Sensitivity analysis of the input parameters impacting summer thermal discomfort in buildings under future climate in Paris.

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RESUME. Dans un contexte de changement climatique, il devient nécessaire d'évaluer la capacité des bâtiments à maintenir le confort thermique l'été d'ici 2050. Dans cet article, une méthodologie d'évaluation des paramètres impactant l'inconfort d'été est présentée. En utilisant des fichiers climatiques recomposés d'un modèle climatique comprenant des projections futures, une analyse de sensibilité avec les méthodes Morris et Sobol est menée. L'analyse permet de déterminer que l'inertie ainsi que les coefficients d'absorptivité et d'émissivité des revêtements extérieurs sont les paramètres les plus influents pour un bâtiment cas d'étude à Paris lors d'un été futur typique et d'une future canicule. Cette analyse fait part d'une méthodologie d'aide à la conception des bâtiments sous l'effet du changement climatique, afin d'aider les acteurs du bâtiment à mettre en place dès aujourd'hui des solutions d'atténuation et d'adaptation au changement climatique pour le bâtiment.

MOTS-CLES : analyse de sensibilité, confort d'été, fichiers climatiques futur

ABSTRACT. As the climate is changing, it becomes crucial to evaluate buildings ability to maintain safe indoor conditions under future summer. In this article, a methodology is proposed to evaluate different input parameters effects on summer thermal discomfort. Using recomposed future weather files from one regional climate model, sensitivity analyses with the Morris and Sobol are conducted. It points out that the thermal inertia and absorptivity and emissivity coefficients of exterior coatings are the most impactful parameters under future typical summer and future heatwave in Paris in 2050. This analysis is part of a methodology to help designing buildings under climate change. The goal is to provide insights to buildings practitioners to allow them to put in place today mitigation and adaptation strategies to future climate.

KEYWORDS: sensitivity analysis, summer comfort, climate change weather data

1. INTRODUCTION

In order to mitigate climate change, in recent years, the French Thermal regulation (RT-2012) has become more stringent regarding building energy needs. Buildings have been constrained to be more energy efficient, usually implementing new features such as thick insulation, low airtightness and a high glazing percentage on South facades. This produced two contrasted outcomes: While new buildings now achieve a low heating consumption during the winter, some of them have started to experience overheating during warm periods. The effects of climate change are only starting to arise, as it is today well-known that heatwaves will only become more frequent, long and intense towards the end of the century. Therefore, it is crucial to ensure that occupants will remain not only comfortable during future heatwaves, but also safe from a heat- health related perspective. For this purpose, it is necessary to take well-informed decisions at the design stage of the building, ensuring a design thought for both winter and summer seasons. In France, analyzing summer thermal comfort is a quite relative new area of research since historically buildings were not used to overheat in the summer. In order to help building practitioners and decision-makers to take these decisions, a methodology is being developed to contribute to the design of buildings under the effect of climate change induced warmer temperatures.

2. METHODOLOGY

2.1. OVERALL METHODOLOGY

This work is part of a PhD thesis in partnership with La Rochelle Université and the CSTB. The objective is to develop a methodology to contribute to the design of buildings under the effect of climate change. In the first part of the project, future climate data were assessed in order to reconstruct future typical years and future heatwaves weather files. A case-study apartment was modelled with the software EnergyPlus to assess the building's potential and limitations to ensure comfortable indoor temperatures under future climate by the use of appropriate passive cooling strategies and systems. The proposed adaptations have been chosen to also mitigate climate change, therefore they have very low or no energy consumption in contrast to energy-consuming air conditioning systems. The investigated adaptations concern building materials, architecture and the control of windows opening and shades use. Two sensitivity analysis methods are used to investigate and discuss which design input parameters have a significant impact on the summer thermal discomfort.

2.2. SENSITIVITY ANALYSIS METHODS

Sensitivity analysis (SA) methods allow to identify and rank the input parameters that have an impact on an output objective function. According to the method, a matrix design is followed to create a minimal number of simulations corresponding to an optimal number of combinations of the input parameters within the full factorial design. Building thermal simulations were run with EnergyPlus. Two sensitivity analysis methods were used : The Morris method was first used for a quick screening (Morris, 1991). For each input parameter and in between two simulations, the absolute mean μ* and the variance σ of the elementary effects could be calculated. A high value of μ* is an indication of a high influence of the input parameter on the output. A small value of $\sigma/\mu *$ indicates that the input parameter j has a linear effect, whereas a value of $\sigma/\mu * > 0.5$ indicates that the input parameter is either nonlinear, either has interactions with other input parameters (Garcia Sanchez et al., 2014). As all input parameters were identified with $\sigma/\mu * > 0.5$, the Sobol method was applied to identify potential interactions in between parameters. The design matrix chosen for the Sobol method was the one advised in the Python SALib library, the Saltelli design matrix (Saltelli et al., 2004). From the output of the EnergyPlus simulations we could calculate the first, second and total order sensitivity indices for each input parameter. The first order is an indicator of the direct effect of a parameter on the output, the second is an indicator of the coupled effect of two parameters on the output, and the total order is the sum of the first and second orders (and higher orders if they exist). The sum of all the orders should be close to 1 (Saltelli et al., 2004). SA methods have been used for building thermal simulations since the 1980s, usually investing the energy consumption of buildings. Only recently in France, SA methods have been used to identify impactful parameters on warm indoor temperatures during summer (Gondian et al., 2019).

3. CASE-STUDY

3.1. BUILDING CASE STUDY AND MODELLING

The building case-study is a low-rise residential collective building. In this study the top floor flat is investigated. It has a 120m² living space located in between a 50m² unconditioned veranda South oriented and a 0.6m width glazed cavity zone located North, modelled as three distinct thermal zones (Figure 1). These features are an interesting bioclimatic design, as the two unconditioned zones act as buffer spaces for the living space. The windows disposition favors cross-ventilation. All flats have exterior balconies beyond the glazed façades which act as overhangs for the flats under them, and therefore reduce solar heat gains in the summer. In addition, light-colored external shutters are placed on the south-facing windows of the veranda. The walls are composed of 20cm concrete, the exterior walls of the living space have an additional 14cm polystyrene insulation for a U-value of 0.23 W/m².K. The floor and ceiling are made of 20cm of concrete with 3cm and 15cm polyurethane insulation respectively. The ceiling has a U-value of 0.16 W/m²K).

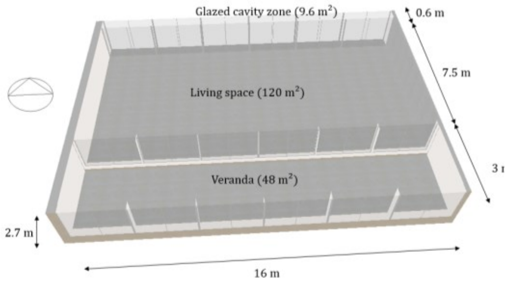

Figure 1: Rendering of the apartment case-study

3.2. FUTURE CLIMATE DATA

In this study the city of investigation is Paris. A historical typical year (IPSL-RCA4_historical_typical) reassembled from the period 1976-2005, a future typical year (IPSL-RCA4_future_typical) reassembled from the period 2041-2070 under the socio-economic scenario RCP 8.5, and a year containing a future heatwave (IPSL-RCA4_future_heatwave), more intense than the 2003 heatwave were used for the simulations. These climates were assembled during previous work

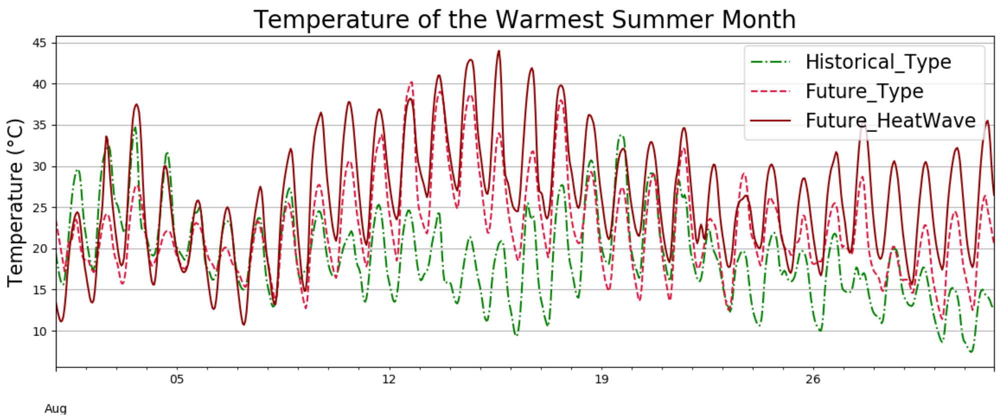

Figure 2: Hourly temperatures during the warmest week for different weather files in Paris

described in (Machard et al., 2020), climate data were downloaded from the EURO-CORDEX platform. On Figure 2, the temperatures of the warmest month of each weather file are displayed. Temperatures during the historical period showcase maxima up to 35 °C and night maxima up to 22 °C. During the future typical summer, daily maxima are up to 40 °C and night maxima up to 25 °C. Investigating the future heatwave, night maxima are around 27 °C and maxima around 44°C, therefore an almost +10°C and + 5 °C increase in daily and night maxima respectively in comparison to the historical period. The sensitivity analysis was conducted with the three climates.

3.3. OBJECTIVE OF THE SENSITIVITY ANALYSIS

The objective of the sensitivity analysis is to identify the effect of each parameter on the summer thermal discomfort. A criterion to assess thermal discomfort needed to be defined. Since the building is naturally ventilated and without air-conditioning, the adaptive comfort model from the standard EN-15251 is applicable to assess the indoor thermal comfort. Following the standard, the expected level of comfort in new and refurbished buildings is the category II. Therefore, in order to assess the summer thermal discomfort, we counted the degree hours above the category II upper limit.

3.4. DESIGN INPUT PARAMETERS AND THEIR SELECTED RANGE OF VARIATIONS

3.4.1. Optical properties of exterior coatings

The absorptivity and emissivity coefficients were modified in order to model the passive cooling potential of selective coatings, such as advanced cool paints. The ideal cool selective material should have a low absorptivity in the solar short-wave length combined with a high emissivity in the infrared long-wave length. These two parameters were changed simultaneously in the design matrix. Therefore, for the best-case, if the absorptivity in the solar wave-length was 0.05, the emissivity was modified to 0.95. These coefficients were applied to the exterior surfaces of the exterior walls and the roof of the apartment for all simulations.

3.4.2. Thermal inertia of the apartment

In the exterior and interior walls, ceiling and floor, the 20cm concrete was replaced with alternative materials with different thermal inertia. For the SA with Morris, three other materials were used (brick, earth and wood). In the design matrix, when the density of the material with thermal mass would change, the associated thermal capacity, thermal conductivity and thickness would be modified in conjunction and in order to keep constant the U value of the construction. For the SA with Sobol, as the material density could take any value in between its lower and upper limits, correlations were made to calculate the conductivity, thermal capacity and thickness of the material with thermal mass.

3.4.3. South façade shutters control

In order to prevent solar heat gains, a control is set on the incoming solar radiation on the exterior windows of the veranda. The maximal value chosen is 500, which corresponds to using the shutters only during the few most sunny hours of a summer day, while the minimal value of 5 corresponds to the shutters used almost all day. The North windows, unshaded, allow to ensure a daylight of 100 lux in the living space even when the shutters are fully closed on the South façade.

3.4.4. Glazing percentage on the North and South facades

A minimum glazing percentage of 15% was chosen in order to ensure minimal daylighting into the apartment. This percentage value is lower than the one imposed by the RT-2012 (for this apartment, a glazing ratio of 23% of the North and South facades would be required). However, in order to consider an extended range of possible values, we decided to extend this minimal glazing percentage.

3.4.5. Windows opening control

The condition for windows opening of a zone was set to the minimum set-point operative zone temperature. This set-point is assumed the same for the three thermal zones. Previous simulations showed that during warm periods, the temperatures are higher in the buffer zones than in the living space, therefore when it reaches the set-point temperature it should also have been reached by the two other zones. Design input parameters for the sensitivity analysis and their range of variation are given in Table1.

Parameter	Range	Unit	Parameter modified simultaneously	Location of the parameters
1 - Absorptivity of exterior coatings (AE)	0.05-0.95	-	Emissivity of exterior coatings	Exterior walls, ceiling
2 - Density of the material with thermal mass (Inertia)	650-2300		Thermal capacity, thermal conductivity of the same material	Interior wall, exterior walls, ceiling, floor
3 – Incoming solar radiation on windows for shutters control (Shades)	5-500	W/ m²		External windows of veranda
4 - Glazing % (Glazing)	15-95	%		North and South facades
5 - Operative temperature controlling windows opening (NV)	15-24	°C		3 thermal zones

Table 1: Input parameters for the sensitivity analysis and range of variation

4. RESULTS OF THE SENSITIVITY ANALYSES

4.1. ANALYSIS FOR THE DIFFERENT SUMMER CLIMATES IN PARIS

The SA was first run with the Morris method (Figure 3). Simulations were conducted from 10 to 500 trajectories and convergence was found from 50 trajectories. For 5 input parameters, 4 levels and 50 trajectories, 300 EnergyPlus simulations were run for the entire summer of the future typical year (June to September included). Simulations were run in parallel on 15 processors for a simulation time of 26 minutes. According to the Morris sensitivity indexes, the ranking of the input parameters is similar for all three climates: the thermal inertia has a predominant impact, followed by the optical properties of exterior coatings (E & A), the glazing percentage has a medium impact and the shades and natural ventilation control only a minor impact. The low effect of the shades control can be explained by two reasons: The presence of the overhang located on the South façade, and the fact that the direct solar gains enter the veranda but are then transmitted only as diffuse towards the living space (please see EnergyPlus Documentation, Engineering Reference, 2016). The low effect of the natural ventilation control is questionable since the presence of large windows induces high airflow rates. We can also observe that the Morris indexes have higher absolute values for the future climate's files, indicating that the building sensitivity is higher under warmer climates. Furthermore, all input parameters exhibit a $\sigma/\mu* > 0.5$, which means they either have a non-linear behavior, either interactions exist between the input parameters. For this reason, we decided to investigate further with the Sobol method, to understand the possible interactions and or non-linearity effects of the different input parameters. Simulations were conducted for 500 samples, first for the three climates files (historical & future typical year, future heatwave), each during the month with the warmest temperatures. The convergence of the total orders was found at 500 samples, but the uncertainties of the second order were still high. With 1500 samples (representing 18,000 simulations following the design matrix), the second orders uncertainty could be divided by two in comparison with the one calculated from 500 samples, at the cost of the computational time (9 hours versus 3, with 15 processors parallelized).

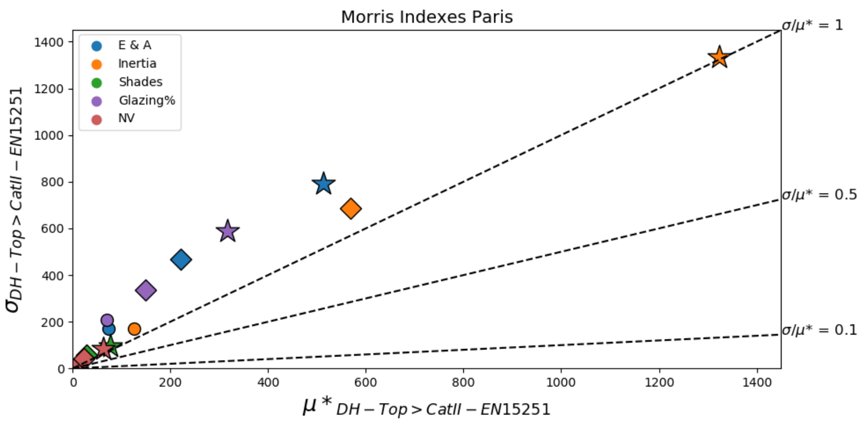

Figure 3: Sensitivity indexes from the Morris method for the historical typical summer (dots), future typical summer (diamonds) and future heatwave (stars)

The results of the Sobol method are presented on Figure 4. The ranking is similar to the ranking obtained with the Morris method, and all second order indices are relatively small, except the interactions between the absorptivity and inertia.

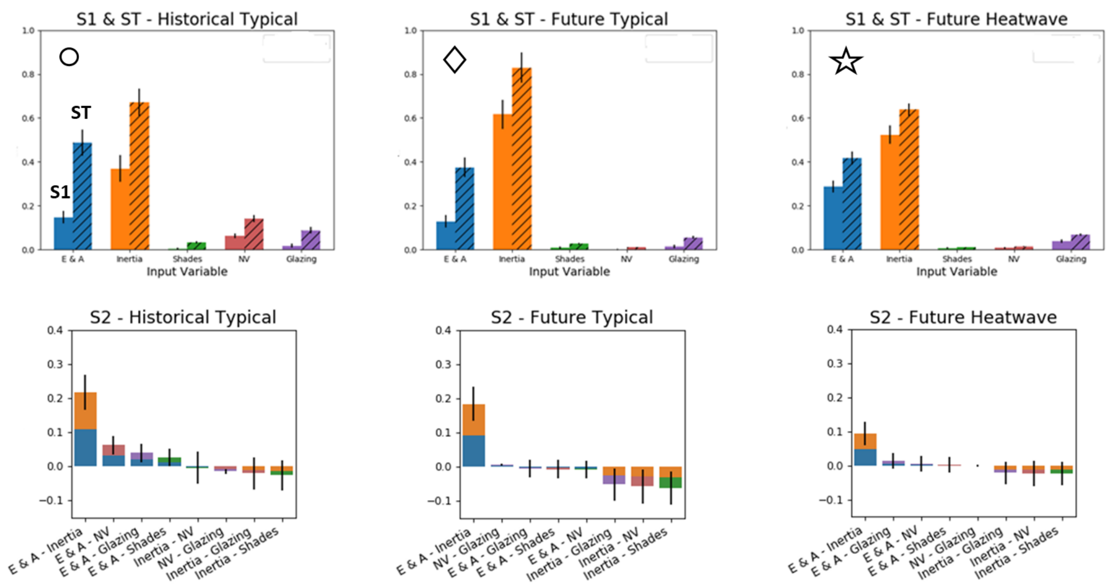

Figure 4: Sensitivity indexes from the Sobol method for the three climate files

In order to understand the temporal variation of these indexes, we conducted a temporal sensitivity analysis, i.e. the sensitivity analysis is realized for each hour of the month, resulting in 744 hourly indexes (while the initial method is an integral over the period).

4.2. TEMPORAL SENSITIVITY INDEXES AND PARTIAL VARIANCES

On Figure 5, temporal sensitivity indexes are presented, inspired by the work of (Gondian et al., 2019). The Sobol indexes are normalized between 0 and 1, however the variance represents the absolute effect of the variation in input parameters on the output. Indeed, we can observe that the variance for the discomfort indicator (DH Top > Cat-II EN-15251) is superior to zero only when the operative temperature of some simulations exceeds the threshold. The disparity between the Top_Max and Top_Min is representative of the variance: At hour 340, it is at its maximum, while Top_Max – Top_Min is around 15 °C. It can also be observed that most of the simulations (Top_25% to Top_75%) have an output variation of 4 °C, while the variation is much higher for the end of the distribution tail. To understand at which moment the variation of input parameters has an effect on the output (Top > Cat-II EN-15251), the partial variances are shown: they represent the absolute effect of each input parameter. It can be observed that when the variance is very small, the Sobol indexes and partial variances are very high, which are computational errors. When the variance is high, the sum of the Sobol indexes (total orders) is close to 1, which is expected (Saltelli et al., 2004). As already demonstrated by the integrated indexes on Figure 4, the inertia and absorptivity have the strongest impact on the output.

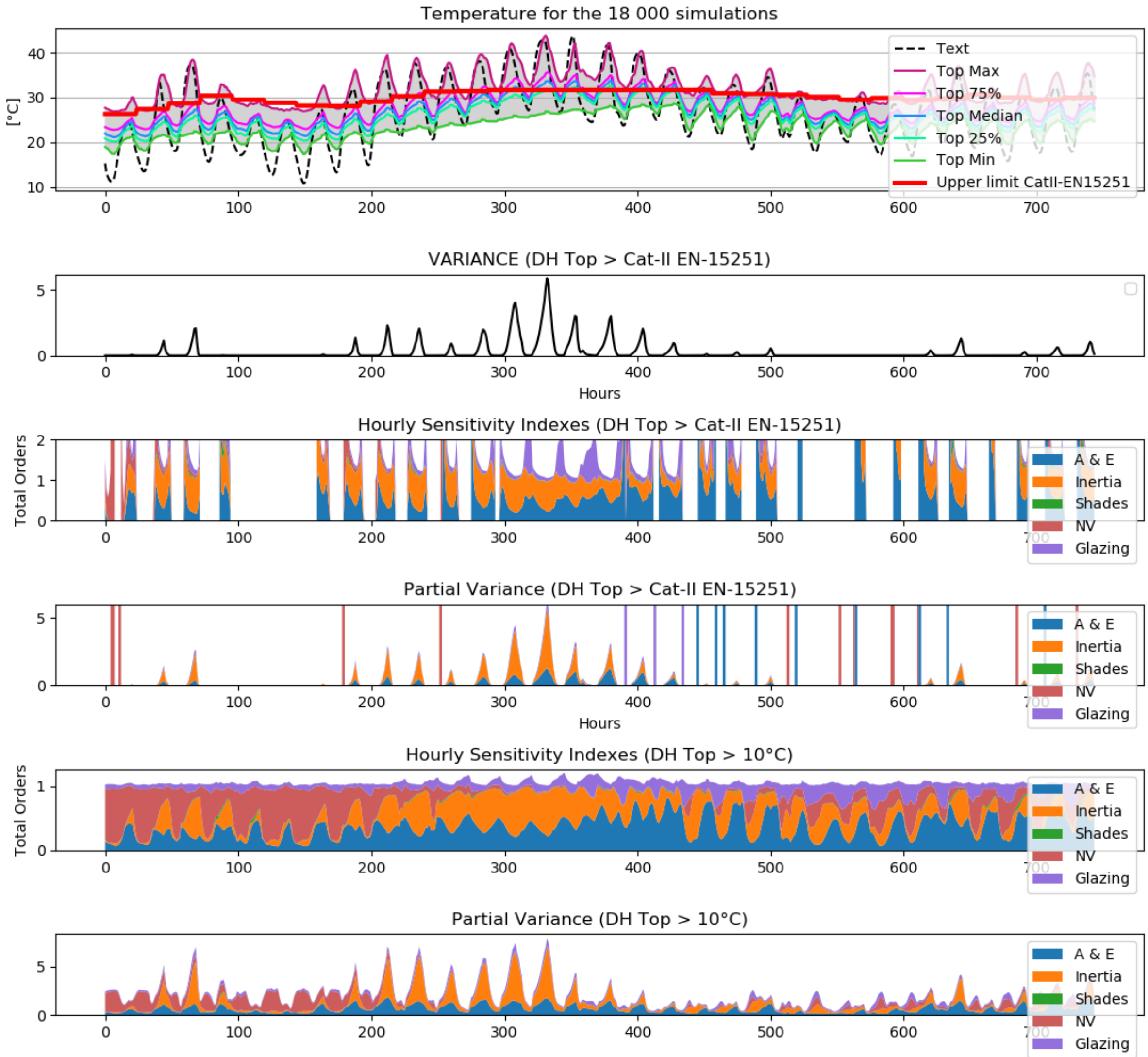

Figure 5: Temporal sensitivity indexes and partial variances of the design input parameters from the Sobol method for the future heatwave period in Paris

As the chosen threshold is representative only of a small portion of the outputs, we conducted the analysis for another indicator, which englobes all simulations outputs, the DH when Top > 10 °C. As the operative temperature for all simulations is always above 10 °C, the variance is always positive and therefore the sum of Sobol indexes always close to 1. Again, it can be observed that the variance has the highest value when the exterior temperature is the highest. Before the heatwave period, we can observe the influence of the natural ventilation control. During the heatwave, as the night operative temperature is above 24 °C for all simulations, the variation of the control has no influence on the output.

5. CONCLUSIONS AND PERSPECTIVES

A sensitivity analysis of the key design input parameters effect on summer thermal discomfort was conducted. While the Morris analysis revealed that all parameters were non-linear or with interactions, the temporal analysis with the Sobol indexes and partial variances allowed to understand at which moment the input parameters have the strongest impact on the variance. We can conclude that the operative temperature sensitivity to the variation in input parameters is the strongest when the exterior temperature is high, which suggests that the building robustness is lower under warmer climate. The results also showed that choosing a high threshold as output for the sensitivity analysis can complexify the analysis of the indexes and induce computational errors, and therefore care should be taken when selecting the threshold. The methodology presented in this paper is a first-step in determining which key adaptation strategies will allow to reduce summer thermal discomfort in future climate and increase the building robustness to overheating. It is a proposal to help building practitioners make the right decisions in the early stages of the building design. Modelling the building with future weather files ensures that buildings built today will provide safe indoor conditions under future climate.

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