Combined Fire Safety and Comfort Study Using Moment Independent and Variance Based Method

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Abstract

In tropical context and particularly in Reunion Island, promoting passive design is compulsory, but cannot be achieved without considering fire safety. This article aims at evaluating the interactions that exist between fire safety and thermal comfort in buildings, using variance based and moment independent methods. Two stategies are proposed: a first one, dissociated, where fire safety assessment and thermal comfort are evaluated separately and a second combining both considerations. Input parameters that influence the most the selected output indices are investigated for each strategy. A normalized index combining thermal comfort and fire safety is suggested introducing a new methodology. Difference between the two strategies is highlighted.

Introduction

Fire safety is one of the most important considerations when designing buildings and could have a significant impact, not only on the way to build, but also on building cost. At the same time, a new construction has to be more and more energy efficient with environmental design consideration. It is understood that these environmental strategies cannot be achieved without taking into account the occupant's comfort and behavior.

Thus, new buildings must enhance passive design strategies, with active users inside, especially in tropical context, as well as a high safety level. Therefore, the thermal comfort study and prediction should also be part of the initial design strategy for a building. Considering fire safety and thermal comfort as the root of a sustainable project, one should be careful of the interactions that can exist between these two key considerations. Indeed, the same parameter could have significant impact on both fire safety and thermal comfort in buildings. For instance, passive design that enhances natural ventilation has an impact on smoke extraction (Gao et al., 2016) and a given smoke extraction system can significantly influence the way to design the ventilation strategies implemented in a building. This is one of the multiple cases where fire safety and environmental design are dealt with separately despite of the relation that exits between them.

Identification of physical quantities such as interface height, smoke layer temperature and mass flow rate through openings, is crucial in order to quantify the risk. However, to minimize the risk, one should be aware of the uncertainties related to the hypothesis stated, and also identifying which inputs affect the most these quantities. Salem (2016) gives a sense of what could be the impact of uncertainties on the available safe egress time (ASET) defined by the standard ISO/TR 16738 (2009). ASET is defined as the time when integrity of occupants is not compromised during a fire event while RSET, also presented in ISO/TR 16738 (2009), is the amount of time required to escape from the building. ASET takes into account toxic and irritating gas as well as radiant and convective temperature effects on human bodies by setting threshold levels. Another study proposed by Kong (2014) specifies that uncertainties should not be neglected while elaborating fire scenarios using fire models. Allard and al. (2011) evaluate different parameters, including fire characteristic, that most impact the risks associated to fire using the CFAST software.

Thermal comfort is subject to a large number of studies (Rupp et al., 2015). Several models exist in order to assess indoor thermal comfort such as analytical models and field models. Fanger (1970) introduced the Predicted Mean Vote (PMV) in order to assess comfort in controlled environments. Climatic diagram (Givoni, 1969) and adaptive thermal comfort (De Dear et al., 1998; Nicol and Humphreys, 2002) model have been developed for naturally ventilated buildings. Sensitivity analyses have been conducted in order to evaluate the parameters that most affect thermal comfort and energy consumption for energy simulation model (Breesch and Janssens, 2005; de Wit and Augenbroe, 2002; Hu and Augenbroe, 2012; Tian, 2013). The literature review shows a lack of studies combining fire safety and thermal comfort targets, especially in tropical climate.

The objective of this paper is to discuss if the same key parameters are found by considering fire safety analysis and thermal comfort separately, as per the usual practice, or considering fire safety and thermal comfort together, as well as to investigate potential conflicting parameters. By definition, a contentious parameter has a relative significant impact on both safety and comfort index, but its impact is negative for one and positive for the other one.

Two methods are set out. A first conventional dissociated study is described, where thermal comfort and fire safety indices are defined separately. Then, the Sobol total-order sensitivity indices are calculated in order to assess which inputs most affect the outputs obtained. A moment independent study is performed using Probability Density Function (PDF) so as to analyze the entire output distribution. Such a study allows analysts to measure the inputs' influence on given model outputs (Borgonovo, 2006). The extended Givoni's zones, proposed by Lenoir (2013) for application in a tropical climate, are chosen here to construct the thermal comfort index (7). According to Allard and al. (2011) study, the chosen index for fire safety evaluation is based on three threshold values (8): A maximal upper layer temperature, a lower layer temperature and a minimal layer height. The authors have based their indices on the French fire safety regulation.

In the second approach, a new index is constructed combining comfort and fire-safety indices (9). The main aims are to understand the interactions that exist between safety and comfort, to analyze the rank of the different parameters for the two approaches and finally to highlight the contentious parameters.

Sensitivity Analysis

The aim of a global sensitivity analysis is to measure the input X_i uncertainty on the model output Y. The given factor distribution gives the model inputs. It is understood that the distribution function of a given parameter depends on its uncertainties. By definition, a sensitivity analysis is global when, on one hand, parameters vary simultaneously and, on the other hand, sensitivity is measured on the overall space of each parameter (Saltelli et al., 2000). In this article, the analysis of variance test, and more particularly the Sobol' indices, will be used. To estimate the contribution of each parameter, the Sobol' decomposition of the variance is applied (Sobol' 1990).

The key idea consists in representing the output Variance V_Y as a summation of increase order terms:

$$V_Y = \sum_{i=1}^{p} V_i + \sum_{1 \le i \le j \le p} V_{ij} + \cdots + V_{1\ldots p} \tag{1}$$

With V_Y the variance of the output distribution.
The V_i and V_{ij} terms can be calculated as follows:

$$V_i = V(E[Y|X_i]) \tag{2}$$

$$V_{ij} = V\big(E\big[Y\big|X_i, X_j\big]\big) - V_i - V_j \tag{3}$$

In this case, V_i is a linear term measuring individually input parameters' effects, while the second order term V_{ij} measures the interaction effects between the i^{th} and the j^{th} term. The other higher order terms follow the same principle. Sobol' has introduced his first and second order indices as follows:

$$S_i = \frac{V_i}{V_y} \tag{4}$$

$$S_{ij} = \frac{V_{ij}}{V_y} \tag{5}$$

The first order index is also known as the correlation ratio. It quantifies how the output is sensitive to the only parameterX_i. More specifically, S_i (4) shows the variance part of the output Y relative to X_i. Thanks to this index, it can be observed if a parameter is significant or negligible. However, the first order index does not allow classifying parameters between them and quantifying the interactions that exist between inputs parameters. This is the reason why Homma and Saltelli (1996) worked on a total order index, which is by definition the sum of all order sensitivity indices relative to the parameters X_i :

$$S_{T_i} = \sum_{k\#i} S_k \tag{6}$$

With $\#i$, all the indices that contain i (i, ij, ijk, ijkl ...). This index always remains up to or equal to 1. Moreover, the X_i parameter implication on the interaction that exists between parameters can be evaluated by simply making the difference between S_i and S_{T_i}. According to Bontemps (2015), if only the most influential parameters are of interest, one should use the first order index. Otherwise, the total order index is used in order to identify the less influential parameters and, as a result, to keep only the key parameters.

Different authors studied how to quantify the relative importance of total order indices. Chan and al. (1997) tried to develop a quantification method based on the study of total order index (S_{T_i}) values. They concluded that the parameter can be classified as:

- "Significant" if: $S_{T_i} > 0.8$
- Important if: $0.5 < S_{T_i} < 0.8$
- Not significant if: $0.3 < S_{T_i} < 0.5$
- Free of interest if: $S_{T_i} \le 0.3$

The mathematical definition of S_{T_i} shows that the value of the total order index for one parameter is relative to all the other parameters. In other words, the significance of one or multiple parameters is relative, since they are compared between them. However, variance-based methods such as the Sobol' Total Order index, allow identifying the parameters that most influence the outputs' variance (Borgonovo, 2006). According to Borgonovo (2006), the distribution reflects the decision maker's state of knowledge. Hence, probability as well as conditional probability distribution of model outputs will be used.

This study will focus on defining groups of important parameters for each approach: fire safety and thermal comfort studied separately, and a proposed combined study. The sampling of parameters is performed with the quasi-random sampling method based on Sobol' LPt sequence (1976), extended by Saltelli (2002). According to Campolongo and al. (2000), the Sobol' sampling algorithm generates quasi-random numbers that are characterized by an enhanced convergence rate (Saltelli et al., 2000). The methodology is well explained in Bratley and Fox (1988). Saltelli's scheme reduces the error rates in the resulting sensitivity index calculation. In order to identify the predominant consideration between fire safety and comfort, as well as the contentious parameters, a Latin Hypercube Sampling (LHS) is performed.

Building fire and energy models

Building simulation models can be divided into three categories: zone models, multizone network models, based on nodal approach, and field models. The nodal approach is widely used in building simulation, for both energy and fire models. Nodal models are based on the assumption that zone air temperature, contaminant concentrations and other physical quantities are uniform, and represented by a node. This assumption, which allows to obtain results without high computational cost, can be discussed in terms of precision. For both fire and advanced thermal models, the studied zone can be divided into two or more nodes (zones) in order to estimate smoke layer or thermal stratification. These models are also known as zone models. Multizone network models allow to connect multiple ambiances, represented by nodes, so as to measure the different exchanges that exist between them. Hence, low computational cost and the modelling procedure allow to easily integrate physical phenomena, which can provide new opportunities in fire research.

Field models are used in order to perform a more refined study. These models are usually used so as to estimate thermal bridge, flow characterization or wind potential. Several methods exist in field modeling area, but all of them are time consuming and have high computational cost.
Hence, zone models are the most appropriate solutions. Sensitivity analysis requires a multitude of simulations conducted at the same time. This study does not aim neither at evaluating a specific quantity in particular nor investigating a detailed physical phenomenon. In order to assess thermal comfort, the EnergyPlus model will be used.

The CFAST software, developed by the NIST (Peacock et al., 2013), allows performing fire simulations so as to assess safety level. CFAST is a two-zone model used to evaluate smoke, species and gas distribution resulting from a fire. The model can also calculate the layers temperatures distribution with respect to the time in the upper and lower layers. CFAST model is based on a set of ordinary differential equations derived from the fundamental laws of mass and energy conservation. According to the French regulation, three main values are essential when quantifying a risk of fire, which are the upper and lower temperatures as well as the interface height. All these values are calculated with CFAST.

EnergyPlus is an open source software, using zone modeling. Performing whole building energy and thermal simulation, EnergyPlus is capable of simulating thermal building behavior over a full year, using a weather data file and the building characteristics. The tool allows designing complex ventilation systems, for cooling and heating. In order to quantify thermal comfort, EnergyPlus seems to be one of the most relevant tools for this study.

Case study and boundaries description

In order to perform sensitivity analysis, a simple geometry case study is defined. The objective is to evaluate, for a simple case, what could be the impact of different building parameters (characteristics) for fire safety and thermal comfort. It has to be underlined that the two models, i.e. EnergyPlus (E+) and CFAST models, have the same initial parameters in terms of buildings and windows geometry, as well as ventilation rate (design flow rate for E+, mechanical ventilation for CFAST), resulting in seven common parameters (Figure 1).

Table 1: Parameters and their range

Parameters	Range	Comments
Room width (m)	[15m ; 19m]	##
Room height (m)	[6m ; 12m]	##
Room length (m)	[20m ; 25m]	##
Window width (m)	[1m ;10m]	##
Window soffit height (m)	[2.11m ; 6m]	Never reaches max sill height
Window sill height (m)	[1m ; 2.10m]	Never reaches min soffit height
Air change per hour (ACH)	[0 ACH ; 80 ACH]	Estimated from the chosen weather data file using EP airflow network module
Material thickness (m)	[0.05m ; 0.2m]	Same for all
Room orientation (°)	[0° ; 360°]	
Outdoor temperature (°C)	[15°C; 35°C]	Min and max extracted from weather file
Indoor temperature (°C)	[18°C ; 37°C]	Estimated
Indoor RH (%)	[50% ; 80%]	Estimated

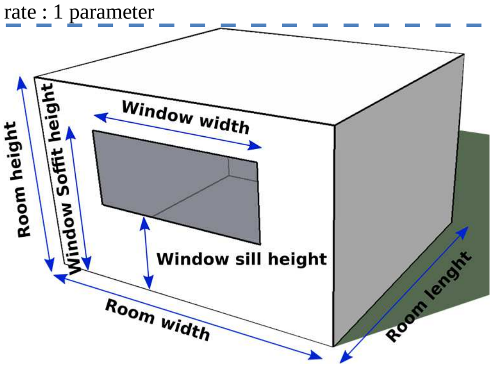
Specific parameters are defined for Energy Plus and CFAST simulations. Concerning the EnergyPlus specific parameters, the impact of the different components' thickness and the room orientation are evaluated, representing eight parameters (Figure 1). Only three parameters are specific to the CFAST model: Relative

Humidity, Indoor Temperature and Outdoor Temperature (Figure 1).

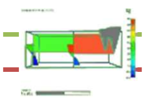
Concerning building geometry, data very closed to those used by Allard and al. (2011) have been taken. The room studied is large with high ceilings. The outdoor temperature range is typical for Reunion Island, with a tropical climate. Considering a naturally ventilated building (without air conditioning), indoor temperature and indoor relative humidity are within the range of local weather data. Climate conditions inputs are only used within the CFAST software. All the parameters and the related boundaries are given in Table 1.

One can notice that indoor temperature and relative humidity are not used as inputs in EnergyPlus. Indeed for this case study, thermal comfort in tropical climate is evaluated. As a result, relative humidity and thermal comfort are model outputs. Moreover, thermal comfort is evaluated using the extended Givoni's climatic diagram proposed by Lenoir (2013). The simulated room is considered as naturally ventilated. All parameters are assumed as normally distributed.

Common parameters
Window geometry : 3 parameters (sill, soffit, width)
Room geometry : 3 parameters (sill height, soffit height, window width)
Flow rate : 1 parameter



EnergyPlus parameters
Wall material thickness : 3 parameters (cladding, insulati plasterboard)
Roof material thickness : 3 parameters (deck, insulation, plasterboard)
Floor material thickness : 1 parameter (concrete)
Room orientation : 1 parameter



CFAST Parameters :
Indoor Conditions : 2 parameters (Temperature, Relative Humidity) ;
Outdoor Temperature : 1 parameter

Figure 1: Description of the assessed model

Methodology

The EnergyPlus software is used for thermal comfort assessment while CFAST (NIST) simulations are performed for the fire safety risk assessment. Python language, with its SAlib library, is used to conduct the sensitivity analysis and as a coordinate layer (Figure 3). A first dissociated study, where thermal comfort and fire safety indices are defined separately, is achieved. In addition, the Sobol total-order sensitivity indices are calculated in order to assess the most critical inputs, which affect the proposed outputs.

Moment independent study, by means of PDF and conditional PDF, allows finding contentious parameters as well as the most important consideration between fire safety and thermal comfort for this case study. Indeed, even if a parameter ranks well with Sobol' total order indices, it cannot be concluded for the global index that these parameters have a positive or a negative impact nor which between comfort and safety is the most critical one.

The impact of fifteen parameters is studied for EnergyPlus while the CFAST model includes nine inputs for this study. The same fire and the same heat release rate are considered for all the simulations. The fire is set at 1000 W/m^2 and reaches its maximal value at the mid-simulation time. In addition, the main objective concerning fire risk assessment is to evaluate the ability of the occupants of a building to escape in case of fire. Hence, the first 15 minutes of a fire event are simulated. The heat release rate increases and decreases linearly. The extended Givoni's (Givoni, 1969) zones proposed by Lenoir (2013) and chosen here to define the thermal comfort index named C (7), are exposed in Figure 2.

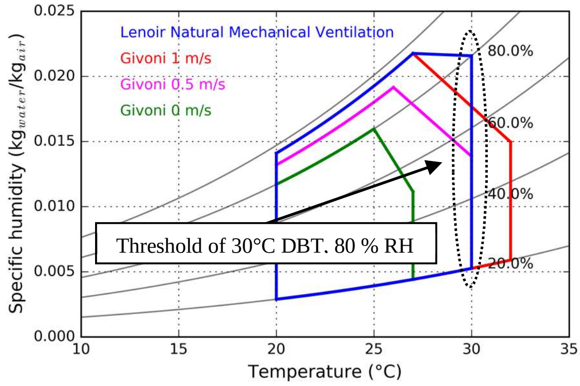


Figure 2: Extended Givoni's zones (Lenoir 2013)

According to Allard and al. (2011) study, the index selected for fire safety evaluation, S (8), is based on three threshold values: a maximal upper layer temperature (ULT), a lower layer temperature (LLT) and a minimal layer height (LH) with respect to the French fire safety regulation. In order to enhance the comparison, all indices are normalized:

$$C = \frac{Nb_{values} - \sum_{1}^{Nb_{values}} Nb_{(T_{air}>30°C\ or\ HR_{int}>80\%)}}{Nb_{values}} \quad (7)$$

$$S = \frac{Nb_{values} - \sum_{1}^{Nb_{values}} Nb_{(T_{ULT}>206°C\ or\ T_{LLT}>60°C\ or\ LH<1{,}80m)}}{Nb_{values}} \quad (8)$$

1
0

Nb represents the number of values or number of simulation points. $Nb_{(T_{air}>30°C\ or\ HR_{int}>80\%)}$ is defined as the amount of time when dry bulb temperature is above 30°C or relative humidity is above 80%. 'C' index represents the percentage of time below conditions of extreme discomfort. The aim is to be close to unity. 'S' index gives the percentage of time during which tenability is not compromised. The goal is also to reach unity. For the first study, the input parameters that most affect the C and S indices are investigated separately for each EnergyPlus and CFAST model. A second approach consists of the definition of a new index, I (1), by combining the comfort and fire-safety indices:

$$I = \alpha \times S + \beta \times C \quad (9)$$

Where α and β are weighting coefficients that range between [0,1]. In order to keep the new index normalized, we set: $\beta = (1 - \alpha)$. The impact of fire safety and thermal comfort is evaluated, throughout α and β, depending on the designer's choice in terms of weighting coefficients. In order to provide a consistent basis for comparison, all indices are normalized. To perform each study, about 4 000 simulations have been run for both EnergyPlus and CFAST models.

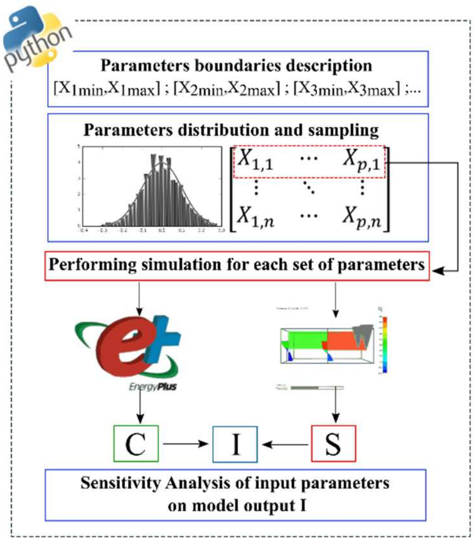


Figure 3: Python process for sensitivity indices calculation

The first objective is to analyze the key parameters for the global study as well as the comfort and safety studies separately. Concerning the global study, α is set at 0.5, i.e. the same importance is given to fire safety and thermal comfort, knowing that the two models have common input parameters. The second problem to be resolved is to evaluate how key parameters change with respect to α values. Indeed, do key parameters remain the same depending on the importance given to safety or comfort? Finally, contentious parameters are investigated using a second more in-depth analysis. LHS is used in order to obtain a sufficient amount of data.

Results

Conventional study

Global sensitivity analysis applied on comfort study shows the importance of flow rate when considering indoor temperature and relative humidity thresholds. Compared to all other parameters, it can be noticed that the flow rate parameter is by far the first one (Figure 4).

In tropical climate, flow rate control can have a significant impact on comfort levels in terms of temperature and relative humidity. Concerning this study, flow rate boundaries match the typical flow rates reached when natural ventilation operates.

For comfort study, only one parameter is relatively important while the others are free of interest. In this case, flow rate appears to be the most influential parameter. In other words, flow rate most influences comfort index. It can cause wider variations in the comfort index than in the other parameters.

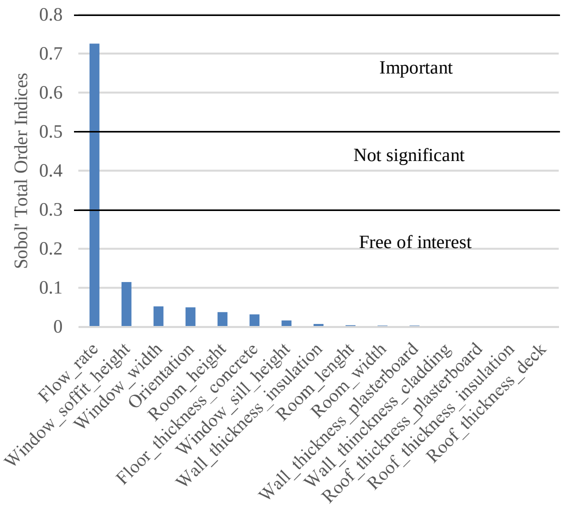


Figure 4: Total Order Indices ST for comfort study

The second most influential parameter is the window soffit height. According to Chan and al. (1997) classification, this parameter should be considered insignificant for comfort study. However, considering that natural ventilation does not operate at maximal rate all year long, designers should also pay attention to window geometry and orientation. When natural ventilation operates at its minimal flow rate, window soffit height, orientation and room height become key parameters.

Designers, who only consider thermal comfort, should focus on passive design strategies, which provide sufficient rates of ventilation. Secondly, they should pay attention to window soffit height and width. In order to find out why window soffit height and flow rate are important, a more detailed study will be conducted later in this article.

Concerning fire safety analysis, one parameter is important and one parameter is not significant whereas all the others are considered free of interest in this specific case. The flow rate appears to be the most important parameter. Besides, the window dimensions (soffit height and width) form the second most significant group of parameters (Figure 5). The other parameters are not relevant compared to the ones listed before. Outdoor and indoor conditions are free of interest in this case because of the range of temperature and relative humidity considered. Indeed, in Reunion Island, except for specific micro climates, temperature does not vary significantly.

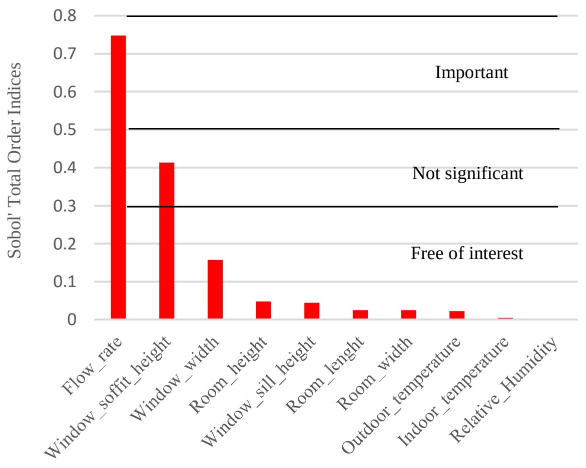


Figure 5: Total Order Indices ST for fire safety study

Concerning the key parameters, it seems obvious that flow rate is crucial in order to maintain a high level of fire safety. Indeed, in order to evacuate a building without compromising people health and integrity, particular attention should be paid to the smoke extraction system, and more precisely the extraction flow rate, which can be natural or mechanical.

In addition, in the case studied, smoke is extracted through windows. This is the reason why the group of parameters in relation with window geometry is in the second position of importance. In fact, depending on the window position and more particularly on the window's soffit height and its width, smoke extraction can be optimized. If a window is near the ceiling, smoke is extracted more rapidly. On the contrary, if a window is not sufficiently high, smoke layer can cause temperature elevation and does not extract well.

To conclude, the parameters of the dissociated study that are of interest are the flow rate and the window soffit height for both thermal comfort and fire safety. On one hand, designers should pay attention to the optimization of the ventilation flow rate in buildings in order to maintain a suitable level of comfort. On the other hand, designers should consider the window size and position so as to enhance fire smoke extraction in case of fire. Moreover, high ventilation rate is essential for proper smoke removal. It can be noticed that flow rate is essential for both fire safety and comfort. Natural ventilation potential has a significant impact on fire safety and comfort level as well. These parameters, which interact with both fire safety and thermal comfort, raises a number of questions. Firstly, do key parameters remain the same if the two studies are dissociated or associated? Do key parameters remain the same by changing the α value? Which could be their impact on the pre design process of a building? These are the questions explored in the next section, which focuses on the combined study.

New approach (α =0.5 or 0.1 or 0.9)

The first results are presented for a value of α of 0.5. This means that the same importance is given to fire safety concern and thermal comfort. Figure 6 presents the total order indices ST for all the parameters relative to the combined study as well as for the dissociated studies. Different information can be extracted from the figure above. Firstly, the first two parameters are the same for the global and the dissociated studies.

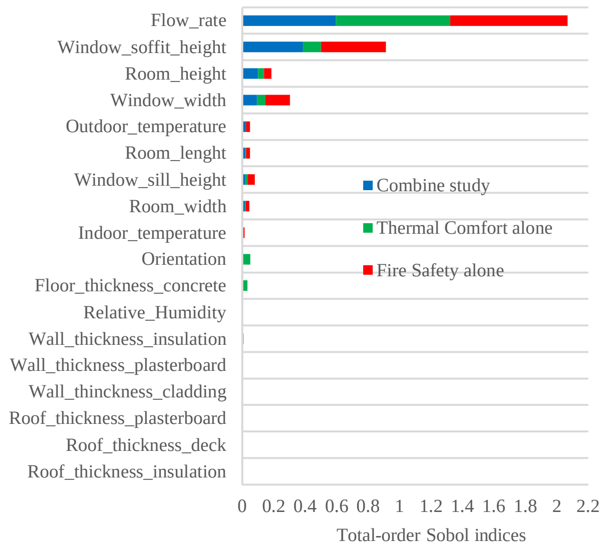


Figure 6: Total Order Indices ST for the combined and the dissociated studies, with α=0.5

Secondly, designers should focus on different parameters for a combined or a dissociated study. Indeed, the first fourth parameters are common parameters for both studies. In addition, room height is the third parameter of interest for the global study whereas it is only the fourth and fifth parameters respectively when considering fire safety and thermal comfort alone. It can be clearly observed that different conclusions can be drawn from the dissociated and the combined study.

For the global study, all the parameters relative to comfort study that are not common parameters have the lowest values in terms of total order indices. Taking into account fire safety and thermal comfort at the same level, flow rate is the parameter that requires the greatest attention. The variation of the alpha value gives a sense of the given importance to thermal comfort or fire safety.

Figure 7 presents the total order indices for different values of α, i.e. α = 0.1 α = 0.5 and α = 0.9, for the first five parameters. Figure 7 shows that different orders can be observed for the three values of α. Flow rate has a higher total order effect when studying safety and comfort separately or together, for α =0.1

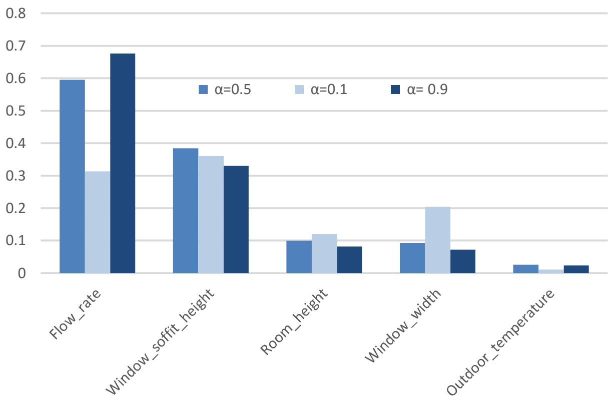


Figure 7: Total Order Indices ST for the combined study, α=0.5, 0.1 and 0.9

Even if emphasis is laid on comfort (α=0.1), different results can be observed compared to the comfort study alone. Indeed, flow rate and window soffit height, which have switched their ranks, as well as room height, window width, and outdoor temperature (fire safety parameters) are the five first parameters. In order to understand these contrasts between combined and separate study, a more detailed data analysis is required. To provide sufficient data, a new parameter sampling is performed using LHS. Ten thousands model outputs are now studied for α = 0.1 or 0.5 or 0.9.

Even if the analysis of the variance method through Sobol' indices allows classifying parameters and identifying the most influential ones, this method cannot be used in order to determine which parameters are contentious, and which concern, between fire safety or thermal comfort, have the greatest impact when considering both of them together at the design stage of a building. Only the relative order of the different parameters is given here. The following part of this section focuses on window soffit height and flow rate, which are the two main parameters of interest, in order to identify if they are contentious or not.

In-depth study using PDF and scatter plot

To highlight contentious parameters, the first step is to plot all the ten thousand flow rate and soffit height points, according to the global index. Hence, tendencies for different values of α can be observed.

Figure 8, Figure 9, and Figure 10 show the soffit height and flow rate according to the global index, for α = 0.5, 0.1 or 0.9. Figure 8 depicts several patterns for both soffit height and flow rate. First and foremost, a clustering of points can be observed around a global index value of 0.9. Secondly, scattered points are observed for a global index ranging from 0.7 to 0.8 with a concentration of points, as well as for a global index around 0.5, for lower values of flow rate and soffit height.

This graph shows the values obtained for safety and comfort issue considered at the same weight of importance and a clear tendency cannot be drawn from it.

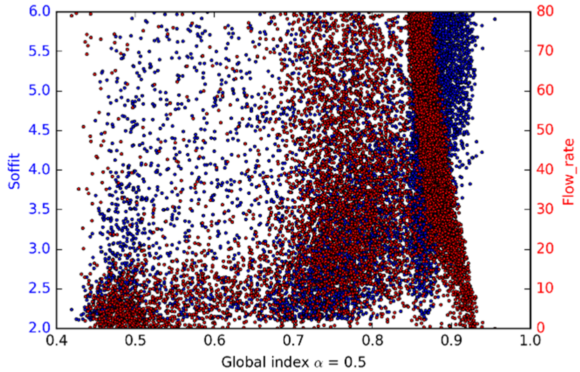


Figure 8: Flow rate and soffit height according to the global index, with α=0.5

Thus, both cases when priority is given to fire safety or to thermal comfort need to be investigated.

Figure 9 and Figure 10 allows identifying which concern between fire safety and thermal comfort is responsible for the results observed above.

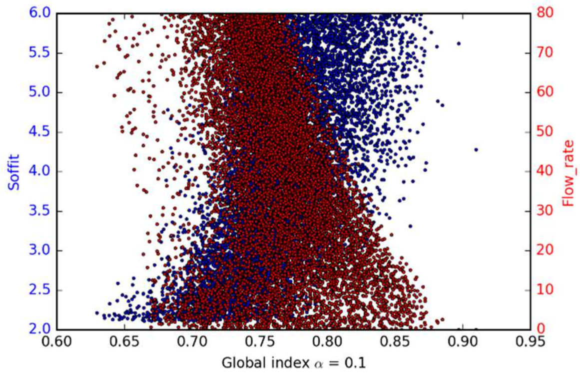


Figure 9 : Flow rate and soffit height according to the global index, with α=0.1

Figure 9 shows that the global index varies from 0.64 to 0.92. Considering comfort with a weighting value of 0.9, it can be concluded that, in this case, the building is globally suitable in terms of thermal comfort regarding the range of inputs' uncertainties. In addition, two typical tendencies can be observed for flow rate and soffit height. Indeed, the higher the soffit height, the higher the global index. This can be explained by analyzing the comfort index set out. Indeed, the more the indoor temperature exceeds a set threshold, the lower the index is. Moreover, the comfort index is defined for all hours of all days, including nighttime. Consequently, the higher the window, the more the exchange surface is important, allowing reducing extreme temperatures inside a room by night or when the window is not sun-exposed. It should be noticed that the results discussed in this article strongly depend on the index defined.

Different trends can be observed from the flow rate values. The higher the flow rate, the lower the global index. In this case, there are no internal loads, and therefore, flow rate brings hot air inside instead of extracting internal loads. Thus, flow rate could be responsible for the extreme temperatures reached inside the building. Nevertheless, the decrease in the global index value when diminishing soffit height is not significant since the index is above 0.64 and a concentration of points can be observed for a global value around 0.78. In addition, the trends observed for both soffit height and flow rate are not clearly linear and even if α=0.1, fire safety index could have a significant impact regarding the range of variation for the global index, with α=0.1. The variation for the global index is around 0.25.

Knowing that the weighting coefficient on fire safety is set equal to 0.1, in the cases where its index (S) reaches unity or zero, this could lead to an impact around 0.1 on the global index (I with α=0.1). This is the reason why it is of great importance to analyze the case where α=0.9.

Figure 10 shows soffit height and flow rate according to the global index, for α=0.9. A large line of points can be observed for a global index equals to approximately 0.98. In addition, a dense scatter of points for a global index that ranges between 0.6 and 0.9, for a soffit height between 2.11m and 4.5m, and for a flow rate between 0 and 50 ACH can be seen. A second dense scatter can be observed for low global index values, as well as low soffit height and flow rate values.

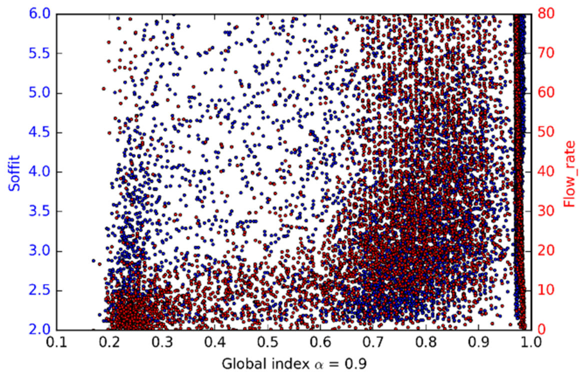


Figure 10: Flow rate and soffit height according to the global index, α=0.9

However, one cannot clearly examine quantitatively how the global index can vary in response to different values of ***α***. Hence, to better understand Figure 10, a probability density function should be plotted for the global index (with α=0.1 or 0.5 or 0.9). Furthermore, a conditional probability density function is helpful so as to highlight how the soffit height and the flow rate values interact with these probability repartitions.

Figure 11 presents the probability density functions of the global index I for α=0.1 or 0.5 or 0.9. For this specific case, if alpha equals to 0.1, the values obtained show less scatter than for alpha equals to 0.9. Consequently, focusing on thermal comfort for this building will lead to a small variation of the global index whereas focusing on fire safety leads to a wider dispersion of the global index.

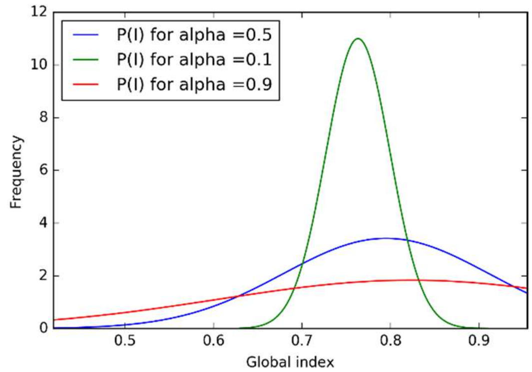


Figure 11: Probability density function of I repartition for the global index, with α=0.1, 0.5 and 0.9

As a result, fire safety can be considered as the issue with the greatest impact on the global index for this study. The conclusion that can be drawn is that the use of probability density function can help to identify quantitatively which concerns between fire safety and thermal comfort most influence the global index. This probability analysis could help designers to focus on the objective that most impact a global index set up. For instance, in this study, less attention can be paid on thermal comfort but parameters that increase fire safety level need more thorough study.

In order to evaluate which values of soffit height and flow rate are responsible for high or low global index, the conditional probability density functions are plotted for each of the two parameters. Figure 12 shows the conditional probability of the global index for different ranges of soffit height while Figure 13 presents conditional PDF of I for several ranges of flow rates. It can be observed in both graphs that increasing window soffit height as well as flow rate induces a more satisfactory global index.

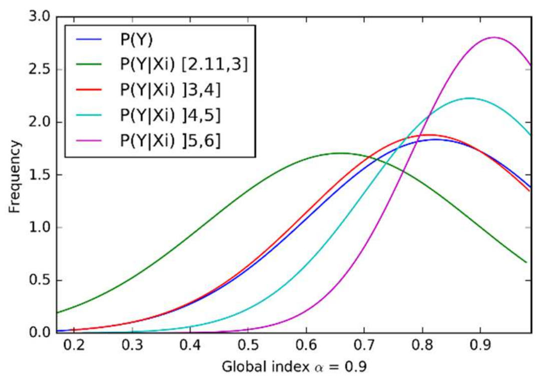


Figure 12: Conditional probability density function of global index I, for different ranges of soffit height (α=0.9)

In order to have a global index that ranges between 0.6 and 0.9 considering fire safety at 90%, soffit height should have a value between the maximum range of]5m, 6m]. The flow rate should also have a value in its highest range, i.e.]60 ACH, 80 ACH], in order to maximize the chances to reach the best possible global index.

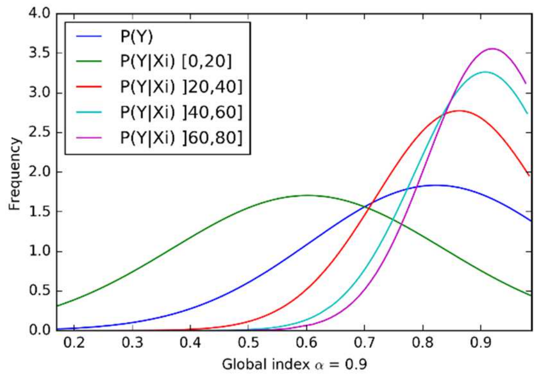


Figure 13: Conditional probability density function of global index I, for different ranges of flow rate (α=0.9)

In addition, the window soffit height conditional probability density function shows that the higher the range of soffit height, the more the maximum of conditional PDF function is reached for high global index, and the less the values are scattered. It can also be observed a homothety between the conditional PDF curve of window soffit between]3m, 4m] and the PDF curve of I. Furthermore, concerning the conditional PDF of the global index for different ranges of flow rates, it can be noticed that values are less sparse than soffit height and are more concentrated towards high values of global index. To conclude, flow rate values have the greatest impact on the variations of the global index for this case and ventilation has a positive impact on global study considering fire safety at 90% of importance.

Investigation on contentious parameters

In order to evaluate if a parameter is contentious or not, conditional density probability function should be plotted for α=0.1 for both soffit height and flow rate. Figure 14 and Figure 15 present conditional probability of global index for different ranges of flow rate and soffit height.

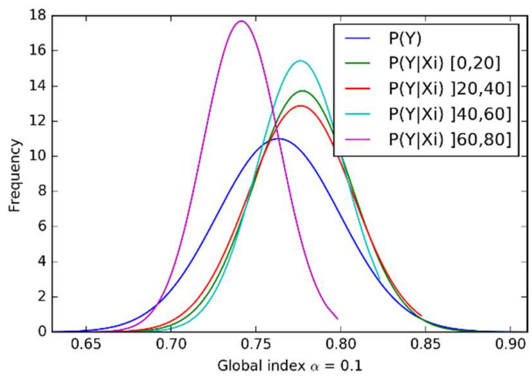


Figure 14: Conditional probability density function of global index I, for different ranges of flow rate (α=0.1)

Figure 14 shows that increasing flow rate, when considering an α of 0.1, has a negative impact on global index. Therefore, a compromise should be found in order to maintain a high fire safety level and a satisfactory thermal comfort level. Flow rate is typically a contentious parameter. Optimizing flow rate is, consequently, essential for this study.

Concerning window soffit height, Figure 15 shows that the same trend is observed when α=0.1 and α=0.9, suggesting that this parameter is consequently not contentious. Nonetheless, this study reveals that, for this specific case, objectives for fire safety should be taken with a greater weight than thermal comfort ones, keeping in mind that, for each study, the aim is to reach unity in terms of index values.

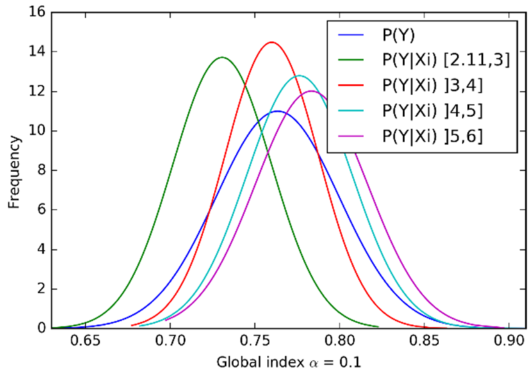


Figure 15: Conditional probability density function of global index I, for different ranges of soffit height (α=0.1)

Conclusion and future work

This study shows the interactions that exist between fire safety and thermal comfort for a simple room model, in the range of set boundaries, using a new index that combines fire safety and thermal comfort indices. Sensitivity analysis has been performed in order to highlight the key parameters for fire safety and thermal comfort on the same building. Probability density functions were used to examine contentious parameters, as well as to identify which concerns between fire safety and thermal comfort presented the greatest influence.

Two strategies were proposed. The first one is to dissociate comfort and fire safety while the other one is to combined these two concerns through a global index. In addition, considering thermal comfort and fire safety alone gives different approaches than considering these two concerns together. Indeed, flow rate and window soffit height are key parameters when considering dissociate and combined study, except for α=0.1. For this value, soffit height and flow rate switch their ranks. Flow rate, which is the first parameter of interest, comes at the second position in the global study when α=0.1. Perception of a designer can thus change on complex buildings design depending on α value while designing systems such as window geometry or air inlet/extraction.

In-depth analysis using LHS and probability density function was performed in order to investigate contentious parameters. The two most influential parameters were identified. The use of probability density function allowed understanding which consideration between fire safety and thermal comfort has the most significant impact on global index. Furthermore, the conditional probability study for window soffit height and flow rates demonstrated the greatest impact of flow rate on global index results. In addition, the flow rate appeared to be a contentious parameter in our case. Indeed, on one hand, increasing flow rate also increases the global index when the emphasis is laid on fire safety (α=0.9). On the other hand, it makes the global index decreases, when considering thermal comfort with a greater weight (α=0.1).

By way of conclusion, this study presented a combined study methodology in order to assess both thermal comfort and fire safety in buildings using sensitivity analysis and probability density function analysis. The results obtained demonstrated the importance of considering both comfort and fire safety targets together knowing that these two considerations have common inputs parameters. This paper also highlighted the limits of analysis of the variance method for global studies. In fact, the total order index used in this study did not allow finding contentious parameters or understanding the interaction between the two considerations correctly. The use of additional indices is required for such a study.

Future studies on global index combining two considerations, i.e. comfort and fire safety, should use moment independent index such as the delta of Borgonovo (2007). Moreover, global study must be applied on real case studies with natural ventilation consideration for both fire safety and thermal comfort, using an airflow network approach, in tropical or temperate climate zones. Other indices, such as solar heat gain coefficient for comfort or safe egress time for fire safety, can be used to assess buildings.

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