Conflict Investigation between Thermal Comfort and Fire Safety in Naturally Ventilated Building Located in Tropical and Hot Climate.

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Abstract

Safety performance is one of the most important considerations in building design. Moreover, new environmental building design allows construction to have a sustainable relationship with the outdoor climate, especially in tropical context. This paper aims at evaluating how conception that allows natural ventilation by mean of passive strategies, affects fire safety performance in buildings. A methodology, combining safety and comfort through a global index, is proposed in order to understand how the consideration of fire safety can affect initial passive design. The use of dynamic thermal simulation associated with fire simulation gives the opportunity to quantify fire performance annually. Sensitivity analysis is performed by using delta moment index. This allows to evaluate the absolute impact of input parameter on both fire safety and thermal comfort outputs. A refined study is then performed by the use of conditional output distribution. It takes into account the relative importance given to fire Safety or thermal comfort concerns. The strong dependence of fire safety, in terms of smoke extraction, on weather conditions, building orientation, occupation profiles and seasons, is demonstrated in naturally ventilated buildings.

Keywords:

Fire safety, Thermal Comfort, Smoke extraction, Natural ventilation, Critical Safety Period, Safety design, Hot Climate, Tropical Climate.

1. Introduction

Insular areas are impacted by energy supply constraints, affect both directly and indirectly the building sector. In Reunion Island, the overall consumption due to construction represents more than 45 % of the overall electric energy consumption [1]. Knowing that Reunion Island aims at being autonomous in terms of energy supply by 2030, one could not achieve this goal without thinking about how to build better, in a sustainable way. New construction should hence provide free running building that combine passive design, acceptable thermal comfort, energy efficiency, and last but not least, a high level of safety. Two questions are then arisen: How to integrate safety consideration into passive design process? And why is it important to associate comfort and fire safety?

Firstly, it is important to highlight how safety and comfort is commonly covered in Reunion Island. Concerning fire safety, the same standard is prescribed in Reunion as in mainland France. Hence, standards for fire safety is mostly prescriptive [2]–[5]. In others terms, in each situation related with safety, systems and solutions are imposed contrary to objective standards, which are based both on factual measurements and the setting of safety performance goals. These standards are, for most of them, designed for closed building with mechanical air supply and conditioning system. In the case of the extraction of toxic smoke during a fire event, both natural and mechanical exhaust is prescribed by the building regulation. For inlet and outlet related to the extraction of fire smoke, rules are given in terms of dimensions, distances, as well as numbers of openings. Fan characteristics are also given in order to satisfy the standards' requirements. However, the impact of passive ventilation strategies on fire safety design is not taken into account. This is where issues meet. The wind is variable and fluctuate by nature, then natural smoke extraction potential has to be quantify depending on wind variation and building characteristics. This is not the case in French fire regulation.

Some research has payed attention to the issue of natural exhaust of smoke for building under natural ventilation [6]–[8] and outlined the importance of uncertainties of the hypothesis when calculating physical quantities related to fire smoke. Salem [9] 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 [10].The ASET is the time when integrity of occupant is compromised during a fire event ; while the Required Safe Egress Time (RSET), also presented in ISO/TR 16738, is the amount of time required to get out of the building. ASET takes into account toxic and irritating gas as well as radiant and convective temperature effects on Human bodies by setting thresholds. Another study proposed by Kong [11] specifies that uncertainties should not be neglected while elaborating fire scenarios using fire models. Allard et al. [12]evaluate different parameters, including fire characteristic, that most impact the risks associated to fire using the CFAST [13] software. 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 [14]. Thermal comfort is subject to a large number of studies [15], [16]. Several models exist to assess indoor thermal comfort such as analytical models and field models. Fanger [17] introduced Predicted Mean Vote (PMV) in order to evaluate comfort in controlled environments. Climatic diagram [18] and adaptive thermal comfort [19]–[21] 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 [22]–[25]. However, literature review shows a lack of studies combining fire safety and thermal comfort targets, especially for naturally ventilated room in tropical climate.

This study focuses on the effect of the weather as well as the effect of initial design on thermal comfort and fire safety for a naturally ventilated building. Moreover, an investigation on potential conflicts between the two considerations is led. A combined index approach, with a disjunction connective function, is proposed using delta moment measures [26]. Four climate zones, two occupation types, and four building types are considered. One of the objective is to discuss the impact of fire on smoke exhaust performance in naturally ventilated buildings. Another objective is to discuss on the existence of conflicting parameters for comfort and safety. By definition, a contentious parameter has a relative significant impact on both safety and comfort index, but its impact is negative for the one and positive for the other one [14].

In order to assess thermal comfort, the extended Givoni's zone proposed by Lenoir is considered. Available Safe Egress Time, by means of Fractional Effective Dose related to toxic gases, as well as Critical Velocity, as defined by Chen et al. [27], are chosen as a fire safety performance measures.

Moreover, another fire safety measure is introduced under the name of Critical Safety Period (CSP). It corresponds to the percentage of time when windy condition can significantly affect smoke extraction. The CSP hence depends of the wind conditions, the orientation of the building, as well as the opening location. The emphasis on passive design interaction with fire safety level is demonstrated. In addition, conditional distribution of the output allows to underscore conflicting parameters by considering uncertainty and setting scenarios. According to [28], The study of output distribution allows analysts to measure the inputs' influence on given model outputs.

2. Why integrating fire safety in passive design?

Inlet and outlet position in naturally ventilated room has been studied by Tominaga and Blocken [28] . They made wind tunnel experiment in order to assess the impact of opening position on flow dispersion. They conclude on the fact that inlet position has a strong impact on contaminant dispersion in naturally cross ventilated buildings. Moreover, depending on the configurations of the openings studied, flow rates varied within a range of 40 %. It is obvious that inlet and outlet position have a strong impact on thermal comfort measures, based on climatic chart, in tropical area since air change rate is one of the most impacting parameter [14]. Now, thinking about smoke extraction, one can ask if the same opening configuration will be positive for both thermal comfort and smoke extraction efficiency, knowing that safety during a fire event depends on where the flow is coming in [27]. Smoke extraction and its impact on a building should be introduced.

A suitable definition of smoke can be find in the (National Fire Protection Association) handbook whereby "smoke is defined as airborne solids and liquid particulates and gases evolved when material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into mass"[31]. Since the seventies, fire plume and smoke has been widely studied [32]–[35]. In order to understand fire smoke, Nelsen and Klote present several phenomenon that occurs during fire event [36]. According to

[36] when smoke is produced, it is cooled down: by surrounding air, by thermal exchange with surrounding solid material and by radiant energy lost. As soon as the smoke is cooled down, the same behaviour of a pollutant can be observed. Different forces will impact the smoke movement. The first one is the thermal buoyancy, creates by temperature and density difference between the fire smoke and surrounding air. The second main force that can affect smoke movement is wind force [7], [8], [27]. Moreover, another factor that can act on smoke displacement is pressure force caused by mechanical ventilation system [37], [38]. It has been proved that smoke extraction, management and control can have a significant impact on the safety level of a building and on the preservation of human lives [39]. SFPE guide pinpoint the fact that during a fire, tenability conditions is compromised by the exposure of radiant and convective heat, inhalation of toxic gases and obscuration cause by smoke [40]. A suitable system of fire smoke control is one of the driving factors that can lead to high safety performance. Identification of physical quantities such as interface height, smoke layer temperature, and mass flow rate through openings, is crucial for quantifying the risk. Hence, the difference between fire induced smoke and isothermal contaminant dispersion study is the strong presence of thermal forces which is one of the two main driving forces of natural ventilation[41]. This makes wind tunnel analysis not adapted to quantify the effect of window position on smoke extraction in naturally ventilated spaces. Some research have been conducted in order to characterize the effect of wind on smoke extraction depending on dual window position. For example, Chen et al. introduced wind effect on smoke extraction by considering Bernoulli approach [27] with a full mixed indoor ambiance. They demonstrate the existence of a critical velocity which appears when top opening was windward and bottom opening was leeward. Critical Velocity is the wind velocity at which smoke do not extract thought the windward façade when wind force opposed buoyancy. In this case wind opposed buoyancy and . Yi

et al. [7] also studied wind impact on smoke extraction considering two zone indoor ambiance and roof outlet. They concluded on the influence of net wind pressure coefficient value on the smoke extraction performance.

In addition, a series of reduced scale experiments have confirmed, by means of observation, the existence of a critical velocity when wind opposed buoyancy. The experimentation is based on Tominaga and Blocken [28] setup. The chosen geometry represents a generic isolated building with two opposite asymmetric openings placed respectively in the windward and leeward façade. The chosen geometry in one of the five geometry tested by Tominaga and Blocken [28]. The geometry under study has a top opening on the windward façade and a bottom opening in the leeward one and represents one of the most efficient configuration in terms of passive pollutant dissipation and net flow rate according to Tominaga and Blocken [28] study. In order to reproduce the effect of hot fire smoke, helium is used based on Vauquelin et al. study [42]. The results, in terms of critical velocity observation is presented in Figure 1.

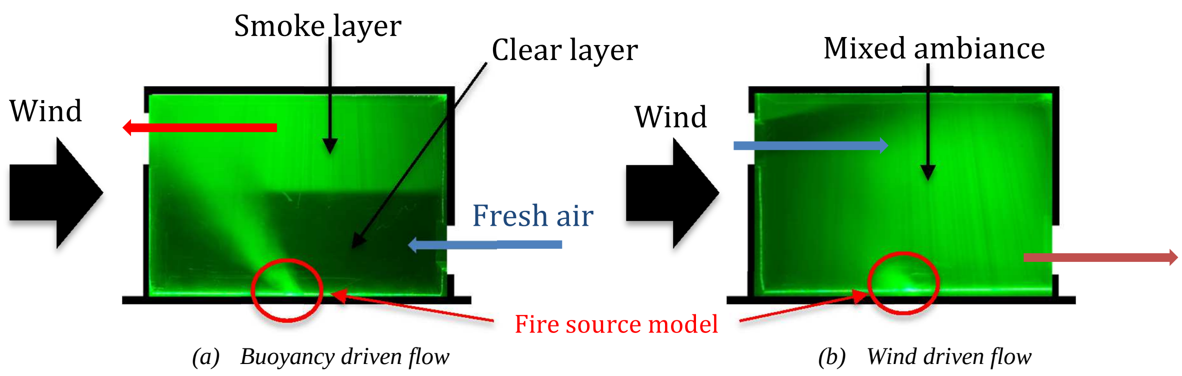


Figure 1: Observation of critical velocity on a reduced scale experiment set up in IUSTI Laboratory, for a simple geometry with top opening facing the wind and buoyant injection in the middle of the room. (a) represents typical pattern for a buoyancy dominated flow while (b) shows flow pattern for a wind dominated flow when critical velocity is exceed.

All these study shows that wind as both a strong impact on safety level as well as on air quality and comfort. Then it should be necessary:

- on the first hand, to consider fire safety level as a function of time and depending on climatic conditions, and
- on the other hand, to approach the interaction that could exist between sustainable and safety design.

These two points, will surely lead to a better approach when designing or retrofitting a building in a sustainable way for both tropical areas and areas where natural ventilation can be used as passive strategy. Hence, the presented study is held is four steps:

- **Step 1** consists in evaluating most impacting parameters for fire safety alone when natural ventilation operates, using CFAST.
- **Step 2** consists in combining measures while evaluating the model using sensitivity analysis and disjunction connective function.
- **Step 3** is relative to the optimisation using Kernel Density Estimator (KDE) and the use of weighing coefficient.
- Step 4 consists in the research of contentious input parameter, using weighing coefficient.

One of the best way to integrate fire safety in the early sustainable design is to use the same reflexion as in [27]. Critical Velocity appears when top opening is windward and bottom opening is leeward (Figure 1). It is hence necessary to estimate the amount of time when top opening will be windward thanks to the weather file of a given location and especially the wind rose. This amount of time when critical velocity can appear is called here the Critical Safety Period. The more the CSP will be long during the year, the less safety level will be regarding smoke extraction performance. In this study the CSP and Critical velocity will be used as safety measures. The dependence of safety level on the location will be then demonstrated. All buildings performance measures for both comfort and safety are presented in the next part.

3. Building performance measures

3.1. Thermal comfort measures

The Lenoir extended Givoni's zone is chosen here as a comfort index. The objective here is to show how comfort and safety can interact.

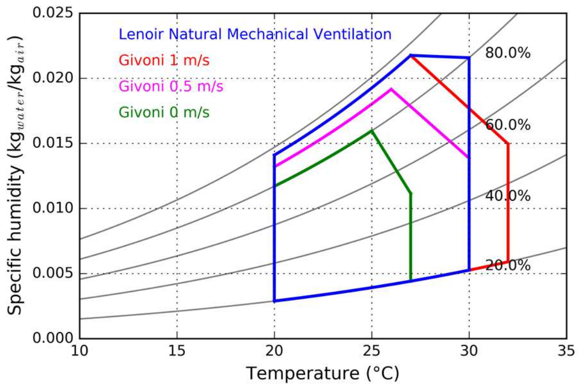


Figure 2: Givoni's and lenoir's zones represented on climate chart

Hence, for this study the extended Givoni's zone proposed by Lenoir [43] is chosen. The percentage of point within the studied zone, for a given period of simulation, represents the measures of comfort knowing that a point correspond to an indoor dry bulb temperature as well as an indoor relative humidity at a given hour of time (Figure 2). This data is given by dynamics thermal simulations. The chosen thermal comfort measure is normalized, the objective for each case is to reach unity. This measure is named as C_{NMV}.

3.2. Fire safety performance measures

In order to enhance safety level, in accordance with the Available Safe Egress Time (ASET), people have to exit the building as rapidly as possible in the best conditions. In order to achieve such a goal, fire smoke should be defined and quantify the best way as possible. Different type of study can be done to understand the fire smoke impact during fire event. Three types of analyses exist: A reduced scale analyse using scale model [44]–[46], real scale model analyses [7], [37], [38], [47], [48], and numerical simulation using zone model or computational fluid dynamics [49]–[53]. Zone model is used here to identify the quantities that most affect safety measures. Four main fire safety measures will be consider into this article: the Critical Safety Period (CSP), The Fractional Effective Dose of toxic gas [54], the critical velocity, and the same safety index used in [14] based on Allard et al. work [12].

3.3. Critical Safety Period measure (CSP)

This measure represents the percentage of the time when top inlet is located in the windward part of the building. It hence. Considering a simple volume with wind pressure coefficient on both site as in Figure 3, CSP is when $Cp1 - Cp2 > 0$.

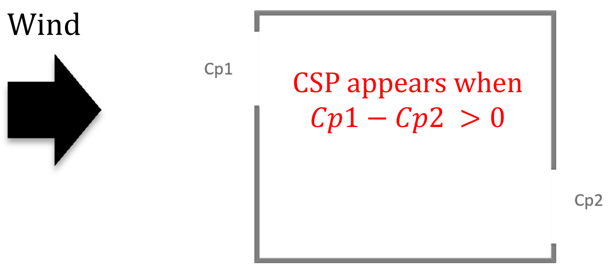


Figure 3: Description of CSP condition

With Cpi the wind pressure coefficient of the façade i. Then the fraction of time outside of the CSP during the studied period represents the CSP measure S_{SCP}. In other terms favourable wind condition to smoke extraction is considered. If $S_{SCP} = 1$ then there is no CSP. If $S_{SCP} = 0$, we are always under CSP.

3.4. Critical Velocity measure

The critical velocity measure is based on the correlation proposed by [27]. This correlation is defined as follow (1):

$$V_{cr} = \sqrt{\frac{2\left(1-\frac{T_a}{T_g}\right)gh}{\Delta C_p}} \quad (1)$$

With T_a: the outdoor air temperature, T_g: the mixed indoor air temperature, g: the gravitational constant, h: the height difference between top opening and bottom opening and $\Delta C_p = C_{pW} - C_{pL}$. C_{pW} is the wind pressure coefficient on the windward facade and C_{pL} is the wind pressure coefficient on the leeward facade. The critical velocity index S_{VC} is then defined as the ratio of time, within the CSP, when wind speed is inferior to the Critical Velocity (1). The objective for this measure is to be close to unity. The S_{VC} measure is only evaluated within the CSP.

3.5. FED measure

Fractional Effective Dose (FED) for toxic gas is calculated according to the standards ISO/TR 16738. Toxic gas concentration can then be calculated with the following equation (2):

$$X_{FED} = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{1}{t_i}.\Delta t \quad (2)$$

With t_i the time when tenability is compromised due to the toxic component i. and Δt the time step. The aim here is to calculate FED for carbon monoxide and carbon dioxide which are the two main toxic gas during a fire event. Then global FED is estimated as follow (3):

$$FED_{toxicity} = (FED_{CO} + FED_{O2}) \times V_{CO2} \tag{3}$$

V_{CO2} is the over ventilation correction which depends on the CO_2 fraction. The expression of V_{CO2} is presented in (4)

$$V_{CO2} = \frac{\exp(0{,}1903 \times \%CO_2 + 2{,}0004)}{7{,}1} \tag{4}$$

The safety measure S_{FED} is then equal to the percentage of simulated period during when the tenability is not compromised. Tenability is considered as compromised when X_{FED} is up to a fixed threshold given by the standards ISO/TR 16738. The threshold is set here to 0.3 that correspond to a limit at which 11.4% of the people, affected by fire conditions, will not able to egress. The aim for S_{FED} is also to be near to unity.

4. Climates description and chosen micro-climate.

Reunion Island (21°16'10.1"S ; 55°30'23.5"E) can be divided into four climate zone according to the PERENE local green buildings guideline [55]. As a consequence Reunion Island can clearly help in order to evaluate microclimate impact on thermal comfort in naturally ventilated room.

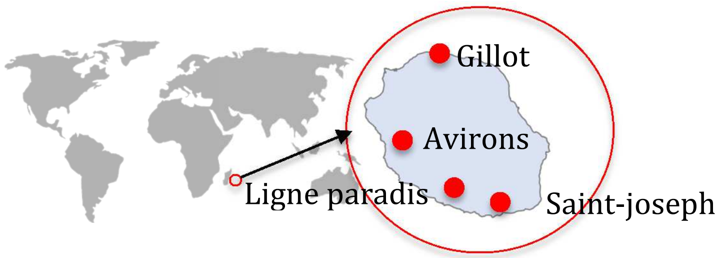
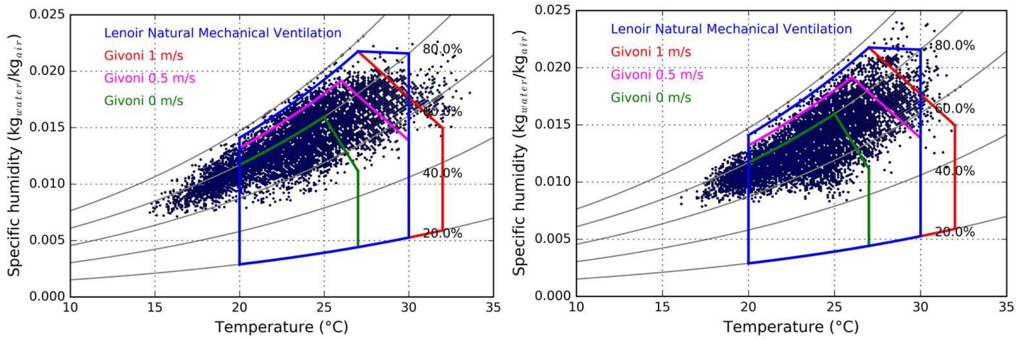
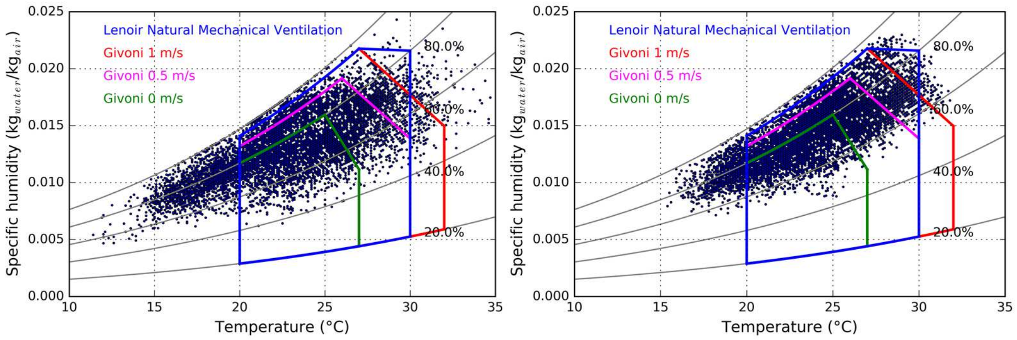


Figure 4: Location of the study

Low land of Reunion Island is the most appropriate places to build passive building enhancing natural ventilation. This is the reason why all weather for this study is located in this area (Figure 4). To appreciate environmental conditions for each chosen weather file, relative humidity and dry bulb temperature are plotted on the climatic diagram. In most of cases outdoor conditions is suitable in order to reach thermal comfort conditions according to Givoni's and Lenoir's zones (Figure 5).



(a) *(b)*



(c) *(d)*

Figure 5: Climatic diagram representing Givoni's and Lenoir Zone for four different location in Reunion Island (a) Avirons (b) Gillot (c) Ligne-Paradis (d) Saint-Joseph

According to Figure 5, relative humidity varies in most of the case from 40 % to 95%. Ligne-Paradis is the place with the most extreme temperature whereas Gillot's points is more "compacted". It will hence be interesting to evaluate if the four location will have a significant impact on thermal comfort measures.

5. Building model for fire and energy

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 not only in fire but also in energy research. The CFAST software [13], 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. Moreover FED and zone temperatures can be calculated with CFAST.

Performing whole building energy and thermal simulation, EnergyPlus is capable of simulating thermal building behaviour over a full year, using a weather data file and the building characteristics. Moreover, it allows to estimate pressure coefficient on each façade according to Swami and Chandra correlation. Hence, this tool allows designing complex ventilation network, considering passive design and natural ventilation. In order to quantify thermal comfort, Critical Safety Period and ASET, the combination of EnergyPlus and CFAST is relevant for this study. Therefore, in the case studied, if referring to equation (1), T_a is given with the weather file hour by hour, T_g is calculated thanks to CFAST at mid time of fire event. T_g is then equal to the mean temperature between upper and lower layers weighed by each layer volume. Finally, ΔC_p is calculated thanks to EnergyPlus software.

6. Sensitivity analysis

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 [56]. Various indicator families exist in order to measure the impact of uncertainties on a given model. For this study, the delta moment of Borgonovo is used [28]. The delta moment importance measures is given as follow (5):

$$\delta_i = \frac{1}{2} E_{X_i}[s(X_i)] \qquad (5)$$

Where:

δ_i is the uncertainty importance of input X_i ;

$s(X_i) = \int \left| f_Y(y) - f_{Y|X_i}(y) \right| dy$;

$E_{X_i}[s(X_i)] = \int f_{X_i}(x_i) \left[\int \left| f_Y(y) - f_{Y|i}(y) \right| dy \right] dx$;

Where $f_{X_i}(x_i)$ is the density of X_i.

In other term $s(X_i)$ represents the output distribution shift when X_i.is fixed to one of its possible values. $s(X_i)$ indicates how the view of the decision maker on output distribution will change when X_i is fixed to a known value. When fixed X_i value changes the output distribution significantly, then the parameters can be registered among the relevant ones.

At the contrary, if fixing X_i does not change significantly Y distribution, parameters is considered not impacting.

Another measure is also given by δ_{ij}. This measure allows to identify the impact of groups of two parameters on model output. The measure is defined as follow (6):

$$\delta_{ij} = \frac{1}{2} E_{X_i X_j}\left[s(X_i, X_j)\right] \quad (6)$$

Where:

$$s\left(X_i, X_j\right) = \int \left| f_Y(y) - f_{Y|X_i X_j}(y) \right| dy \quad (7)$$

This study will use sensitivity analysis as a mean of understanding the relationship between smoke extraction during a fire event and thermal comfort. Firstly, sensitivity analysis will focus on smoke extraction performance using CFAST, in order to analyse the influence of inlet position and Window to Wall Ratio (WWR). Secondly, the impact of climate on fire safety is demonstrated thought S_{VC} and S_{CSP}. Latin Hypercube Sampling (LHS), with a number of 16384 set of parameters, will be used in accordance with Monte Carlo methodology.

7. Case study and model description

A simple geometry is considered. The objective is to evaluate how fire safety consideration interacts with passive building design strategies. Different building parameters (characteristics) for fire safety and thermal comfort are evaluated. A first "dissociated" fire safety study is conducted in order to evaluate the influence of WWR and inlet position with CFAST. Parameters related to the first study are describes in Table 1. Two sensitivity analyses are then carried out. The first consists in the evaluation of the impact of several parameters including inlet position, and flow rate but excluding WWR, on the fire safety measure defined in [14]. The exclusion is due to a CFAST model characteristic which does not allow to simulate wind driven ventilation like in EnergyPlus. Hence, to mimic natural ventilation, the assumption is to model inlet and outlet mechanical vent (Figure 6). Inlet position and flow rate are here considered as input parameters. CFAST does not allow to give length and height of mechanical vents. As a consequence, the influence of WWR is evaluated through another sensitivity analysis with no mechanical vent but just natural vent exhaust (Windows).

Table 2 presents input parameters information for the combined study. 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, resulting in four common parameters (Figure 7).

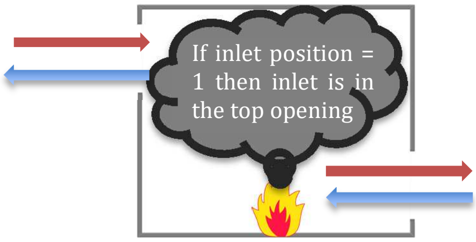


Figure 6: Inlet and outlet position set up in CFAST

Table 1: Parameters and their range for smoke extraction study

Parameters	Distribution	Range	Type
Room width	Uniform	[4m ; 6m]	Continuous
Room height	Uniform	[m ; m]	Continuous
Room length	Uniform	[2.5m ; 3.5m]	Continuous
Window to wall ratio	Uniform	[0.05m ;0.6m]	Continuous
Outdoor temperature	Uniform	[15°C ; 35°C]	Continuous
Indoor temperature	Uniform	[18 °C; 37 °C]	Continuous
Relative humidity	Uniform	[50% ; 80%]	Continuous
Inlet Position	Uniform	[1 ; 2]	Discrete
Flow Rate	Uniform	[0ACH; 40ACH]	[ ]

Specific parameters are defined for the Energy Plus and CFAST simulations. Concerning the EnergyPlus specific parameters, the impact of the different components' thickness and the room orientation are evaluated. This represents eight parameters (Figure 7). Only three parameters are specific to the CFAST model: Relative Humidity, Indoor Temperature and Outdoor Temperature (Figure 7).

Table 2: Parameters and their range for combined fire and comfort study

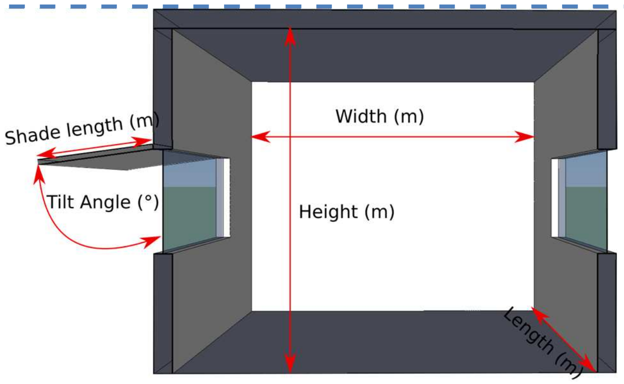
Parameters	Distribution	Range	Type
Room width	Uniform	[4m ; 6m]	Continuous
Room height	Uniform	[6m ; 12m]	Continuous
Room length	Uniform	[2.5m ; 3.5m]	Continuous
Window to wall ratio	Uniform	[0.05m ;0.6m]	Continuous
Delta_h	Uniform	[0.5m ;1.5m]	Continuous
Insulation thickness	Uniform	[0.02m ; 0.08m]	Continuous
Shading tilt angle	Uniform	[90° ; 140°]	Continuous
Shading length	Uniform	[0.1m ; 1.5m	Continuous
Discharge coefficient	Uniform	[0.35 ; 0.67]	Continuous
Room orientation	Uniform	[0° ; 360°]	Continuous
Outdoor temperature	Uniform	[15°C ; 35°C]	Continuous
Indoor temperature	Uniform	[18 °C; 37 °C]	Continuous
Relative humidity	Uniform	[50% ; 80%]	Continuous
Occupation type	Uniform	[1 ; 2]	Discrete
Weather file	Uniform	[1 ; 4]	Discrete
Building type	Uniform	[1 ; 4]	Discrete

Common parameters

Window to wall ratio : 1 parameter

Room geometry : 3 parameters (Height, Width, Length)

Delta_h : (height difference between the two openings (2))



EnergyPlus parameters

Wall insulation thickness : 1 parameter

Roof insulation thickness : 1 parameter

Room geometry : 3 parameters

Room orientation : 1 parameter

Window geometry : 1 parameter (Window to wall ratio)

Discharge coefficient : 1 parameter

Tilt angle : 1parameter

Length : 1 parameter

Discrete parameters:

Weather file : 1 parameter

Occupation profile : 1 parameters

Building type : 1 parameter

CFAST Parameters :

Indoor Conditions : 2 parameters (Temperature, Relative Humidity) ;

Outdoor Temperature : 1 parameter

Figure 7: Description of the assessed model

Heat Release Rate is set at 3 kW/m^2 and is placed in the middle of the room for each case. Hence HRR lies between 30 kW and 70 kW which correspond to shelf wood bookcase burning with files on. The fire size is 5% of the floor surface area. The fire 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 to escape in case of fire. Hence, the first 15 minutes of a fire event are simulated. The room studied has typical single room ratio. The outdoor temperature range is also typical for Reunion Island, with a tropical climate. Considering a naturally ventilated building, indoor temperature and indoor relative humidity are within the range of local weather data. Climate conditions inputs are used within the CFAST software as well as for the critical velocity calculation (2). All the parameters and the related boundaries are given in Table 2. The variable h defined in (1) is relative to the difference between the middle of the top opening and the middle of the bottom opening. This value is only implemented in the Critical Velocity calculation and not in CFAST or EnergyPlus model for the second analysis. However, the top opening in EnergyPlus is assume to be always in the same façade. This allows to calculate CSP. Thermal comfort in tropical climate is evaluated. As a result, relative humidity and thermal comfort are model outputs used in order to evaluate comfort performance. The extended Givoni's climatic diagram proposed by Lenoir [43] allows to plot the data. The simulated room is considered as naturally ventilated. ΔC_p in (1) is calculated thanks to Swami's and Chandra correlation [57].

All parameters are assumed as uniformly distributed. Weather file, occupation type as well as building type are discrete parameters used in order to build scenarios.

7.1. Evaluated building type

The tested building type is based on the commonly building that can be find in Reunion island. Table 3 presents the chosen building composition in terms of wall and roof.

Table 3: Tested building type

Building Type	Concrete	Wood	metal	Concrete + wood

Wall (ext/…/int)	Concrete/Insulation/Plasterboard	Wood/airspace/Insulation /plasterboard	Metal Sheet/airspace/Insulation /plasterboard	Wood/Concrete/Insulation/Plasterboard
Roof (ext/…/int)	(Metal sheet/Airspace/Insulation/plasterboard)	(Metal sheet/Airspace/Insulation/plasterboard)	(Metal sheet/Airspace/Insulation/plasterboard)	(Metal sheet/Airspace/Insulation/plasterboard)

This parameter will be a discrete parameter and will allow to analyse building type impact on comfort measures in naturally ventilated building.

7.2. Occupation profile

Concerning the occupation, only two option is tested: Office occupancy and home occupancy. These information is taken from EnergyPlus default schedule. The objective here is not to specially represents reality but to analyse qualitatively the impact of a day and night occupancy on the way of optimize a naturally ventilated building

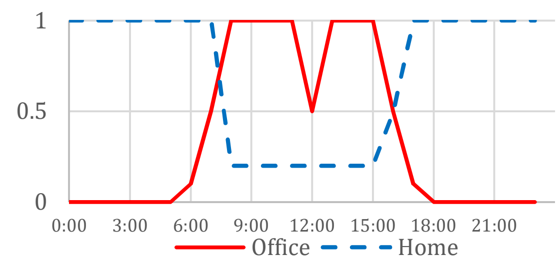


Figure 8: Assessed occupancy profile

This parameter will allow to discuss relative occupancy importance on the designer point of view for free running building which indoor conditions strongly depends on outdoor conditions.

8. Methodology

The first step of this study is to identify the most impacting parameters during a fire event excluding fire characteristics as an input for sensitivity analysis. Fire size will vary with the floor surface area. For this first study only CFAST will be use. The second approach is to use an index that combines fire safety and comfort, since they can interact while natural ventilation operates [14]. The disjunction connective function based combined index (8) is used here to analyse the combination of C_{NMV} and S_{VC}:

$$I = \alpha \times S_{VC} + \beta \times C_{NMV} \quad (8)$$

Weighing coefficients α and β that range between [0,1] are used to give relative importance on one or the other output measure.

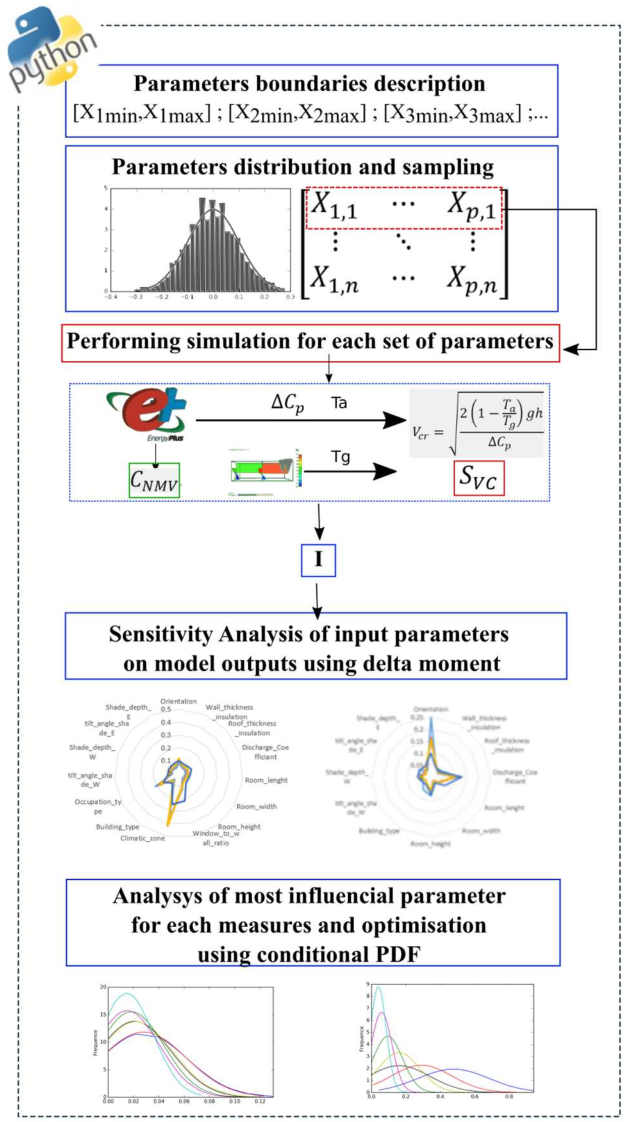


Figure 9: Python process for the proposed optimisation methodology

As in Juhoor et al. study [14], in order to keep the new index normalized, we set: $\beta = (1 - \alpha)$.To realize the analysis, Python software is used as an interfacing layer and its Salib library is used to perform sensitivity analysis [58]. The objective is to give designers the opportunity to understand how safety and comfort can interact and why it is important to consider fire safety in the early design of passive building providing wind driven natural ventilation.

9. Results

9.1. Most impacting parameter in fire model for naturally ventilated room using CFAST

The following sensitivity analysis, using delta moment measures, shows how important inlet and outlet position are in terms of interface layer height, upper layer and lower layer temperature. With a simple multizone layer as CFAST the importance of window position as well as flow rate, during a fire event is demonstrated in Figure 10.

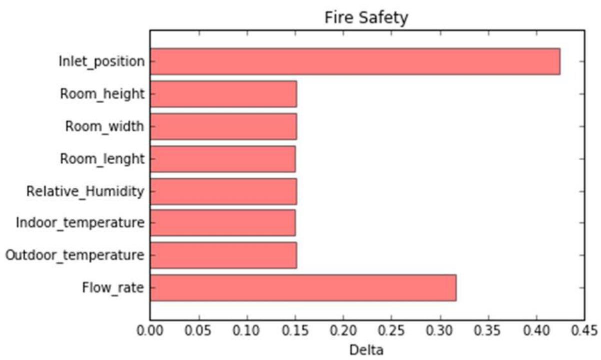


Figure 10 : Delta moment values for Fire Safety Study measuring fire model inputs impact on safety measure set in [14] (Mechanical ventilation to mimic wind driven natural ventilation)

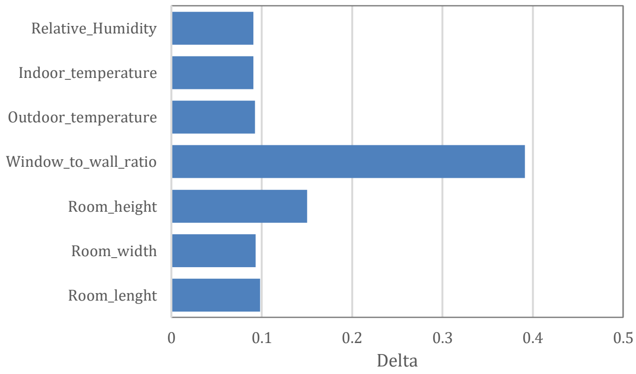


Figure 11: Delta moment values for Fire Safety Study measuring fire model inputs impact on S_{FED}.(Naturally ventilated without wind driven natural ventilation)

In this case wind driven ventilation was simulated with mechanical vent given that CFAST does not consider wind driven flow. It appears that inlet position as well as flow rate have a great impact on the safety measure set in [14].

A second case is simulated while the windows are opened, allowing natural ventilation. The result exposed in Figure 11 presents sensitivity measures for the same room but naturally ventilated without wind driven natural ventilation. Impact on S_{FED} is evaluated.

It appears in this case that Window to Wall Ration is by far the most impacting parameters. As a consequence, WWR, Inlet position, as well as flow rate can be considered as the most impacting in naturally ventilated cases. Knowing that those parameters also play a pivotal role contaminant dissipation in cross and naturally ventilated room [29], one cannot designed passive building without considering smoke extraction performance. It is now important to study the introduced safety index S_{VC} and S_{CSP} to demonstrate the climatic dependence of fire safety in cross and naturally ventilated room using zonal and nodal models as well as the presented combined index (8).

9.2. Comfort and safety interaction through combined Index

In this part the combined index is used to demonstrate the weather importance when studying fire safety in naturally ventilated room by fixing the weighing coefficient α to different values. Figure 12 and Figure 13 shows the delta moment measure associated with the impact of each inputs on global index for summer period and winter period, and for $\alpha = 0.1, 0.5\ or\ 0,9$.

It can first be observed, difference between parameter impact if we set the study in summer or winter, whatever the value of α. The first conclusion is then that both safety through critical velocity measure S_{VC} and comfort thought C_{NMV} are strongly dependent of the location i.e dependent of the weather. Focusing on Figure 12, one can relate that for $\alpha = 0.9$ (importance given on safety), the most impacting parameter is by far is the weather file.

Hence the strong dependence between safety and climate is highlighted in summer period. When $\alpha = 0.1$, both weather file and occupation are important. Knowing that natural ventilation systems are usually designed for summer period, designers could not think about safety without adapting opening position as well as WWR to the specificity of the climate.

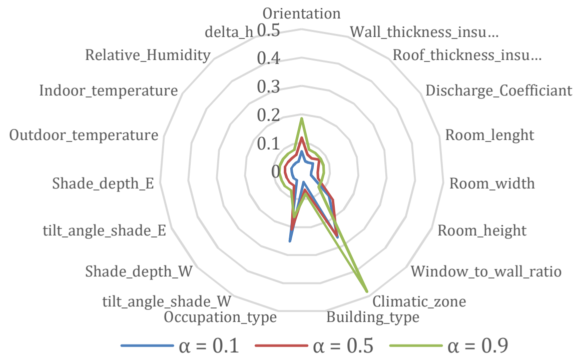


Figure 12: Delta moment for different values of α and for Summer Period

Figure 13 is also very interesting due to its difference with summer period. Indeed we can observe that in winter, the orientation is as impacting as the climatic zone when fixing $\alpha = 0.9$. When $\alpha = 0.1$, occupation and weather file are the most impacting parameters.

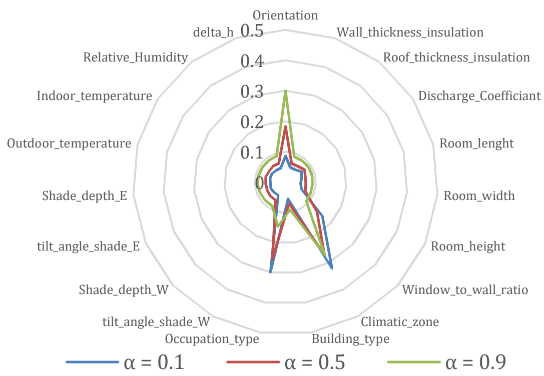


Figure 13: Delta moment for different values of α and for Winter Period

For both summer and winter case, $\alpha = 0.5$ allows to both take into account safety and comfort. Then for a combined sensitivity analysis, it can be recommended to analyze the results when $\alpha = 0.5$. This allows to give to the designer a global view of what is really important to consider when realizing of retrofitting a building. The study of $\alpha = 0.9\ or\ 0.1$ can then be used to find contentious parameters by plotting the conditional distribution of most impacting parameters.

Next part focuses on the study of conditional distribution of the output fixing the most impacting parameter for both cases when $\alpha = 0.9\ or\ 0.1$.

9.3. Conditioned output distribution

This part deals with refined analysis of output distribution and conditional output distribution regarding the most impacting parameters when $\alpha = 0.9 \; or \; 0.1$. In this part, kernel density estimation (KDE) is used in order to plot the output distribution in each case. Firstly, the weather file is fixed in order to observe whether the same climate is favourable to both safety and comfort. Secondly, two climate locations are deeply studied. For a specific location, as well as for a specific occupation type, global output distributions fixing Window to Wall Ratio to specific range are plotted. Thirdly, the same method is applied to the room's orientation

Output distribution fixing Weather Files

Figure 14 and Figure 15 present kde of the output knowing the location for $\alpha = 0.1 \; or \; 0.9$. It can be highlight that a huge difference exists between the different locations whether $\alpha = 0.1 \; or \; 0.9$. Moreover, comparing the two graphs, it can be observe that the same location could be very positive when weigh is put on comfort but negative when importance is given to safety. Let's take for example the case of Gillot. Typically, Gillot has a high wind potential (cf. part1) and can thus be favorable when natural ventilation is allowed in building, considering building element allowing to regulate wind speed. Hence for Gillot, the output varies between 0.6 and 1 with two pikes from 0.7 and 0.8 as well as from 0.8 and 1.

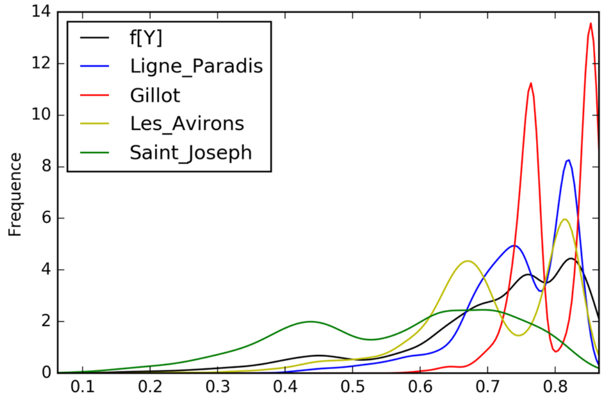


Figure 14: Kernel density estimation of the output knowing the location for $\alpha = 0.1$.

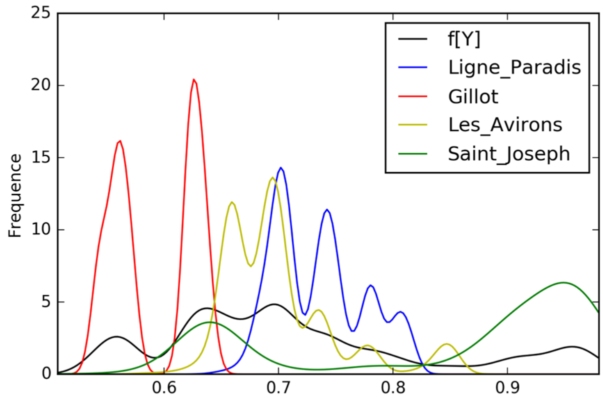


Figure 15: Kernel density estimation of the output knowing the location for $\alpha = 0.9$.

The two spikes, or kernel, observed are related to the occupation type. Observing now the same location but fixing $\alpha = 0.9$, Gillot is the climate with the most negative impact, with a combined index ranging approximately from 0.55 to 0.65. The same trend regarding α value can be observed for each climate location but except for Saint-Joseph. The reason of the observed difference is that Saint-Joseph weather file has an irregularity regarding wind speed and direction.

This study allows to conclude on the weather dependence of fire safety in naturally ventilated room, for the case study, as thermal comfort is link to climate. In the one case, a given weather file can be suitable to reach appropriate thermal comfort level, but in the other case, can be responsible to a poor fire safety level amplitude. Then, indepth study should be realize for each location, each microclimate, in order to not only consider thermal comfort but also in order to take into account fire safety as a key consideration to bioclimatic and sustainable construction. For next discussion, Gillot with office occupancy will be used to understand how most impacting parameters can interact taking different values of α.

Output distribution fixing WWR

Figure 16 and Figure 17 present KDE for the output knowing the location and occupancy for different range of WWR for $\alpha = 0.1$ *or* 0.9. When $\alpha = 0.1$, and knowing that the study focus on summer, it appears that high range of WWR (between 50% and 60%) is more positive regarding thermal comfort compared to low range of WWR (between 0% and 10%). Indeed, when fixing WWR from 50% to 60%, global index varies from 0.72 to 1 whereas it varies from 0 to 1 with a more dispersed density when ranging from 0% to 10%.

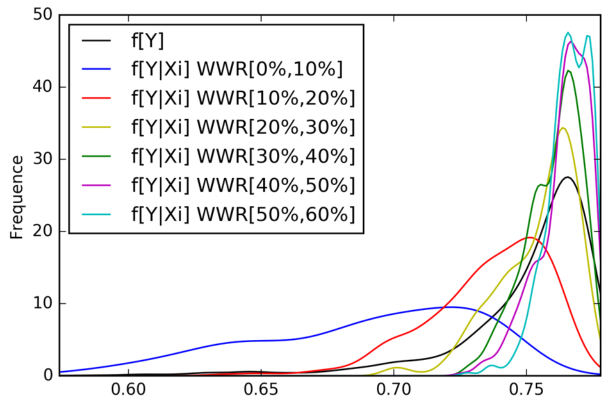


Figure 16: Kernel density estimation of the output knowing the location (Gillot) and occupancy (Office) for different range of WWR and for $\alpha = 0.1$.

However the trend in completely different when the accent is put on safety. Indeed when α=0.9 (Figure 17), two groups of kernel can be identified concerning the conditional output. The results is not as significant as when for α=0.1. Hence there is not high discrepancies when α=0.9 comparing to the case when α=0.1. In order to understand the presence of the two kernel groups, conditional kde is plotted for different range of orientation.

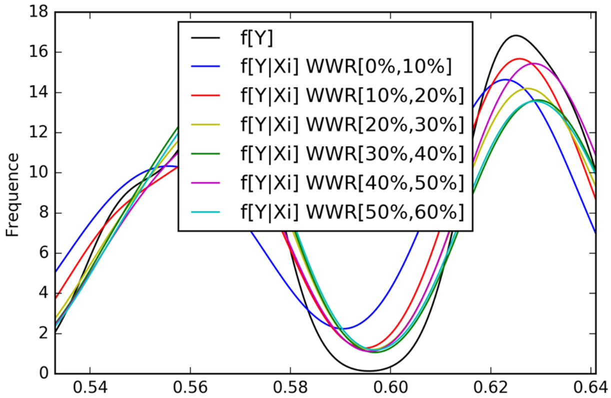


Figure 17: Kernel density estimation of the output knowing the location (Gillot) and occupancy (Office) for different range of WWR and for $\alpha = 0.9$.

Output distribution fixing the orientation

Figure 18 and Figure 19 show kde for the output knowing the location and occupancy for different range of room orientation for $\alpha = 0.1 \; or \; 0.9$. Firsly, Figure 19 allows to understand the presence of two kernel groups observed in Figure 17.

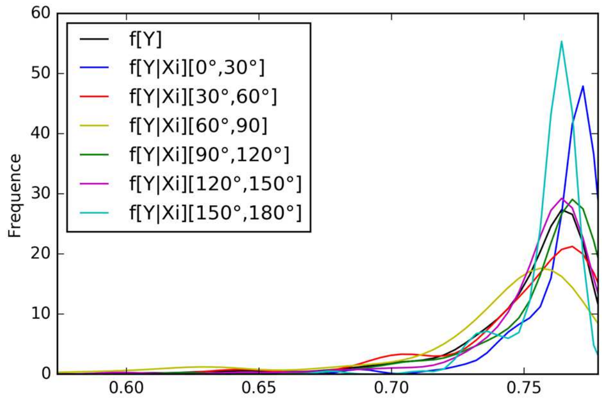


Figure 18: Kernel density estimation of the output knowing the location (Gillot) and occupancy (Office) for different range of room orientation and for $\alpha = 0.1$.

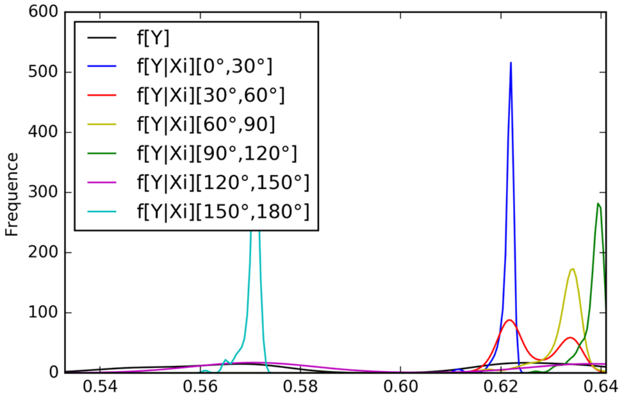


Figure 19: Kernel density estimation of the output knowing the location (Gillot) and occupancy (Office) for different range of room orientation and for $\alpha = 0.9$.

Indeed, it can be observed in Figure 19 that for a range of orientation between 150°and 180°, global index is very low compared to the other range. Two groups are also observed in this case. This discrepancies causes the observed groups of densities in Figure 17.

Secondly, it can be concluded that orientation is typically a conflicting parameter when fixing it to some range and more particularly when it is fixed between 150° and 180°. Indeed, this range of orientation induces high values of global index when α=0.1, but also really poor index when α=0.9. Designers should be careful about the orientation of a room or openings position when thinking about construction that allows natural ventilation if fire safety is also taken into account.

10. Conclusion

This study has numerically demonstrated the relation between fire safety and thermal comfort in naturally ventilated room using nodal and zonal models and sensitivity analysis by mean of Delta moment introduced by Borgonovo. The advantage of using this methods here is to have an absolute impact of sensitivity measure. A simple case study was taken in order to check fire safety level taking into account a wide range of uncertainties. A combined index methodology was applied to find the relation between thermal comfort and fire safety.

A first dissociated study was conducted in order to show how fire safety level, in terms of Fractional Effective Dose of toxic gas, is sensitive to the inlet position as well as to the Window to Wall Ratio (WWR). Using a disjunction function based global index, a global study was realized combining a critical velocity measure as a safety index, and a climatic diagram based comfort index as a thermal comfort measure. It appears that global index is sensitive to the location, the WWR, as well as the occupation when both fixing weighing coefficient α to 0.1 or 0.9. Hence the climate dependence of fire safety level was demonstrated.

The use of kde allows in the last part of the study to highlight the room orientation as a conflicting parameter when fixing its values to a specific range. It is hence important to apply this kind of methodology when allowing natural ventilation inside a building in order to avoid poor safety level that can lead to casualties in case of fire event.

By way of conclusion, this study is the first of its kind that tries to evaluate the link between thermal comfort and fire safety level in passive buildings. The study highlights the strong dependence between fire safety level, using Critical Safety Period and Critical Velocity, and environmental and building variables as location (wind speed and direction), inlet position, orientation and WWR. However the use of Critical Velocity is here a first step and can be questionable since it is based on a macroscopic model that considers a full mixed ambiance inside the room. Further study should be conducted either numerically by mean of KDE or experimentally.

11. Acknowledgment

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