

OPTIMISATION METHODOLOGY FOR THE DESIGN OF SOLAR SHADING FOR THERMAL AND VISUAL COMFORT IN TROPICAL CLIMATES

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ABSTRACT

The aim of this paper is to propose a methodology using simulation to help optimising the design of passive buildings through a comfort approach. The study will concentrate on the design of solar shading that plays an extensive role in tropical climates and that has a direct impact on the thermal and the visual comfort of the building users. Indicators to describe thermal and visual comfort are presented and parametric studies on the type and dimensions of the solar shades are developed with regard to their impact on the percentage of thermal comfort and the availability of daylight in the room. The methodology, based on a multi-physics approach, is innovative as it concerns the optimisation of the passive behaviour of the building (as opposed to the conventional approach incorporating the energy use) and because it involves the coupling of the thermal and the visual comfort of the building users.

INTRODUCTION

Aiming to design highly efficient buildings while limiting their financial and environmental costs, optimisation represents an interesting approach for finding appropriate values of several parameters selected. These parameters can be building orientation, insulation thickness, window-to-wall ratio or size of solar shading.

In the tropics, buildings are subject to significant cooling requirements due to the high intensity of solar radiation penetration through fenestration. Although solar radiation prevention is the crucial factor, one drawback of using shading devices is the risk of reducing daylight level and as a consequence increasing the use of artificial lighting and thus the internal loads of the building.

Currently, solar shadings are designed only to improve thermal conditions or to reduce the cooling loads of the buildings but very often no attention is being paid to the availability of daylighting inside. In some cases, the artificial lighting is required inside because of too efficient solar protections. This leads to an overconsumption of the electrical lighting. A compromise must be found between effective solar protections and a suitable natural lighting. The combination of both objectives in terms of reducing the overall building consumption is not obvious.

There is a real need for a methodology combining thermal and daylight simulations to be able to assess the impact of solar shading on both thermal and visual comfort. An innovative approach is proposed in this paper taking into account the passive behaviour of the building both in terms of thermal comfort and availability of daylight.

DESIGN OF SOLAR SHADING

A copious amount of literature is available about the design of solar shading (Dubois, 1997). Previous studies have focussed on its impact on the energy use, for instance the guidebook edited by REHVA on how to integrate solar shading in sustainable buildings (Beck et al., 2010). One way to take into consideration both cooling loads and natural light utilisation in the design of shading devices is to study its impact on energy use for cooling and artificial lighting using an energy simulation programme (Raeissi et al., 1998; Ossen et al., 2005; Tzempelikos et al., 2007). Simple indices are proposed to compare the thermal and visual effectiveness of solar shading in non-residential buildings (David et al., 2011). Those indices also focus on the energy demand of the building with the annual cooling energy and the annual lighting energy. This methodology is not applicable for passive buildings where the aim is to avoid the use of energy. There is a real need for a method based on the comfort approach to design solar shading and to a large extent the envelope of buildings.

A first step was taken in that direction with the development of the PERENE label in 2004 (Garde et al., 2005) and its update in 2009 (Garde et al., 2010). PERENE, which is the acronym of ENergy PERformance of buildings in French, helps to design low energy buildings in the French tropical island of La Reunion located in the Indian Ocean (21.3°S; 55.5°E). The method proposed by PERENE uses the solar factor S to design solar shading systems. The solar factor S is the ratio of solar energy transmitted by the system glass/solar shading. It is directly proportional to the shading coefficient Cm that is the fraction of the beam solar irradiation that impacts the glazing with and without the use of solar shadings. The shading coefficient depends on the type and the size of the solar shading as well as the orientation of the opening. The update of the PERENE standard in

2009 includes a method of calculation of C_m by proposing a wide range of solar shading: overhangs (infinite or limited to the considered window), overhang (with left and/or right) side fins, horizontal slats.

However, this methodology does not take into account the availability of daylighting in the room. As a consequence, the PERENE label can lead to the design of gloomy buildings integrating too much solar protections in which the use of artificial lighting is required almost all year round.

The real need lies in the development of a methodology which will take both thermal and visual comfort for the design of solar shading into account. This paper investigates the effect of solar shading on thermal comfort as well as daylight availability to propose a methodology to optimise the design of solar shading.

PRESENTATION OF THE SIMULATION PLATFORM

Objectives of the optimisation

To achieve optimisation of the building envelope, two methods can be used, either a parametric study or by coupling an optimisation software to the building models. Knowing the complexity of the problem, a parametric study could be difficult to realise. Indeed, in such parametric studies, we usually set all but one variable and try to optimise a cost function with respect to the unfixed variable. However, any change made to a variable makes all the other variables become non-optimal and therefore these variables need to be readjusted. This manual procedure can be extremely time-consuming, often impractical for more than two or three independent variables and only a limited improvement can be achieved (Wetter, 2000). As an alternative, an optimisation algorithm can be useful to reduce the number of required resolutions while ensuring a better convergence to a global minimum.

Usually, a lot of time is spent in generating the input files for a simulation model, but once this is done, the user generally does not determine the parameter values that lead to optimal system performance. This can be due to the lack of time left to carry out the tedious process of changing input values, running the simulation, interpreting the new results and deducing how to change the input for the next trial. The case could arise that the system being analysed is so complex that the user is just not capable of understanding the nonlinear interactions of the various parameters. However, using mathematical programming, it is possible to do automatic single- or multi-parameter optimisation with search techniques that require only little effort (Wetter, 2001).

Selection and presentation of the simulation tools

There is a division within the building simulation community regarding the problem of daylight in

energy simulations (Jakubiec et al., 2011). The “single model” group utilises only energy models to account for daylight, thermal and energy analysis. This is probably warranted in situations where electric lighting is not a large component of the total building loads such as in residential programs. The “hybrid model” group predicts daylighting and thermal consequences in two separate models which share lighting and shading schedules (An et al., 2010). This method accounts for a more accurate representation of reality; however, it also takes more time to run such a two-model simulation along with a concerted effort to organise and transfer data from one simulation environment to another. The method presented in this chapter proposes a more integrated approach to this problem.

In this paper, the models presented are hybrids and composed of a thermal model using EnergyPlus software (Crawley et al., 2000) as well as a daylighting model using Daysim software that relies on the calculation methods of Radiance software (Ward, 1994). A comparison between the daylighting calculation methods of EnergyPlus and Daysim will be accomplished to clarify this choice.

EnergyPlus or Daysim: a comparison for daylight simulations

Both EnergyPlus and Daysim allow us to calculate the annual hourly illuminance data as well as the visual comfort indicators. However, the calculation methods used are completely different.

EnergyPlus utilises the split flux method based upon a representation of complex geometries in plans when predicting interior daylight levels. This kind of calculation works best in rooms where the ratio of width to depth to height is 1:1:1 which almost never occurs in reality, and thus such calculations often result in substantial inaccuracies (Jakubiec et al., 2011). Daysim on the other hand, employs a reverse ray tracing algorithm based on the physical behaviour of light in a volumetric, three-dimensional model which should represent reality in a most accurate way (Ward, 1994). Daysim uses a daylight coefficient method to generate an annual illuminance profile at each point of interest. The contribution for each daylight coefficient is then determined using the Perez All Weather Sky distribution based on values from the TMY data. Furthermore, Daysim considers direct sunlight entering a space whereas EnergyPlus does not.

The above discussion establishes a significant reason to use Daysim for the generation of the distribution of natural light in a space when compared to EnergyPlus and other split-flux methods.

GenOpt

GenOpt, developed by Dr Michael Wetter, was first introduced in 2000 (Wetter, 2000). GenOpt is generic optimisation software to help find the independent variables that produce the best performance of complex systems involving several independent

variables, and where the cost function is computationally expensive, and its derivatives are not available. GenOpt can be coupled to any simulation program that reads and writes INPUT/OUTPUT to text files. It is divided into a kernel part that reads the INPUT files, calls up the simulation program, and stores the results; as well as an optimisation part that contains the optimisation algorithms.

To perform the optimisation, GenOpt automatically generates input files for the simulation program. These files are based on input templates for the particular simulation program. GenOpt then launches the simulation program, reads the function value being minimised from the simulation result file, checks possible simulation errors and then determines a new set of input parameters for the next run. The whole process is repeated iteratively until a minimum value of the function is found.

In the literature, it is possible to find many examples of GenOpt being used with the simulation tools EnergyPlus or TRNSYS. This coupling to EnergyPlus and Daysim undertaken in this study, was never before realised. Furthermore, GenOpt is usually used for the purpose of minimising the energy use of a building, but optimisations on the passive performances of the building have been rarely explored.

Simulation workflow

Figure 1 shows the principle of coupling GenOpt with the thermal and daylighting simulation tools. The inputs of both models are created by GenOpt by varying the parameters selected depending on the previous outputs recovered from EnergyPlus and Daysim. Once the input files have been created by GenOpt, it automatically launches both simulations and waits until the end of the simulations to recover the results and launch a new pair of simulations.

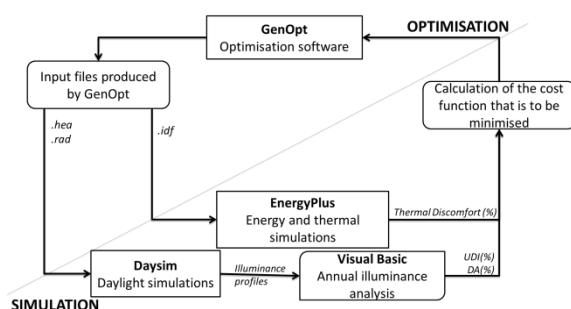


Figure 1. The coupling principle of the simulation tools Daysim and EnergyPlus with GenOpt

EVALUATION OF THERMAL AND VISUAL COMFORT

Givoni zones for thermal comfort

International standards to describe comfortable thermal environments indoors (ISO, 1994; ASHRAE, 2003) were originally based on theoretical analyses of human heat exchange with the environment

calibrated using the results from experiments in special climate-controlled laboratories or climate chambers. However, field studies conducted in tropical climates have found that the International standard for indoor climate, ISO7730 based on Fanger's predicted mean vote (PMV/PPD) equations, does not adequately describe comfortable conditions (de Dear et al., 2002; Humphreys et al., 2002).

The adaptive comfort models that are adapted to buildings without mechanical cooling systems are taken into account the standard EN15251 (EN, 2006), but these models are not dependant on the air humidity that plays a significant role in tropical climates.

In the early design stage, architects and engineers require simple tools and methods to study the climate and the comfort conditions inside the building. Givoni (Givoni, 1976) proposed the use of thermal comfort zones represented on a psychometric chart to assess thermal comfort.

Modification of the zone for a ventilated building

During three summer seasons, a large field study of thermal comfort surveys was conducted in the French tropical island of La Reunion, located in the Indian Ocean. The thermal comfort survey was based on ISO 10551 (ISO, 1995). More than 2,092 sets of environmental and subjective observations were recorded. The results of the survey are presented in (Lenoir, 2013) and led to a proposal for an improvement in the assessment of thermal comfort.

Figure 2 shows the new comfort zone that is proposed. The zone is called NMV for Natural and Mechanical Ventilation as it assumes that the room is naturally ventilated and that ceiling fans are available for the users. The upper temperature limit decreases from 32°C to 30°C. However, in terms of humidity level, the comfort surveys showed that it was possible to be comfortable with higher humidity levels than the limit proposed by Givoni. The proposed zone has a upper humidity limit of 21 gwater/kg_{dryair}.

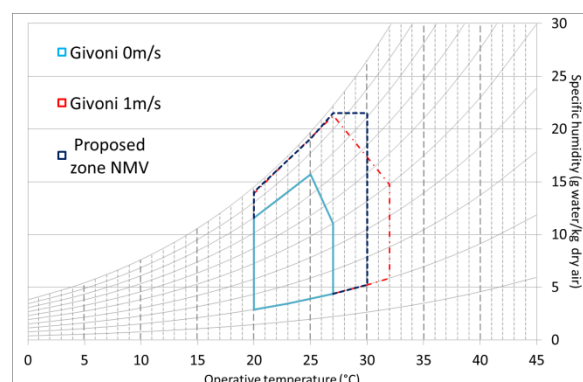


Figure 2. New comfort zone for a naturally and mechanically ventilated room

In this study, thermal comfort is evaluated according to the NMV zone on the psychometric chart that was

defined in the previously. The assumption is made that the occupants have adaptive opportunities and play an active role in ensuring their own comfort (window openings, ceiling fans, range of freedom to dress to one's own wishes). The number of uncomfortable hours (between 8 am and 5pm) that is outside the NMV zone is counted to calculate the percentage of comfort for each simulation.

Table 1 provides the conversion of the percentage of thermal discomfort into a number of hours, days or weeks of discomfort.

Table 1. Conversions of the percentage of comfort into a number of hours, days and weeks of discomfort

PERCENTAGE OF COMFORT	80 %	85 %	90 %	95 %	100 %
HOURS OF DISCOMFORT	457 h	343 h	229 h	114 h	0 h
DAYS OF DISCOMFORT (9 HOURS / DAY)	50.8 d	38.1 d	25.4 d	12.7 d	0 d
WEEKS OF DISCOMFORT (5 DAYS / WEEK)	10.2 w	7.6 w	5.1 w	2.5 w	0 w

Daylighting assessment

In Europe, daylighting is often assessed in early design phase using the Daylight Factor. This index is not adapted to a tropical climate as the levels required have been defined for Europe. The use of the daylight factor in tropical climates may lead to the design of over-illuminated buildings with a high risk of visual discomfort.

The use of the Useful Daylight Index is proposed in this paper. This index is defined as those illuminances that fall within a certain range defined between a lower and a higher value. The UDI corresponds to the ratio of the specific time when the daylight available is considered as to offer useful illumination for the occupants of the space i.e. between the two extreme values. In our case, we choose 300 Lux as a lower value as it corresponds to the usual minimum illuminance value required for an office. The higher limit is fixed at 8,000 Lux. Reasons for this choice are given in (David et al., 2011).

With regard to the offices of the study, a hybrid indicator is used that takes into account the task area of the office. The task area is located close to the window leaving a gap of 0.5m to reduce the risks of glare and sunspots. In this area (represented by the green dots in Figure 3) the illuminance is to be between 300 Lux and 8,000 Lux. The Useful Daylight Index UDI (300-8000) is calculated on those spots. As for the area located close to the walls, the need for light is lower as the space should be mainly used for storage and passage. The illuminance in this area needs to be greater than 100 Lux and the indicator in this case is the Daylight Autonomy with

a lower limit of 100 Lux (purple dots). Depending on the spot considered, the indicators are calculated over the year and then averaged for the whole office. The final indicator that will be used in this study is named UDI_{office} .

This indicator does not claim to solve all the problems linked to visual comfort such as glare. It reduces the risk of sunspots on the desk plan that often leads to the use of curtains or blinds cutting off natural ventilation and daylighting and causing the need for active systems (air conditioning, ceiling fans or artificial lighting) to address the comfort issues.

In the case of the classroom, the mapping is defined in Figure 3. Two parallel strips close to the windows are taken to be unoccupied because the risk of sunspots and glare is high. The illuminance is simulated every meter and the average useful daylight index (UDI 300-8000) is calculated.

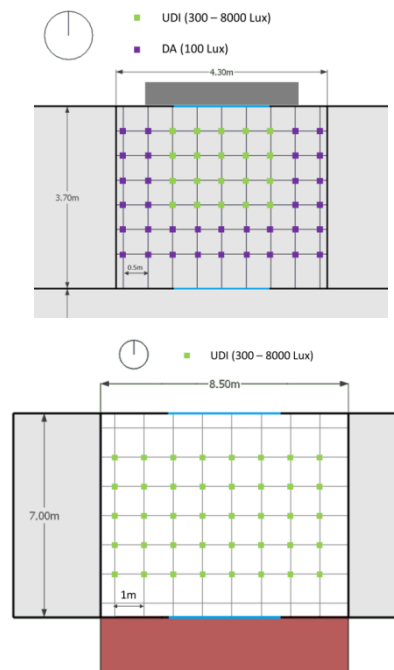


Figure 3. Definition of the useful daylight index for an office and for a classroom.

DESCRIPTION OF THE INPUT PARAMETERS

Office and Classroom Geometry

The optimisation methodology will be experimented on a test cell including an office and a classroom using the example of the ENERPOS building located in Reunion Island (Lenoir et al., 2012). The investigated building is composed of two typical cellular offices, which can be occupied by one or two persons and that are separated by a corridor. The outside window orientation is north-facing. The offices are cross naturally ventilated with interior openings between the corridor and the two offices. On the first floor, a naturally ventilated classroom with two openings on two opposite façades is north-

south orientated. The offices and the classroom are assumed to be surrounded by rooms with a similar temperature on the east and west walls.

The height of the window sill is usually 1.1 m but to improve natural ventilation of the sitting users of an office or a classroom, it is useful to lower the height of the window sill to 0.8 m. This choice was made for the test cell.

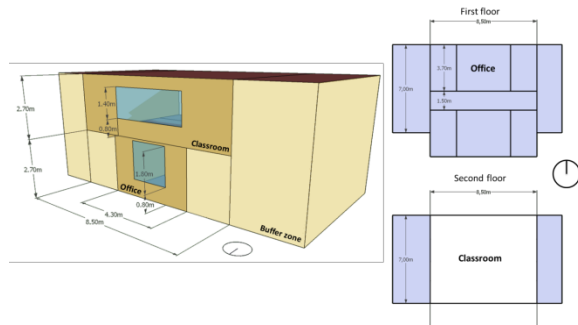


Figure 4. Perspective and cross section of the investigated rooms

Solar shading

For this investigation, all windows are considered not to be shaded by either buildings opposite or neighbouring ones. This might not be realistic for all inner city locations, but it results in higher solar heat gains and is therefore a safe assumption regarding the evaluation of thermal comfort.

For the baseline model, the building does not contain any solar shading for the windows. Shading is added in the process of optimising the building in order to determine the impact of shading devices on thermal and visual comfort. The investigated shading devices for the rooms are:

- an outside overhang that stands on top of the opening;
- an outside overhang with two side fins on each side of the window;
- horizontal slats with a constant gap of 0.3m.

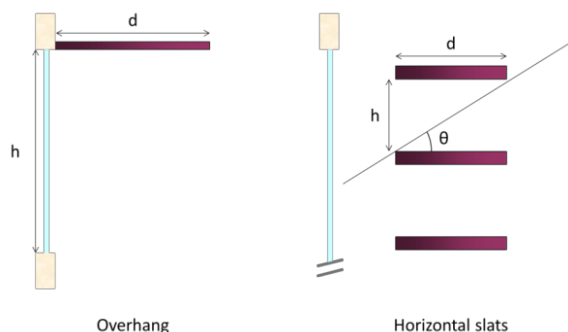


Figure 5. Definition of the ratio d/h for an overhang and of the angle of incidence θ for horizontal slats

The parameters being modified in the optimisation process are related to the geometry of the overhang, the side fins or the horizontal slats according to the case studied. To describe the dimensions of the solar

shading studied, the parameters defined in the PERENE standard are used (PERENE, 2009). For an overhang, the ratio d/h represents the quotient of the length of the overhang (d) on the height of the opening (h) as illustrated in Figure 5. As for horizontal slats, the angle of incidence θ , described in Figure 5, depends on the length of the slats and the height between two following slats.

SIMULATION RESULTS

North-facing Office

For the north-facing office, the solar shading studied is an overhang that stands on top of the opening. Three parameters vary and are described in Figure 6.

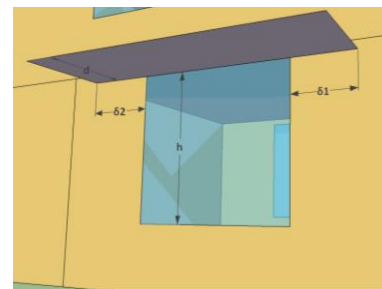


Figure 6. Definition of the parameters of the overhang (d , δ_1 , δ_2 and h)

The impact of the geometry of the solar shading on thermal and visual comfort is estimated by plotting on Figure 9 several outputs obtained using the thermal and daylighting simulations. shows the percentage of thermal comfort (NMV), the daylight autonomy with a lower limit of 300 Lux (DA300), the useful daylight index for an office (UDI_{office}) and the useful daylight index with 300 Lux as a lower limit and 8,000 Lux as upper limit ($UDI_{300-8000}$).

Logically, the percentage of thermal comfort increases with the length of the shade. This can rise by 8% which represents approximately 20 week days of thermal discomfort (4 weeks) and reaches a plateau when the ratio d/h is greater than 1. The slight fluctuations of thermal comfort for a similar length of the overhang correspond to the variation of δ_1 and δ_2 .

With regard to daylighting, the variations are less noticeable than for thermal comfort. By looking at the daylight autonomy (DA300), it can be seen that the percentage decreases when the length of the overhang increases from 93% to 81%. When the ratio d/h is approximately 1.6, the calculation of the daylight autonomy can produce several results, due to the variations of δ_1 and δ_2 . The variations of the useful daylight index ($UDI_{300-8000}$) are different from the daylight autonomy. It can be seen that when the ratio d/h is less than 1, the UDI increases slightly. Indeed, the occupants of the office are protected from direct sunlight by the solar shading when the ratio d/h increases from 0 to 1. This reduces the number of

hours when the illuminance is greater than 8,000 Lux. Afterwards, when the solar shading has a ratio d/h greater than 1, the UDI starts decreasing which signifies that the number of hours when the illuminance is below 300 Lux rises. The UDI curve follows the trend of that of the DA when the ratio d/h is greater than 1.5, meaning that from this value, there will be almost no values of illuminance greater than 8,000 Lux in the office and therefore that the risks of sunspots in the office is low.

The UDI_{office} indicator is less restrictive than the two other daylighting indexes. In the case of a north-facing office, the UDI_{office} increases with the length of the overhang by approximately 5% and reaches a plateau when the ratio d/h is greater than 1.

South-facing office

For the south-facing window, the solar shading studied is composed of an overhang with two side fins. Three parameters vary from 0.01 m to 3 m:

- the length of the overhang d_1 ;
- the side fin on the left-hand side (West) d_2 ;
- the side fin on the right-hand side (East) d_3 .

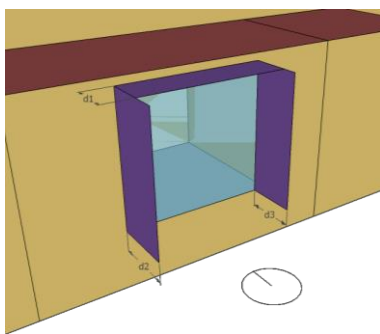


Figure 7. Overhang and side fins for the south-facing window

Figure 9 shows the simulation results of the south-facing office. The percentage of thermal comfort varies from 87% (33 days of discomfort), when the length of overhang and the side fins are close to zero, to 96% (10 days of discomfort) when the length of the overhang is the largest. The variations are not very significant because the south-facing window only receives direct solar radiations for three months per year. However, those three months (November, December and January) are amongst the hottest of the year, and thus, it is essential to shade south openings.

Figure 10 illustrates the changes in visual comfort in relation to thermal comfort when the geometric parameters of the shading vary. First, the increase in the percentage of thermal comfort from 87% to 90% does not have a significant impact on the daylight autonomy and the useful daylight index of the office. However, the increase in the percentage of thermal comfort from 90% to 96% induces a drop in both

visual comfort indexes (by approximately 25% for the useful daylight index and by 60% for the daylight autonomy). Any intentions bring about a significant decrease in the number of days of thermal discomfort of the office will cut down the availability of daylight in the office for the whole year.

East-facing office

In the case of an east-facing window, an overhang does not constitute a suitable form of shading because in the morning the sun is almost horizontal and direct radiation will enter the office causing high risks of glare and sunspots. The solar shading studied is in the form of horizontal slats in front of the window as shown in Figure 5. The impact of the number of horizontal slats is studied by comparing the thermal and visual comfort with 4 or 6 slats in front of the office.

The angle of incidence θ varies from 15° to 88° which corresponds to a variation of the length of the slats (d) of 0.01m to 1m. Figure 11 shows the changes of thermal and visual comfort when the angle θ varies. It is noticeable that the percentage of thermal comfort decreases when the angle of incidence increases as this means that the slats are smaller and thus that the shading is not as efficient. Variations of the percentage of thermal comfort range from 60% (102 days of discomfort) to 80% for 4 slats (51 days) or 85% for 6 slats (38 days).

With regard to visual comfort, the daylight autonomy (DA300) varies considerably in the case of 6 slats. It ranges from 35% to almost 95%. In the case of 4 slats, the variations are less significant as the minimum is 60%. It is very interesting to notice the variations of the useful daylight index for the office in both cases. Indeed, in the case of 4 slats, UDI_{office} remains nearly constant with the angle of incidence. By contrast, UDI_{office} in the case of 6 slats has a variation of 20% depending on the angle of incidence.

Since the percentage of thermal comfort does not change significantly when comparing the two types of shading (the difference is less than 5% corresponding to approximately 10 days of thermal discomfort), choosing a solar shading composed of 4 horizontal slats could be particularly beneficial for visual comfort and daylighting without having a substantial impact on thermal comfort. Moreover, 4 slats in front of the window instead of 6 increase the occupants' view to the outside. Even if there is no widely accepted scientific agreement as to what the benefits of having a work place with a view are, it is conceivable that a view suppresses the feeling of loneliness of building occupants.

A similar methodology has been applied to a west-facing office and to a north-south orientated classroom. The results of those cases are presented in (Lenoir, 2013).

CONCLUSION

This chapter addresses a multi-physics challenge in the building design as it integrates physical issues – i.e. thermal, airflow and daylight design, energy but also human behaviour that is difficult to describe mathematically (thermal and visual comfort, building occupancy, equipment use). The innovative methodology that is proposed focuses on comfort to design buildings rather than the conventional approach incorporating the energy use. A parametric study is suggested for the type and dimensions of the solar shading. The outputs of the model are defined as the percentage of thermal comfort (considering the natural and mechanical ventilation comfort zone defined in chapter three) and the daylight autonomy or the useful daylight index.

Although this methodology raises specific issues which require further thought in terms of building design, there are also limitations to be taken into account. GenOpt has been used to launch both the thermal and the daylight models. This tool does not have a graphical user interface and its implementation is not straightforward. Currently, it is unsuitable for design offices that lack the technical abilities to use such tools. In addition, although the maximum number of independent variables is not restricted with GenOpt, it is preferable not to exceed 10 variables. This is a limiting factor if the methodology is applied to an entire building. The simulation times are also hastily dismissed since it is approximately 2 hours when only one parameter varies and approximately half a day is required for a variation in 3 parameters. Another limitation is the single cost function that makes it very complicated to optimise several outputs.

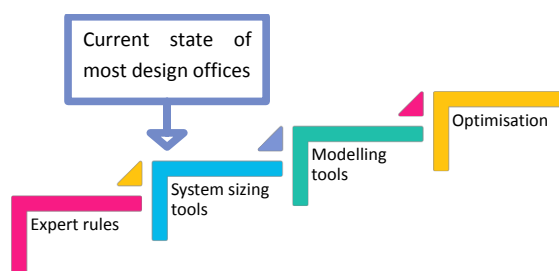


Figure 8. Four levels of requirements for the design of buildings

Figure 8 illustrates in our view the step needed to achieve to improve the building design process. Four levels of design are identified. The first one is the sole use of expert rules such as the one proposed by the PERENE label to size solar shading. The second step is the use of tools to size the systems (air conditioning and electrical lighting for instance). Most design offices currently stand between level one and level two. The use of modelling tools to simulate the passive behaviour of the buildings is the third step. Some design offices use such tools to

study thermal comfort or daylighting. However, no coupling is achieved between the thermal and the daylight simulations. The simulation tools are currently employed more to develop expert rules rather than to simulate and optimise buildings.

The optimisation methodology proposed in this paper that represents the fourth stage of this process is far removed from the current practice. However, we estimate that it is necessary to move towards this direction.

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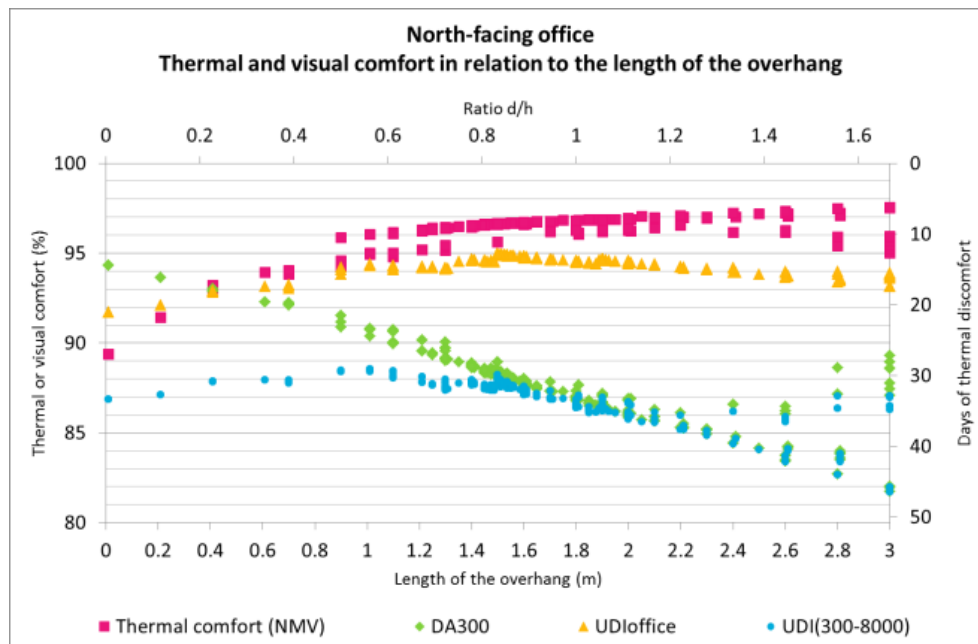


Figure 9. Thermal and visual comfort variations in relation to the length of the overhang

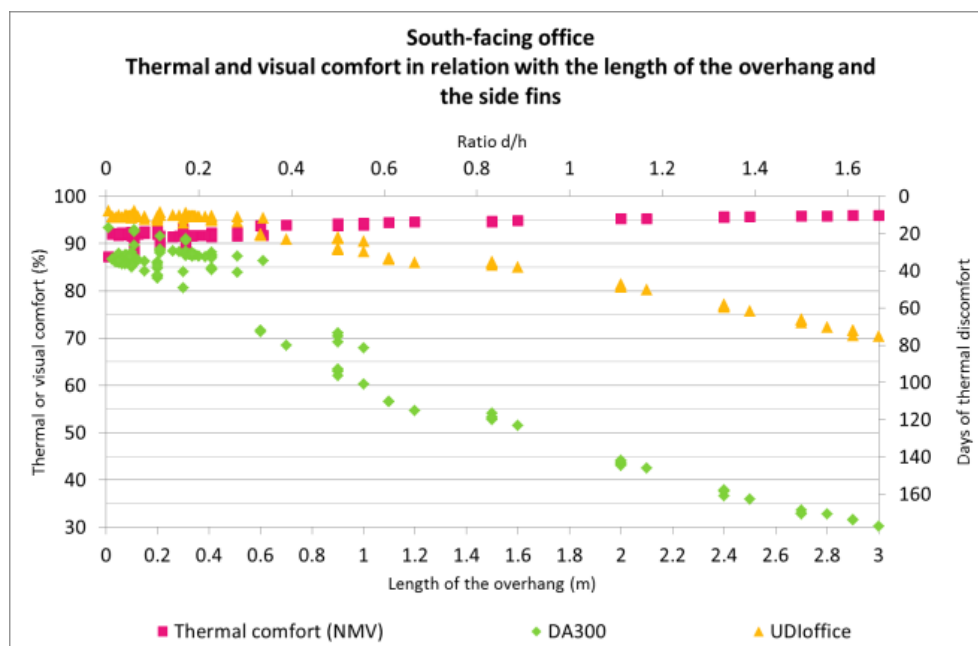


Figure 10. Thermal and visual comfort variations in relation to the length of the overhang

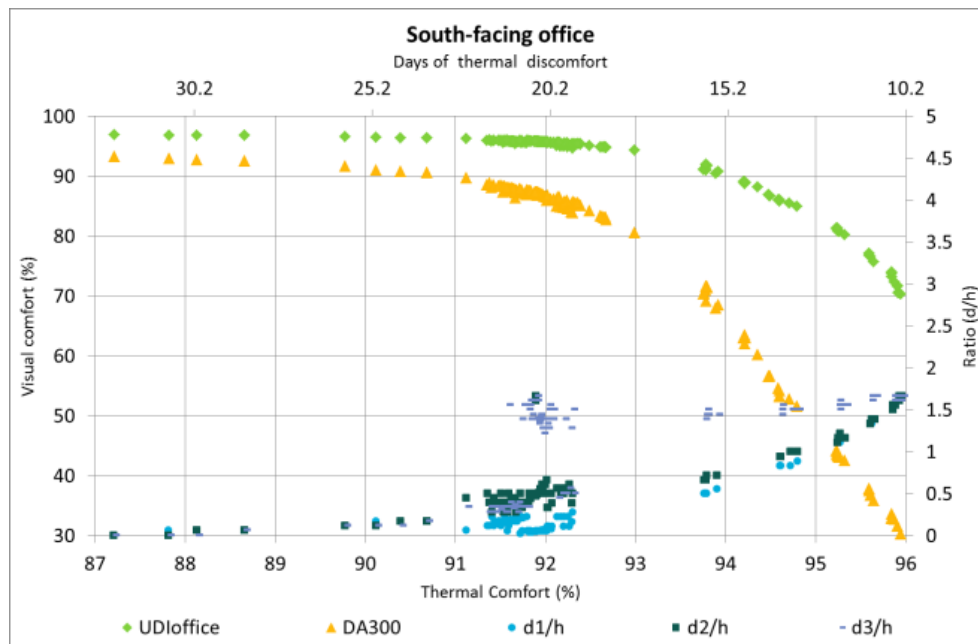


Figure 11. Variations of the visual comfort with regard to the thermal comfort when the geometry of the overhang and the side fins varies.

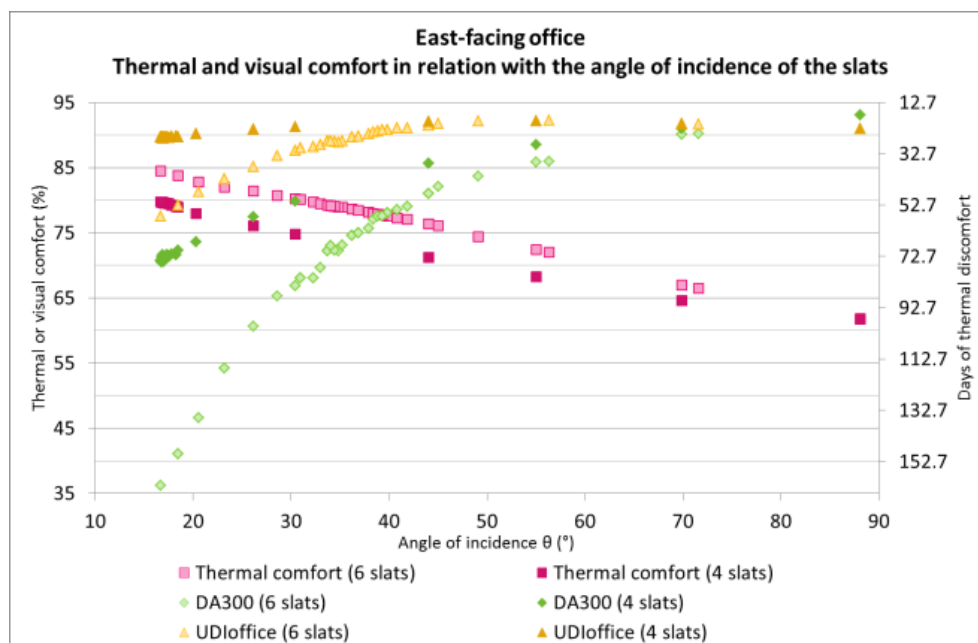


Figure 12. Thermal (percentage of hours) and visual (UDIoffice and DA300) comfort function of the angle