THE INFLUENCE OF THERMOCHROMIC GLAZING PARAMETERS ON ENERGY SAVING AND COMFORT CRITERIA USING MOMENT-INDEPENDENT MEASURE

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ABSTRACT

Windows are central in architecture and they play a significant role in the energy consumption of buildings, particularly in hot climates, where overheating is a critical issue. Innovative glazing technologies, like thermochromic (TC) glazing, could help to overcome those issues. This article aims to identify both the influence and the importance of thermochromic glazing parameters. A sensitivity analysis by means of moment-independent measure with Latin hypercube sampling has been used, taking the uncertainties of the parameters into account, as well as dynamic daylighting and thermal building simulations. The results allow us to put forward the most important set of factors that need to be carefully chosen to design low-energy buildings, with a comfort performance approach. The conclusion of this study provides further knowledge for designers about TC glazing in the early design stage of buildings, for several climates. It demonstrates that the glazing area has the greatest impact on the results, but also several key TC glazing parameters such as the solar or visible transmittance and the switching temperature.

Keywords: Thermochromic Glazing – Building Simulation – Energy savings – Thermal and Visual Comfort.

INTRODUCTION

A major concern of the 21st century is the environmental crisis and ensuing energy context. The building sector is part of the problem, especially because of its significant consumption of fossils fuels. Recently, a considerable amount of literature has been produced about building envelope performance [1]. Indeed, the building envelope has a great influence on the energy consumption of buildings and occupant comfort, specifically for transparent surfaces [2]. Hence, windows have to be carefully designed and have become a critical choice when energy savings and comfort are at stake.

Innovative glazing technologies could help to overcome those issues. These technologies have the capability to modulate, their thermo-optical properties dynamically and reversibly, in response to a stimulus like an electric current, light or temperature [3].
This study focuses on thermochromic glazing (TC), which is a very promising smart passive solution to enhance indoor environmental quality and reduce energy use in buildings.

In a cooling-dominated climate, solar radiation represents one of the most significant sources of potential heat gains. Thermochromic glazing could block and control undesired solar gains, overcome the risk of overheating and reduce the need for cooling, particularly for modern highly-glazed buildings.

TC glazing can modulate its thermo-optical properties reversibly, when a change in its temperature occurs. It responds by absorbing heat from sunlight and when the TC film warms, its solar and visible transmittance level will reduce. By using the sun's own energy, TC glazing adapts itself based solely on the amount of sunlight. It is profitable to reduce the need for cooling but it can also have a negative impact on lighting consumption as the level of natural light will decrease.

The most commonly used material that exhibits thermochromic properties, is vanadium oxide (VO_2). Nevertheless, pure bulk VO_2 has a transition temperature of approximately 68 °C [4], which is obviously too high for use in buildings. Recent studies have shown that it is possible to decrease the transition switching temperature (T_s) by doping the material with metals [5], which is relevant for this purpose.

Many researchers have investigated the performance of TC glazing considering energy savings through building simulations using EnergyPlus [6]. In 2010, Saeli and al. [7] demonstrated that TC glazing has a greater performance in reducing the energy consumption rather than static common glazing, for eight different climates across Europe and North Africa. In 2014, Hoffmann and al. [8] studied the influence of T_s and the switching temperature range (ΔT_s) for a commercial building in two different climates in the USA. Moreover, in 2016 Costanzo and al. [9] put forward the role of T_s in three different climatic conditions in Europe, taking energy consumption and thermal and visual comfort into account. They used six different theoretical types of TC glazing with different T_s and observed the impact on the results in comparison to standard glazing.

From the results found in the literature, one can understand that there is an interest in using TC glazing in terms of energy savings particularly for highly-glazed buildings in hot climates. In the literature, it has also been demonstrated that T_s has an influence on those results. Thus, it is worthwhile to characterize the impact of TC glazing parameters. Nevertheless, no previous study has looked into the influence of TC glazing parameters for hot climates using dynamic building simulations and sensitivity analysis techniques. Hence, this article aims to identify the impact of TC glazing parameters, taking energy consumption and occupant comfort into account.

1   METHODOLOGY

1.1   Case study and assumptions

The case study is a typical office in a building on the core perimeter for four different locations. Its dimensions are 6 m x 5 m x 3 m (length x width x height). The glazed surface is on the façade, which is exposed to solar radiation and the wind. All the other vertical walls, floor and ceiling are considered adiabatic. The external wall is made of a wood cladding (25 mm), separated by an air gap (120 mm) and an insulation board (variable thickness, see *Table 1*), with a concrete layer (200 mm) and plaster board on the inside (13 mm). No exterior obstructions were modelled.
The TC glazing consists of one layer of glass (6 mm) with the thermo-optical properties described in section 1.2 and 1.3.
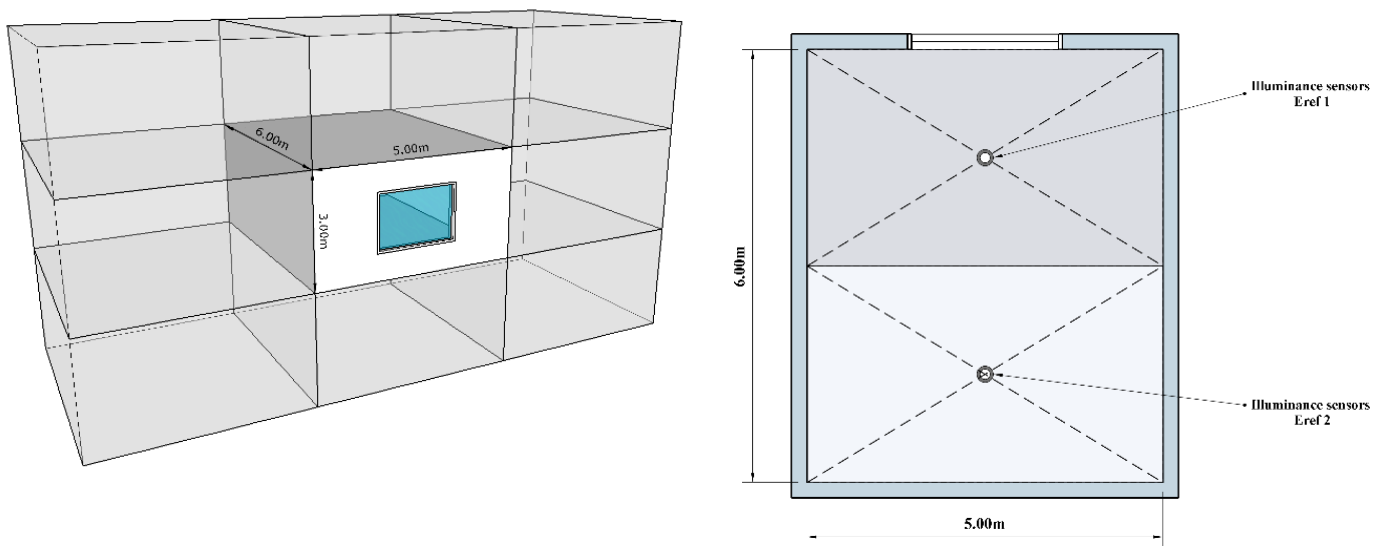
Figure 1. *3D representation of the case study (a)*   *Plan view and illuminance sensors position (b)*

In the simulations, internal loads are considered during occupied time set from 8 am to 5 pm on weekdays [8]:

- Occupant activity: 240W (2 people)
- Electric equipment loads: 150 W/person
- Artificial lighting: 8 W/m²

The artificial lighting system is controlled to meet a set point illuminance level of 300 lux at 0.8m above the floor. This is the minimum required for normal visual tasks according to international standards [10]. The illuminance sensors E_{ref1} and E_{ref2} are located to control each half of the zone (see *Figure 1*).

The air-conditioning system is only activated during occupied time at 24°C, with an air flow rate of 20 m³/h per person. The simulations are performed over an entire representative year.

1.2   Thermochromic glazing model

EnergyPlus [6] is an open-source, validated software. It performs whole building energy and thermal simulations as well as daylighting simulation, using weather data files. Thus, EnergyPlus is the most suitable tool, in this case, to perform this study.

In EnergyPlus 8.4, the TC glazing is characterized by a step-function of the visible or solar spectrally-averaged transmittance against the temperature. The user has to define different types of glazing sets with different spectral properties at a constant and regular number of states. At the beginning of the simulation phase, the previous temperature is used to find the transmittance and the TC glazing state, then after solving the heat balance, the new TC temperature for the next step is found.

An example of the TC glazing model is represented in *Figure 2*. All these variables are varied according to the description in section 1.3.
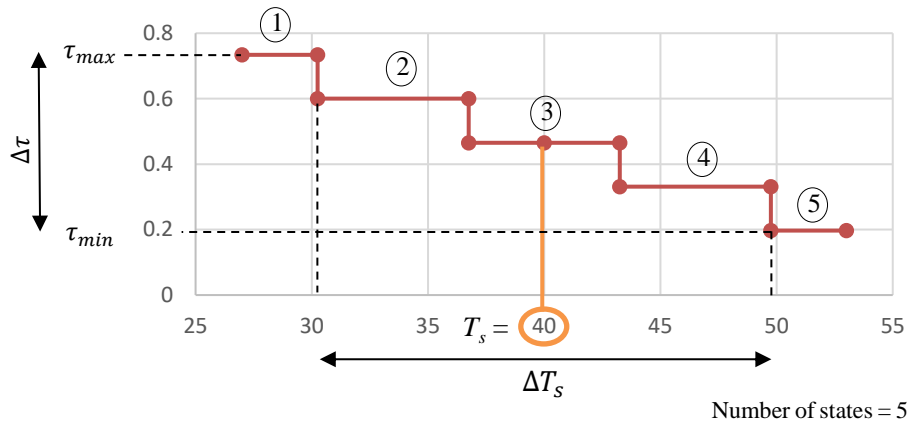

Figure 2. *Transmittance vs. Temperature (°C)*

The switching temperature, T_s, is defined as the temperature when the transmittance is at an intermediate state. The switching range, ΔT_s, is defined as the temperature difference between the lightest state and the darkest state. The solar or visible transmittance range, $\Delta \tau_{sol \; or \; vis}$, is the difference between the highest and the lowest transmittance.

The solar or visible reflectance, ρ, is assumed to be constant through simulations and the absorptance, α, is varied according to the energy conservation:

$$\tau + \rho + \alpha = 1 \tag{1}$$

All the TC glazing parameters in the model are varied simultaneously as explained in section 1.3 below. Its conductivity and emissivity equals 0.9 W.m^{-1}.K^{-1} and 0.84, respectively. They are assumed as constant values.

1.3   Sensitivity Analysis

The goal of the sensitivity analysis (SA) is to quantify, the influence of input variables on an output variable. When global sensitivity analysis (GSA) is used all the input variables have a probabilistic distribution and are varied simultaneously [11]. Hence, this means that the technique allows one to take the entire input distribution into consideration. Among the GSA methods, in this study, the moment independent measure is used. This is defined by Borgonovo [12] as the assessment of "the influence of the entire input distribution on the entire output distribution without reference to a particular moment of the output". This indicator is defined by:

$$\delta_i = \frac{1}{2} \boldsymbol{E}_{X_i} \left[\int \left| f_Y(y) - f_{Y|X_i}(y) \right| \right] \tag{2}$$

where:
- $f_Y(y)$ is the density of the output Y,
- $f_{Y|X_i}$ is the conditional density of Y given that one of the parameters, X_i, assumes a fixed value.

The Latin Hypercube Sampling strategy (LHS) is applied to the input variables, in order to perform the moment-independent measure. The LHS technique has the advantage of obtaining quasi-random sampling across the whole range of variables

In *Table 1*, the eleven chosen input variables for the sensitivity analysis, their range and probability are presented. All the input variables are assumed to be independent.

INPUT VARIABLES	SYMBOL	RANGE	UNIT	PROBABILITY
Building Orientation	BO	0-360	°	Continuous; Uniform
Window to Wall Ratio	WWR	5-99	%	Continuous; Uniform
Insulation Thickness	θ_{ins}	0.01-0.7	m	Continuous; Uniform
Weather File	wea	1-4	-	Discrete; Uniform
Switching Temperature	T_s	5-70	°C	Continuous; Uniform
Switching Temperature range	ΔT_s	1-50	°C	Continuous; Uniform
Solar Transmittance Max	$\tau_{sol,max}$	0.3-0.9	-	Continuous; Uniform
Solar Transmittance range	$\Delta\tau_{sol}$	0.01-0.5	-	Continuous; Uniform
Visible Transmittance Max	$\tau_{vis,max}$	0.3-0.9	-	Continuous; Uniform
Visible Transmittance range	$\Delta\tau_{vis}$	0.01-0.5	-	Continuous; Uniform
Number of states	state	2-20	-	Discrete; Uniform

Table 1. *Sensitivity analysis input variables*

4,096 simulations have been run to take all the distribution and uncertainties of all the input variables into account. The simulation process is managed by a dedicated Python code using the SAlib library [13].

1.4 Model outputs

Several model outputs have been chosen for this study which consists an energy consumption index (I_{ec}), a thermal comfort index (I_{th}) and a visual comfort index (I_v).

I_{ec}, is defined as the normalized sum of the final energy consumed by a building in one year (in this case: cooling and artificial lighting).

I_{th} is defined as the fraction of time when the operative temperature is below 26°C [9] and can be expressed as follows:

$$I_{th} = \frac{1}{N}\sum_{i=1}^{N} Th_i \tag{3}$$

with $Th_i \begin{cases} 0, & if\ T_{op} > 26 \\ 1, & if\ T_{op} \leq 26 \end{cases}$

I_v is defined as the fraction of occupied time when the mean horizontal illuminance of the two reference points is between 300 lux and 2,000 lux [14], also called the useful daylight index (UDI). The index is formulated as follows:

$$I_v = \frac{1}{N_{occ}}\sum_{j=1}^{N_{occ}} w_j \tag{4}$$

$$\text{With} \begin{cases} 1, & if\ 300 > \dfrac{E_{ref1}+E_{ref2}}{2} > 2000 \\ 0, & if\ \dfrac{E_{ref1}+E_{ref2}}{2} < 300\ and\ \dfrac{E_{ref1}+E_{ref2}}{2} > 2000 \end{cases}$$

1.5 Climatic characteristics

The four-chosen cooling-dominated climates are classified as tropical savanna climate: 'Aw' in the Köppen-Geiger classification [15]. This means that all climates have a monthly mean temperature above 18°C all year with a dry winter (precipitations under 60 mm in winter).

In *Table 2*, the geographical coordinates, latitude and longitude, the cooling-degree days, the monthly average outdoor dry bulb temperature and global horizontal irradiation are given. In these climates, no heating is needed.

Climate	Geographical coordinates	CDD-18°C (annual)	Outdoor dry bulb temperature (°C)		Global horizontal radiation (Wh/m²)	
			Summer	*Winter*	*Summer*	*Winter*
Saint-Denis (REU)	20.89 S; 55.52 E	CDD:2140	26.6	21.1	6429	4120
Chennai (IND)	13.08 N; 80.28 E	CDD:3718	31.5	24.2	5722	3621
Weipa (AUS)	12.65 S; 141.84 E	CDD:3039	28.2	24.1	7140	4566
Townsville (AUS)	19.26 S; 146.82 E	CDD:2239	27.6	19.0	6985	3851

Table 2. *Climatic characteristics*

2 RESULTS AND DISCUSSIONS
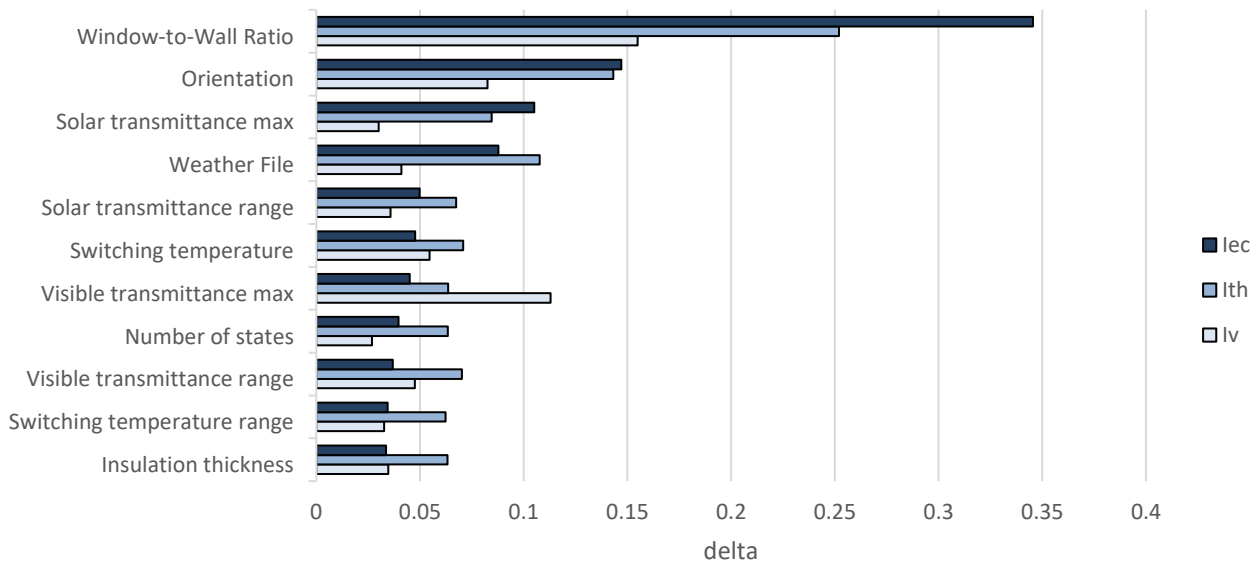
2.1 Delta Moment Measure analysis

Figure 3. *Delta Moment measure for the three indexes*

2.1.1 Energy consumption index

Figure 3 shows that the WWR has the greatest impact on I_{ec}. The glazing area is the first item that a designer has to think about in the early process of building design when energy efficiency is considered. Then comes BO, $\tau_{sol,max}$ and the climate condition (wea), which have to be given priority in the design strategies. For the solar transmittance, the explanation is that it has a direct impact on the quantity of the entering sun radiation and also on the need for cooling. One can understand that the visible transmittance has an influence on the output because it impacts directly the amount of illuminance, thus the artificial lighting consumption.

Furthermore, T_s and all the other TC glazing parameters have approximately the same impact on I_{ec}.

2.1.2 Thermal Comfort Index

Figure 3 demonstrates the same observation found in section 2.1.1: the WWR has the greatest impact on I_{th}. Then, the results show the same pattern with BO, wea and $\tau_{sol,max}$. It has to be noted that in this particular case, T_s has a slightly greater influence on the output than the previous index. Designers should pay attention to this key parameter in the design process when thermal comfort is taken into consideration.

One can conclude that the same parameters in the energy and heat balance model have a similar influence on both I_{ec} and I_{th}.

2.1.3 Visual Comfort Index

As for the two previous indexes, in *Figure 3*, the WWR has the greatest influence on the output I_v. Nevertheless, the pattern here is different. Indeed, the first key TC glazing parameter that needs to be carefully chosen is $\tau_{vis,max}$. In this case, the difference is explained because the visible transmittance has an impact on the amount of illuminance from the sunlight in the room. Furthermore, attention should be drawn to T_s, which has a significant impact on I_v. All the other TC glazing parameters have the same impact on the output.

2.2 Distribution of input parameters

Knowing which inputs have the greatest influence output, it is interesting to see how the TC glazing input parameters relate to the output indexes. This section analyses the distribution of TC glazing input parameters, which have the greatest impact, for the best suitable scenarios, for three different WWR: small (5%-35%), medium (35%-65%) and large (65%-99%)

2.2.1 Distribution for I_{ec}

For this purpose, I_{ec}. has been normalized with respect to the minimum and maximum values. *Figure 4* shows the TC glazing input distribution for I_{ec}. index between 0 and 0.40
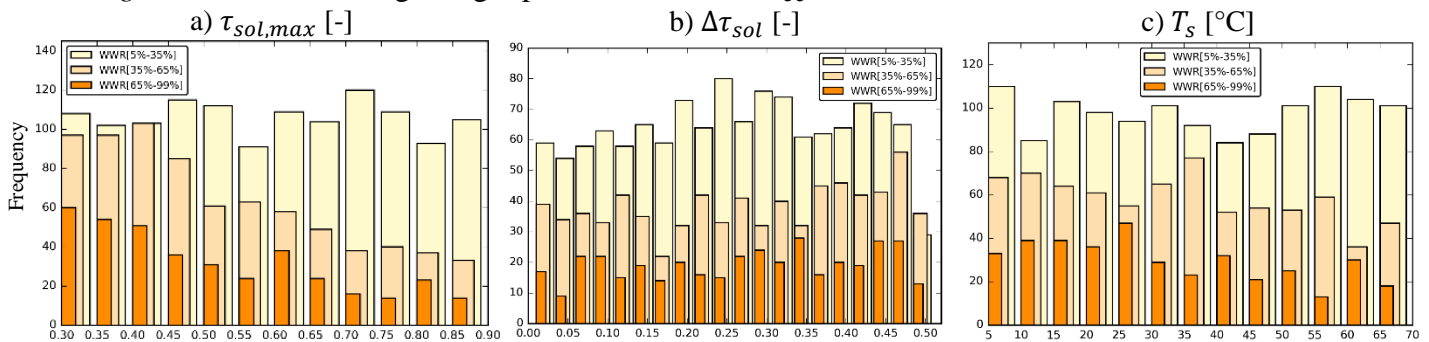

Figure 4. *Distribution of the input parameters for I_{ec} between 0 and 0.40*

It can be observed, for a small window size, that it is more desirable to have $\tau_{sol,max}$ around 0.75 and $\tau_{sol,min}$ value at 0.5, however when the window size is growing $\tau_{sol,max}$ decreases and $\Delta\tau_{sol}$ gets larger. The peak of the distribution is closer to 0.30 for a large window size. For T_s, it is preferable to have a value close 55 °C for a small window size and 25°C for a large size, to achieve the best scenario. Here, the values of T_s gets lower when WWR gets larger, in order to reduce the need for cooling.

2.2.2 Distribution for I_{th}

For the thermal index, it has to be noted that the entire output distribution spreads from 0 to 0.5. It is particularly interesting, because it shows that even with usage of TC glazing the best scenario are a low level of thermal comfort. *Figure 5* shows the input parameters distribution for I_{th}. between 0.35 and 0.50.
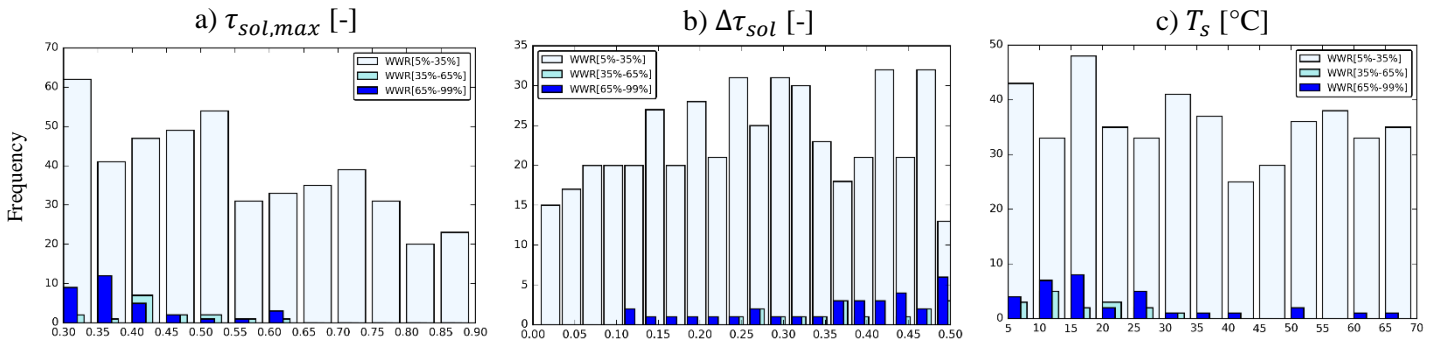

Figure 5. *Distribution of the input parameters for I$_{th}$ between 0.35 and 0.50*

For the thermal comfort scenario in *Figure 5*, it can be observed that it is preferable to have a small value of $\tau_{sol,max}$ when the window size is increasing with a large $\Delta\tau_{sol}$.

It can also be noticed that to have a greater chance to achieve the best scenario, here, T_s has to be between 15 and 30 °C. Indeed, a lower $\tau_{sol,max}$ with a larger $\Delta\tau_{sol}$ and T_s near room temperature may get to the best scenario for any window size.

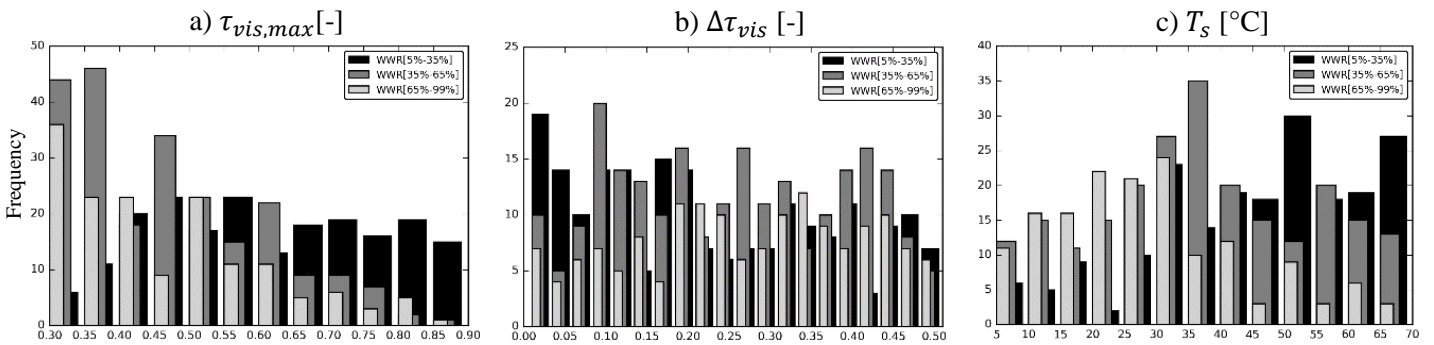### 2.2.3 Distribution for I_v

Figure 6. *Distribution of the input parameters for I$_v$ between 0.70 and 1*

In Figure 6, in order to have a greater chance to obtain the best scenario in term of visual comfort, the TC glazing $\tau_{vis,max}$ has a value between 0.45 and 0.60 for a small window size, with $\Delta\tau_{vis}$ value around 0.20. This trend shift to lower transmittance values, between 0.30 and 0.45 for medium or large window size. Indeed, with larger window the risk of glare is considerable and the daylight autonomy is satisfied.

Moreover, for T_s, the peak of the distribution is near high values of temperature for small window size whereas, it shifts to lower values for larger glazing area. For example, T_s between 30 and 35 °C may attain the goal of visual comfort.

AIRAH and IBPSA's Australasian Building Simulation 2017 Conference, Melbourne, November 15-16.

To summarize, the TC glazing properties that may achieved the best scenarios are a low $\tau_{sol,max}$ and $\tau_{sol,max}$ with a large range of transmittance and a T_s near room temperature. This allows the TC glazing to have a greater range of action in order to reduce energy use and improve thermal and visual comfort, in tropical climates for office buildings.

2.3 Limitations and drawbacks

A limitation of this study is the TC glazing model used in EnergyPlus. Indeed, the step function is not representative of the real thermal behaviour of the TC filter transmittance [16]. An improvement of the thermal and daylighting models has to be done in order to obtain more accurate results.

Another drawback is the geometry and building configuration used as a base case for simulations Several other configurations and construction type as to be tested to check the consistency of the conclusions.

In addition, the input parameters distribution has to be analyze in greater depth. For example, data has to be split between climatic conditions and orientation. Moreover, it would be interesting to test different initial distributions on the input parameters.

CONCLUSION

To conclude, dynamic building simulations were conducted in order to observe the impact of several input variables on several model outputs.

When using EnergyPlus and a TC glazing model, one can establish which input variable influences the results. Those results show that when energy efficiency and comfort have to be considered in a given climatic condition, it is relevant to choose the inputs carefully.

Firstly, designers should pay attention to the size of the glazing area, the building orientation and climate conditions. Secondly, the thermo-optical properties of the TC glazing in addition to the transition temperature, are the parameters which have the greatest influence on the results.
Finally, ΔT_s, $\Delta \tau_{sol}$, $\Delta \tau_{vis}$ and the number of states, seem to have a lesser impact on the output indices but these are not negligible.

This study makes an original contribution by putting forward both the importance and the impact of TC glazing parameters. In addition, the interpretation of the input distribution relating to the indexes reveals which type of TC glazing parameters value has to be chosen to obtain the best suitable scenario for office buildings. Thus, this new data could lead to more accurate design strategies for low-energy office buildings in cooling-dominated climates.

future works may lead to the indication of the optimal scenario with the optimal parameters that reduce energy consumption and improve occupant comfort, both thermal and visual, the most, using optimization techniques. Future studies should answer this question and could lead to the use of this method for office buildings in hot, tropical climates using passive cooling and natural ventilation. In addition, some new parameters need to be added such as the air flow rate and new output indices should be introduced.

These results could also serve as guidelines for the challenging development and improvement of thermochromic thin coating materials.

ACKNOWLEDGEMENTS

NOMENCLATURE

Variables			
AUS	Australia	N	Number of data
BO	Building orientation [°]	REU	Reunion Island
E	Mathematical expectation	T	Temperature [°C]
E	horizontal illuminance [lux]	wea	Weather file
ƒ	density function	WWR	Window-to-wall ratio [-]
I	Model output index	X	Input variable
IND	India		
Greek letters			
α	Absorptance [-]	$\Delta\tau$	Transmittance range [-]
δ	Delta [-]	ρ	Reflectance [-]
ΔT	Temperature range [K]	θ	Thickness [m]
		τ	Transmittance [-]
Subscripts			
ec	Energy consumption	s	switching
ins	Insulation	sol	solar
occ	Occupied time	th	Thermal
op	Operative	v	Visual
ref	Reference	vis	Visible

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