned, the study of partial variances is preferred to the study of sensitivity indices to conclude on the influence of each action because the total variance of the temperature is different for each time step. To determine at each time step which action is influential and with which intensity, it is then interesting to work with indices translating the absolute influence like the partial variances. The partial variances represent the absolute part of the total variance explained by a single action, so the unit of the partial variances is, like the variance, the squared degree Celsius. To obtain these temporal sensitivity indices, the sensitivity analysis is run as many times as the number of time steps included in the study, i.e. 24*15 = 360 times over the study period.

To evaluate how an action impacts the indoor thermal environment it is important to distinguish the actions which tend to decrease the operative temperature to improve the thermal comfort in summer from those which tend to increase it and which thus amplify the discomfort. To do this, the approach is to “sign” the variance, e.g. to associate a coefficient "+1" or "-1" for each time step and for each partial variance.

The signed partial variances associated with each action are plotted separately in Figure 4. In order to visualize only significant influences, two criteria were applied:

- the total variance V calculated at time step t must be greater than 0.06°C² which corresponds to a minimum relative deviation s of 0.25°C
- and the first order sensitivity index associated with an action must be greater than 5%.

Based on the evolution of variances, no single action explains the variability of the operating temperature in the building over all the hours that make up the study period. Instead, different influence scenarios are observable on these plots.

The influence peaks are the most easily observable phenomenon. It results in a value of the partial variance of an action that increases and decreases rapidly. According to the curves, this phenomenon occurs mainly when an action starts. The peaks of influence are the most marked for the actions related to the window opening. Indeed, according to the difference in temperature between the indoor air and the outdoor air, the air renewal rates are important, leading to an increase in convective exchanges with the internal walls of the building and a modification of the air temperature of the room considered. The operating temperature of the room is thus influenced by these two phenomena. As soon as the windows are closed again, the sensitivity indices associated with the window openings decrease quickly after the action is stopped.

When the influence of an action does not appear in the form of peaks of influence, it is impacting progressively the operating temperature over time. In this case, the thermal exchanges during the execution of the action change and explain such behaviour. For example, during the night, the influence of the mechanical ventilation keeps increasing and this could be explained by the decrease of the outside temperature during the night making the cooling more and more efficient and thus more influential on the temperature.

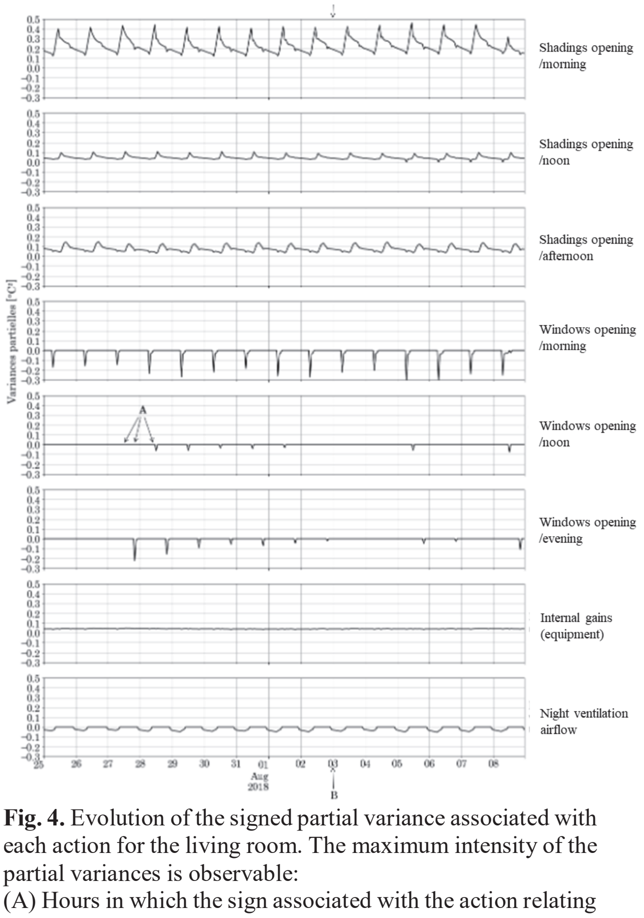

Fig. 4. Evolution of the signed partial variance associated with each action for the living room. The maximum intensity of the partial variances is observable:
(A) Hours in which the sign associated with the action relating to window openings at noon is "+1".
(B) Delimitation of the time corresponding to August 3 at midnight.

According to the profiles of partial variances plotted in Figure 4, the opening of the shadings in the morning is the action that induces the most variability on the operating temperature in the living room in comparison with the maximum values of partial variances associated with the other actions. The second most influential action is the opening of the windows in the morning, but the impact of this action, although important, is only of short duration and occurs mainly at the time of the action.

Taking the example of the opening of the shadings in the morning, the associated partial variance being non-zero after its stop at 12 o'clock, this means that its influence persists on the thermal response of the building throughout the day. At night, the operating temperature in the living room is then partly influenced by this action which took place several hours before. Once again, the temporal approach seems necessary to better understand the behaviour of the building.

If we look at a specific moment, for example August 3rd at midnight, we find that the opening of the shadings in the morning is the action that influences the most the temperature of the living room, and, that this action tends to increase the temperature. On the contrary, mechanical ventilation at night tends to decrease the temperature at the same moment. But the intensity levels of these effects vary from one hour to another. With the profiles presented, it is then difficult to conclude on the robustness of the building with respect to the actions of the occupants or even to conclude on the impact of an action on the whole heat wave period. To facilitate the interpretation of the profiles presented, proposed cooling indicators may be used.

4.3 Cooling indicators values

The calculation of cooling indicators for each action in the living room is presented in Table 2. Only the hours when the living room may be used (7h-22h) are represented. Moreover, the table presents only 4 out of 12 actions, as they are the only ones having non-null cooling indicators. The introduction of *global* cooling indicators is justified by the fact that looking only at the maximum intensity with which an action affects the thermal response of the building is not sufficient to judge the response of the building to this action. Indeed, for example, even if the night mechanical ventilation seems to be the action from which the building gets the least cooling, with the *cooling indicator* of 0.05°C², on the long term, i.e. on the duration of the study period, the *global cooling* generated is 1.88°C².h. The *global cooling* generated by the opening of the windows in the morning is 5 times higher than that of the windows opening in the evening with the *global cooling indicator* of 4.42°C².h against 0.91°C².h respectively.

The situation is somehow different in bedrooms. Bedroom 1 benefits only from the cooling provided by the night mechanical ventilation. The *cooling* and *global cooling* indicators during night hours (22h-7h) are respectively 0.07°C² and 5.96°C².h. Both cooling indices are null for all the other 11 actions in this case.

It should be noted that both cooling indicators consider only actions that decrease the indoor temperature. Consequently, actions that increase it (such as shading opening) give values of 0 and are not represented in the table.

Table 2. Calculation of the cooling indicators in the living room during the day (7h-22h) for the influential actions.

Action	Cooling [°C²]	Global cooling [°C².h]
Windows opening / morning	-0.31	-4.42
Windows opening / noon	-0.08	-0.37
Windows opening / evening	-0.23	-0.91
Use of night mech. Ventil.	-0.05	-1.88

5 Conclusion and Outlook

This paper presented the methodology, based on temporal sensitivity analyses, which leads to the creation of new indicators. These indicators: *cooling* and *global cooling* evaluate the capacity of a building to benefit from an action to be cooled.

Thus, in this study, the global cooling indicator shows us that, in the long term, the action on the night mechanical ventilation rate has the strongest influence to lower the temperature. In the short term, the cooling indicator shows that it is the action of window opening in the morning.

The proposed cooling indicators aggregate the vast amount of information provided by the simulations and temporal sensitivity analyses and facilitate detailed investigations and comparative studies. However, they should be associated with heating indicators, that could evaluate complementary influential actions shown by sensitivity analyses, such as shading openings.

These indicators can be used as decision support to compare design alternatives. The comparison of the indicators could allow to evaluate and compare the robustness of each variant and the summer comfort induced by the different actions. Indeed, the choice of a design variant that is robust to the actions of the inhabitants is not necessarily the choice that induces a better performance with respect to comfort according to the lifestyle of the inhabitants. Another possible use is the promotion of "eco-behaviours" – by indicating to the inhabitants which actions are the most profitable to avoid overheating.

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