Chapitre 4

Développement d'un prototype de volet acoustique en vue de ventilation naturelle

Au chapitre précédent, la méthodologie de simulation numérique du système de ventilation naturelle a été examinée et validée. La modélisation de différentes géométries à l'aide de la CFD permet d'élargir le domaine d'application des solutions de ventilation naturelle.

Dans ce chapitre, on se sert du modèle CFD accompagné d'une modélisation acoustique par éléments finis (FEM) afin de concevoir des prototypes de volets acoustiques capables de réduire la propagation des bruits extérieurs à travers la fenêtre tout en maintenant un taux de ventilation acceptable. Plusieurs prototypes sont envisagés (sur la base d'un remue-méninges): des volets à lamelles et des volets à chicanes. Ensuite, chacun est évalué du point de vue des performances aérauliques et acoustiques (environnement de salles réverbérantes). Ces études se concentrent uniquement sur l'impact de la géométrie retenue et négligent l'effet des matériaux employés. Les meilleures conceptions sont celles qui assurent un compromis entre la réduction de la performance aéraulique et le renforcement de la fonction antibruit.

Ensuite les conceptions retenues sont étudiées expérimentalement au travers d'une mise en œuvre selon 2 matériaux : plaques en mousse, et lamelles de plexiglas. Ces travaux expérimentaux ont été réalisés par l'équipe de l'ENTPE dans le cadre du projet OVI-SOLVE. Les résultats sont brièvement présentés afin de confirmer et valider les caractéristiques obtenues pour les volets (index de réduction de bruit, affaiblissement en taux de ventilation en ventilation mono-façade et traversante, avec matériau translucide ou opaque, etc.). Les paramètres obtenus seront les entrées des simulations de performance du bâtiment qui seront présentées au chapitre suivant.

4.1. Méthode de conception

La performance de la ventilation naturelle est limitée par le fait que le rafraichissement par l'ouverture de fenêtre ne peut pas se concilier avec les contraintes liées aux bruits extérieurs. Ceci conduit à faire porter l'effort sur la conception et la fabrication d'équipements de protection acoustique de la fenêtre, qui restent compatibles avec la ventilation naturelle. La logique de conception a été présentée dans le Chapitre 1.4, et nous avons distingué deux domaines d'application différents: bâtiment tertiaire de type bureaux et bâtiment résidentiel. Afin de limiter le nombre de prototypes à concevoir et fabriquer, la méthode de conception suit le schéma:

a. Remue-méninges visant à imaginer des dispositifs efficaces en termes de ventilation et de protection acoustique
b. Elimination a priori des mauvaises solutions
c. Simulation préalable, non validée, des solutions retenues du point de vue acoustique et du point de vue aéraulique
d. Tri des solutions pour se limiter à deux types de géométrie au maximum

Ces travaux correspondent au Chapitre 4.2.

e. Choix du matériau : translucide pour le dispositif de jour, opaque et poro-élastique pour la nuit
f. Caractérisation acoustique des deux prototypes suivant différentes positions de la source sonore dans la chambre d'essais de l'ENTPE
g. Caractérisation de la transmission lumineuse du prototype translucide

Une partie des travaux ont été menés par l'ENTPE et le CEA INES. Ils seront brièvement présentés puisqu'ils n'ont pas été réalisés dans le cadre de cette thèse. L'ensemble constitue le Chapitre 4.3.

h. Campagne d'essai aéraulique in situ en ventilation traversante d'un dispositif de volets similaires
i. Validation du modèle de calcul aéraulique permettant de faire varier la géométrie et les conditions environnementales.
j. Validation du modèle de calcul acoustique permettant de faire varier les sources de bruit

Les résultats d'essais aérauliques ont déjà été présentés au Chapitre 2.4. Après validation du modèle de calcul, les caractéristiques des volets acoustiques seront utilisées dans la simulation de performance énergétique du bâtiment au Chapitre 5.

4.2. Conception de la géométrie du volet

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How far can “baffle shutters" attenuate outdoor noise while maintaining acceptable natural ventilation rates?

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ABSTRACT

Natural ventilation is an attractive solution for cooling. However its implementation on building is often limited due to privacy, security and external noise. The use of "baffle shutters" could reduce the noise exposition but it also could decrease the air flow rate, particularly in the case of single-sided natural ventilation.

This paper assessed the impact of different types of shutter on the acoustic attenuation and on the air change rate. The methodology is based on numerical simulation using Computational Fluid Dynamics for ventilation study and finite element method for the acoustic study. Two kind of shutters have been studied, one type with chicanes and the other one with louvers. A parametric study on the geometry of both shutter types has been undertaken accounting for the spacing between slats, their width, their inclination angle and their position (vertical or horizontal).

The results are compared to the same simulations without any shutter. The best reduction of noise reached is 13dB while the air change rate is reduced by 80%. The reduction of ventilation rate is unavoidable since the apparent opening surface is reduced by 50% due to the shutter. However, another configuration of shutter shows a reduction of air change rate of 50% only but 3dB on noise. The choice of the best design of shutter is a trade-off between noise attenuation and air change rate.

Key words: Natural ventilation, noise attenuation, numerical simulation, shutter, baffle, louver

1. INTRODUCTION

Natural ventilation is an attractive cooling solution in the design of sustainable building environments. In the past years, many research works have been dedicated to the evaluation and improvement of natural ventilation performance [Jiang and Chen, 2002] [Evola and Popov, 2006] [Caciolo et al., 2011].

Among the different natural ventilation strategies, the single-sided ventilation appears to be the easiest to integrate in buildings since this strategy limits the problems of privacy and noise between rooms. However the air change rate is lower compared to cross or stack ventilation. The single-sided ventilation is rather well accepted by the occupants but its implementation is generally limited by the outdoor noise.

The introduction of "baffle shutters" including air channels and noise obstacles could be a solution to reduce noise exposure and still allow indoor environment to “breath”. Since the shutters are obstacles reducing the air change rate compared to an opening surface, their design should be a trade-off between an adequate air change rate and significant noise attenuation.

This paper provides an analysis of noise attenuation and air change rate for 2 types of baffle shutters based on CFD and FEM numerical simulations. One type of shutters is with two or three rows of baffles and the other one with inclined louvers. A parametric study on the geometry of both shutter types is then undertaken, varying the width, the inclination angle and the spacing of slats as well as the vertical or horizontal position of slats. The objective of this study is to identify the best concepts which will be assessed in later experiments.

In the single-sided natural ventilation, both analytical and numerical methods have been developed in the last decades for the assessments of the air change rates [Linden, 1999][Li and Delsante, 2001]. Analytical models have been successfully developed for top-hung window [Warren and Parikins, 1985][Larsen and Heiselberg, 2008] and have been validated by experiments [Caciolo et al., 2012]. However, in the case of opening with shutters, the geometry is more complex, so that the numerical simulation turns to be the most appropriate tool which can reveal the impacts of various shutter design parameters, especially on the stack and wind effects which are the two driven forces in single-sided natural ventilation.

2. NUMERICAL SIMULATION METHODS

2.1. General description

In this paper, two types of shutters have been studied. The shutter is installed on a window with dimension of 1m*1m. The first shutter type consists in multi-layer slats: each slat is 20cm high (H1) with a thickness (e) of 1 cm or 2 cm; the slats are disposed on the windowsill; the slats are side by side from a view in normal direction; the shutter width (E) is of 10 cm or 20 cm. Two examples are shown in Fig. 1(a&b). The second type consists in parallel louvers: the thickness of louvers 5 cm or 10 cm; the height for each louver is 2 cm or 4 cm and two inclination angles (11° and 22°) are studied. Two examples are shown in Fig. 1(c&d). Both the slats and louvers could be set horizontally or vertically.

This work employs Finite Volume Method for ventilation study and Finite Element Method for acoustic study, respectively within the commercial calculation environment Fluent 14 and Comsol Multiphysics 4.3. In the CFD part, a RSM model is introduced and several conditions concerning the indoor and outdoor temperature as well as the wind speed and its direction are examined. For the FEM study, an external noise source is set up facing the facade and representing a plane incident sound wave in the normal direction. Sound Reduce Indices are obtained by evaluating the weakened sound transmission through the aperture. The details of the phenomena of absorption and diffraction on noise frequency are presented according to different shutter geometries and spacing between baffles.

2.2. CFD simulations methodology

In the 3 main turbulence models existing (Direct Numerical Simulation, Large Eddy Simulation and Reynolds-Averaged Navier Stokes), the RANS can capture well the turbulent characteristics of air flows while consuming less calculation resource. Caciolo et al. [Caciolo et al., 2012] confirms that in most situations the RANS provides acceptable results with 20% of inaccuracy in about 30 times less computation time than the LES. We apply the Reynolds Stress Model (RSM) which is expected to increase accuracy compared to eddy-viscosity models. As an anisotropic turbulence model, additional transport equations are solved for each term of the Reynolds stresses tensor and the dissipation of the turbulent kinetic energy [Franke et al., 2007] so that the individual effects of the fluctuating quantities on the flow are taken into account.

The equations are solved by the commercial software Fluent. The pressure is interpolated by a "PRESTO!" scheme.

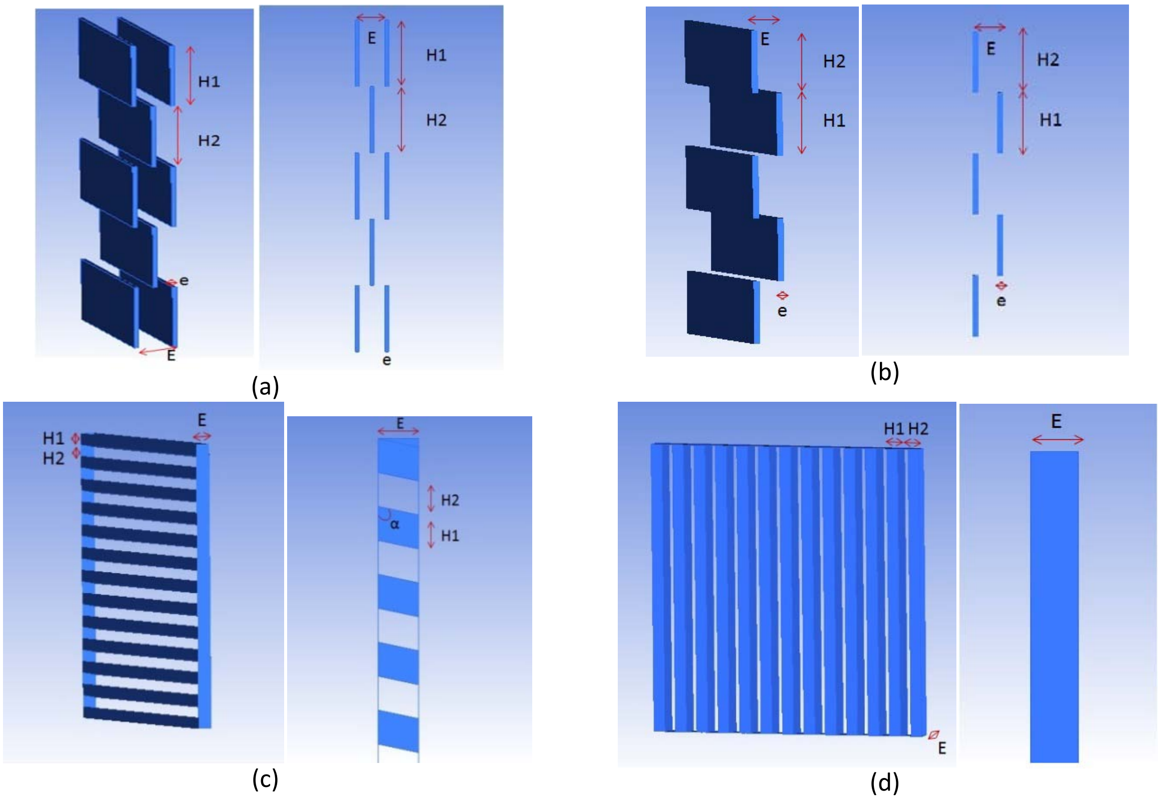


Figure 1. Shutter typology:
(a) 3 layers slats (b) 2 layers slats, 3 slats outside and 2 slats inside (c)horizontal louvers (d)vertical louvers

The convective term, the diffusive term, the pressure term and the energy term use a second order upwind scheme. Pressure and velocity are coupled in the SIMPLE algorithm. Solution is considered to be converged while all residuals are confined in at least 10^{-3} of the initial calculation and remain stable for around 50 iterations. The convergence is also verified by checking the mass and energy balances between indoor and outdoor environment with user-defined functions (UDF).

The domain is discretized in two structured meshes, separating as indoor and outdoor domain, linked by conformal interfaces. In order to restrict the border effects, the inlet, outlet and upper boundaries are apart from the indoor domain (L*L*H) with a distance of 5L, 10L and 5H. The resulting mesh consists of around 600 000 cells.

The inlet boundary condition is based on the incident wind profile of imposed reference speed and turbulence intensity. The inlet speed uses a logarithmic profile neglecting the thermal effects which makes the advantage of consistency with the terrain roughness model [Blocken et al., 2007]. The outlet boundary uses a pressure profile following the Boussinesq approximation, which presents a hydrostatic stress. In the room, a heat source, representing a computer and a printer, is set as convective surface with a heat flux of 100 W/m^2. The indoor walls are hold to a constant temperature (299K). The outdoor walls are smooth and adiabatic. The outdoor temperature is 295K.

2.3. FEM parameters

The fluid model for pressure acoustics used in this study is a linear elastic fluid by defining the density ρ and the speed of sound c. The pressure acoustics application solves for the acoustic pressure, p [Civoli and Neta, 2004] [Bayliss et al., 1982] [Temkin, 2001][Bauer, 1977].

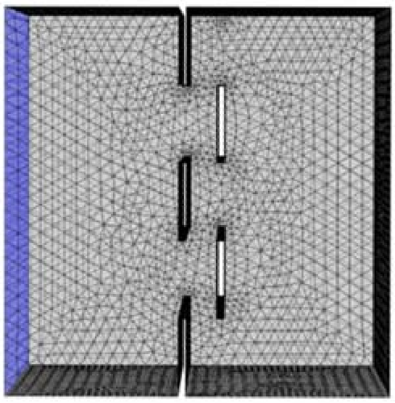


Figure 2. Example of FEM model (geometry and mesh) for pressure acoustics

Moreover, losses are accounted by introducing corrections related to the distortion of flow and increment of the mass participating to the total motion of air. The FEM modeling of the acoustical domains corresponding to holes, slats and louvers is a crucial point. In fact, from previous studies it has been demonstrated that using real valued density and sound speed for the air, the FEM model does not account correctly losses. The formulation used here is based on the equivalent dissipative fluid approach. According to this theory the holes, slats, louvers and porous materials can be considered as an equivalent fluid completely described by means of "equivalent" sound speed and density, complex valued, that are able to justify internal energy losses (visco-inertial and thermal effects) and phase shifts between pressure and particle velocity. In the widely used equivalent fluid model of Johnson-Champoux-Allard [Allard, 1993] (mainly utilized for porous materials but also for holes or perforated plates [Bonfiglio and Pompoli, 2009]), expressions for "equivalent" sound speed and density are proposed. An example of the domains is depicted in Figure 2

A brief description of the domains and boundary conditions is given as follows:

-Air: ρ=1.21 kg/m3 and c=343 m/s

Boundaries:

-Inlet (source): radiation condition (p=1 Pa)

-Outlet: radiation condition (p=0 Pa)

The radiation boundary conditions allow an outgoing wave to leave the modeling domain with minimal reflections.

-Remaining: hard wall (particle velocity is equal to zero on those boundaries).

The **Sound Hard Boundary (Wall)** feature node creates a boundary condition for a *sound hard boundary* or wall at which the normal component of the acceleration is zero.

Mesh (free tetrahedral) has been created according to the rule of 10 finite elements per wavelength.

The transmission loss is defined as:

$$\mathrm{TL} = 10\log\frac{P_{in}}{P_{out}}$$

where P_{in} and P_{out} denote the total acoustic power at the inlet and the outlet, respectively. The transmission loss is thus defined as a function of sound frequency.

P_{in} is defined by the surface integral:

$$P_{in} = 2\int_{Sinlet}\frac{p_0^2}{2\rho c}$$

The power through the outlet is defined in an analogous surface integral over the outlet boundary, but with the computed pressure instead of the applied one:

$$P_{out} = 2\int_{Soutlet}\frac{|p|^2}{2\rho c}$$

3. RESULTS AND DISCUSSION

CFD and FEM simulations have been for the different configurations of shutter s as described in § 2.1. For each configuration, CFD simulations are carried out with wind speeds of 0 m/s, 1.5 m/s, 3.5 m/s and 5.5 m/s; in windward direction (30°) and leeward direction (150°). All these shutters reduce the apparent opening surface by 50%. The results of a CFD simulation are given in terms of average pressure, velocity and temperature fields. As shown in Tables 1 and 2, the air change rate results in column 5 are the range of all wind speeds and are compared to the reference simulations without shutter in column 6. The noise diminution in column 7 is the arithmetic average on 500, 1000, 1500, 2000, 2500 Hz. The 3-layers cases have the layer of 3 slats outside. The two layers cases can be distinguished by having the layer of 2 slats inside (2i) or outside (2o).

Table 1. Slats shutter ventilation and acoustical performance

slatslayers	Horizontal / vertical	E (cm)	e (cm)	Air change rate (vol/h)	Comparison (%)	Noise diminution (dB)
3	H	20	2	1.0-2.0	15%	13
3	V	20	2	2.0-2.8	22%	13
3	H	10	2	1.1-2.0	15%	5

3	V	10	2	1.6-2..6	19%	5
2i	H	10	2	2.4-3.2	25%	10
2i	V	10	2	2.5-4.0	30%	10
2o	H	10	2	2.2-2.6	22%	11
2o	v	10	2	2.5-3.6	29%	11

Despite of the reduction on apparent opening surface of 50%, the air change rate (ACR) reaches between 15% and 60% of the ACR without shutter. The best noise reduction is 13 dB with the 3-layer shutter while the ACR is reduced by about 80%. The air recirculation is largely stopped by the shutters so that this configuration should not appear as favorable.

Table 2. Louversshutter ventilation and acoustical performance

Horizontal / vertical	H1(cm)	E(cm)	□	Air change rate (vol/h)	Comparison (%)	Noise diminution (dB)
H	2	5	22	1.3-2.6	18%	3
V	2	5	22	2.9-4.8	50%	3
H	4	10	11	2.0-3.5	25%	2
V	4	10	11	4.4-6.6	60%	2

For louvers shutters, the ACR could reach even more than 50% of the ACR without shutter in the vertical position, which means that both the stack and wind effects are well preserved, but the noise attenuation is limited.

3.1. Ventilation performance

In the following part, a focus on 4 shutters is undertaken by analyzing the flow fields referring to the vertical section in the middle of window (view A) and the opening plan section in the center of shutter from an indoor view (view B). With the simulation results, the air change rate is calculated as the sum of convection and diffusion flows over the opening plane.

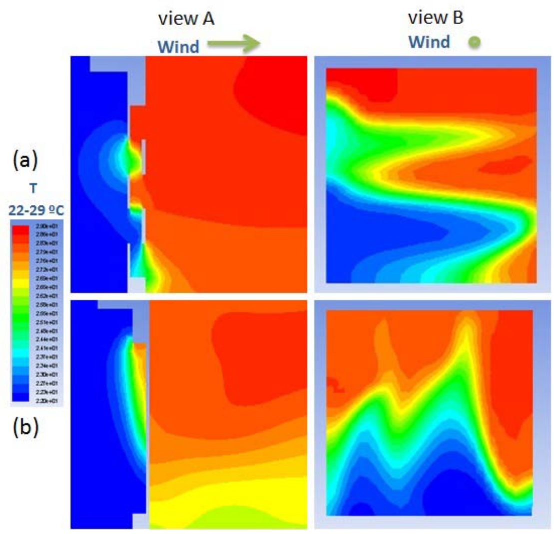


Figure 3 Steady-state 2D temperature fields: (a) horizontal slats (b)vertical slats

In the two cases presented, the horizontal and the vertical shutters have exactly the same geometry characteristics from an acoustic point of view with the noise source stemming from normal direction so that the acoustical performance is the same.

First cases are horizontal and vertical 2-layer slats shutters (2i). Fig. 3 shows the computed temperature fields.

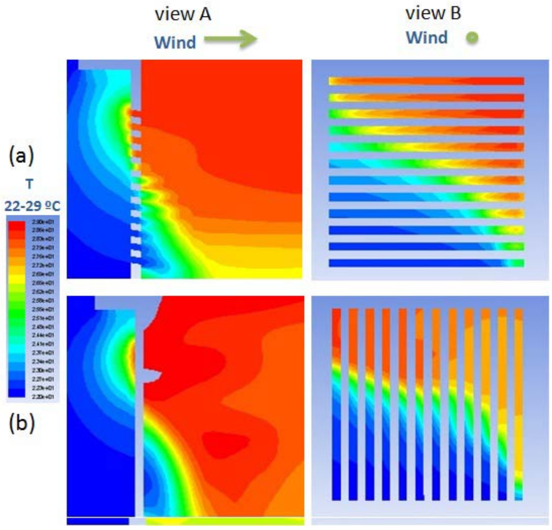


Figure 4. Steady-state 2D temperature fields : (a) horizontal louvers (b) vertical louvers

For both horizontal and vertical cases, the air enters in the room by the bottom apertures and goes out through the top apertures. As the stack height is truncated by horizontal slats and is kept with vertical slats, the horizontal ones tend to reduce the buoyancy effect contrary to the vertical ones. The wind effect is strongly reduced in both cases. Finally the horizontal slats have lower air change rate than the vertical slats.

For horizontal and vertical louvers, the temperature field (Fig. 4) clearly shows that stack effect is well preserved for both shutters. In vertical louver case, the vortex in front of the shutters is amplified and forms a larger mixing zone.

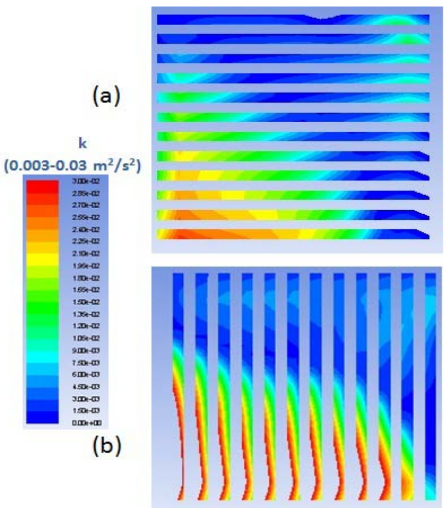
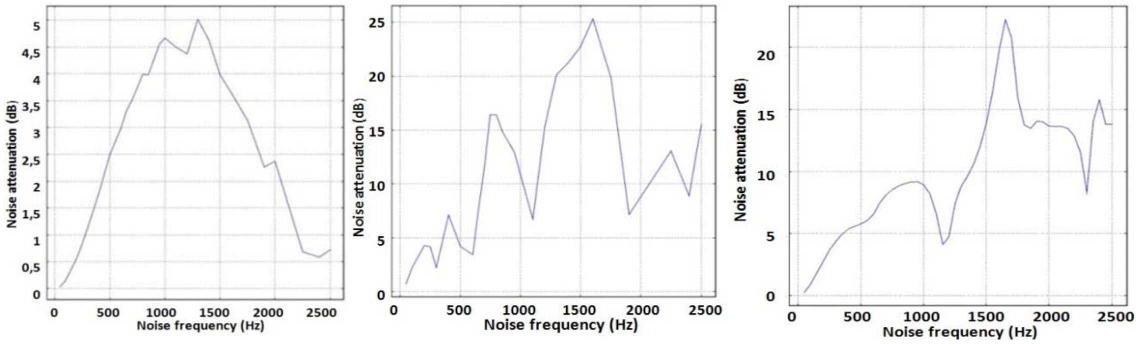


Figure 5. Steady-state 2D turbulent kinetic energy fields : (a) horizontal louvers (b) vertical louvers

The calculated turbulent kinetic energy is higher over the opening plane (Fig. 5). By this contribution of wind effect, the vertical shutters reach a better air change rate.

3.2. Acoustical performance

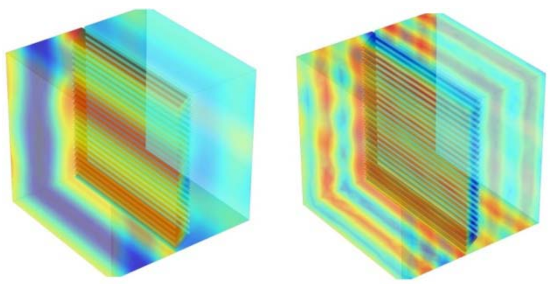
In the following part, different shutters tested are picked out as examples to show the main differences between slats or louvers. Indeed, as shown in Table 1 and in Fig. 6, there is a large difference in attenuation between louvers (around 3dB) and slats (more than 10dB).



(a)horizontal louvers (b)horizontal 3-layer slats (E=20cm) (c)horizontal 2-layer slats (2o)

Figure 6. Transmission Loss (dB) in function of Frequency (Hz)

For louvers, evenif there is a peak in Transmission Loss around 1000Hz, this peak is very small (around 5dB) so the attenuation is very low. Outside the frequency range where the peak is localized, the sound is transmitted so the isolation is very bad (Fig.7).



(a) (b)

Figure 7. FEM model: pressure distribution for louvers : (a) around 1000Hz and (b) around 2500Hz

For slats louvers, the Transmission Loss is more interesting, where the pressure distribution shows the efficiency of slats (there is no direct transmission through slits). The acoustic pressure can be very low behind the slats (Fig. 8).

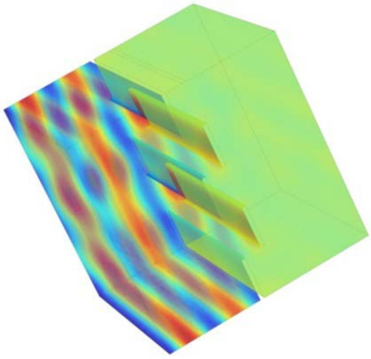


Figure 8. FEM model: pressure distribution for 2-layer slats around 2500Hz

A good compromise can be found with 2-layers slats where the performance is quite good (around 10dB).

4. CONCLUSION

In order to design new shutters reducing external noise while maintaining acceptable natural ventilation, this study has been carried out using CFD for ventilation aspect and the FEM for acoustical aspect.

The louver shutters limit the reduction of the air change rate compared to the reference case without shutters. However the acoustical diminution is of 3dB on average. The slat shutters, on the contrary, reducing significantly the noise by 10 dB, lowers strongly the ventilation rate. Two designs with the best trade-offs, the 2-layers vertical shutters and the vertical louvers, are selected to be studied experimentally in future works.

4.3. Caractéristiques des volets (synthèse des résultats obtenus par l'ENTPE et le CEA INES)

La fabrication des prototypes s'est donc limitée aux configurations issues du travail de modélisation qui précède. Afin de caractériser effectivement ces volets prototypes, des essais expérimentaux sont effectués pour les aspects aéraulique, acoustique et lumineux. Les résultats de performance aéraulique en ventilation naturelle mono-façade et traversante ont été présentés au Chapitre 2.3. Les résultats d'essais acoustiques et lumineux réalisés par l'ENTPE et CEA INES sont cités ci-après, ce qui permettront le paramétrage lors des simulations de performance énergétique du bâtiment qu'on trouvera au Chapitre 5.

4.3.1. Essais acoustiques (réalisés par l'ENTPE)

Les essais acoustiques ont été menés dans les salles réverbérantes et la cellule Hybcell de l'ENTPE. Le prototype a été installé entre 2 cellules par l'intermédiaire d'une paroi de support. Les deux salles de part et d'autre sont conçues pour permettre d'émettre un son statiquement homogène en tout point. (Fig. 4-1.)

Figure 4-1. Implantation du prototype « chicanes » en mousse (gauche) et en plexiglas (droite) dans des salles réverbérantes découplées

Un sonomètre analyseur 2250 de classe 1 conforme à la norme NF S 31-009, un haut-parleur multidirectionnel, un microphone à condensateur, un amplificateur Type 2716 et un télémètre laser sont utilisés pour mesurer la transmission acoustique à travers l'ouverture où est installé le prototype. Les résultats sont les suivants.

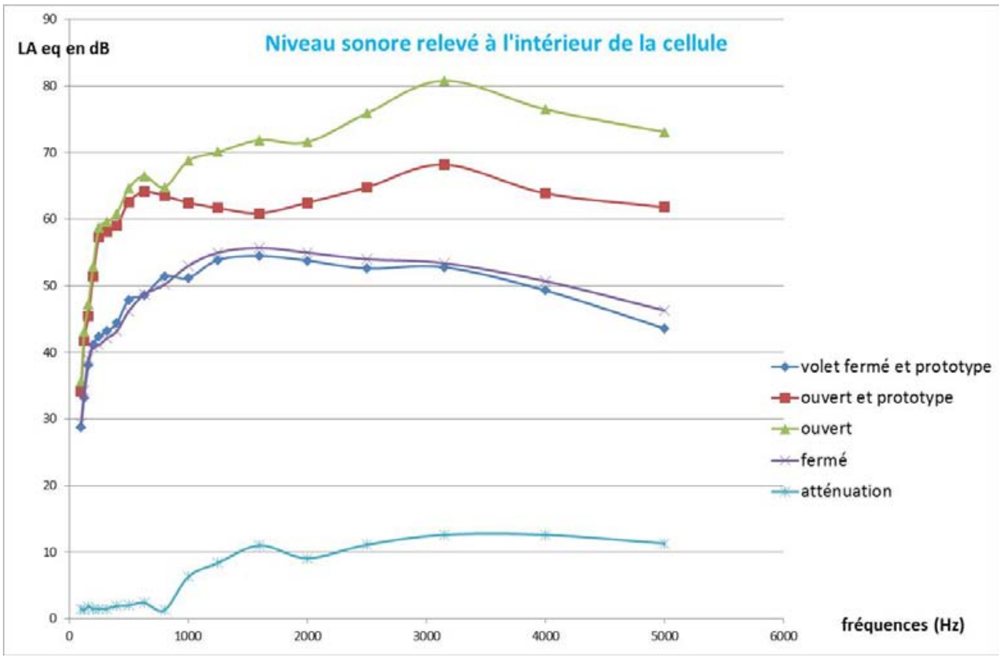


Figure 4-2. Affaiblissement du niveau sonore par le prototype à « chicanes » en mousse dans des salles réverbérantes

Les mesures d'atténuation acoustique du prototype à « chicanes» en mousse sont présentées dans la Figure 4-2. La courbe d'affaiblissement acoustique du volet en plexiglas évolue de la même manière. Les affaiblissements acoustiques des prototypes à « chicanes » sont en général de l'ordre de **10 dB**. On note une moindre atténuation aux basses fréquences.

4.3.2 Essais lumineux (réalisés par l'ENTPE et CEA INES)

Les mesures lumineuses ont été également menées dans la cellule Hybcell de l'ENTPE pour le volet à « chicanes » en plexiglas. Compte tenu des facteurs influençant la transmission lumineuse, à savoir, les obstacles telles que les fenêtres en aluminium et les murs en saillie aux extrémités, le prototype a été positionné à l'extérieur de l'ouverture, au centre et collé au châssis en aluminium.

Figure 4-3. Prototype installé dans la cellule Hybcell pour mesures lumineuses

Les mesures d'éclairement sont réalisées de manière comparative entre deux fenêtres : une fenêtre dite de référence (sans volet), la seconde équipée du volet en plexiglas.

Les capteurs ont été positionnés à hauteur du plan de travail et en façade comme indiqué dans la Figure 4-4.

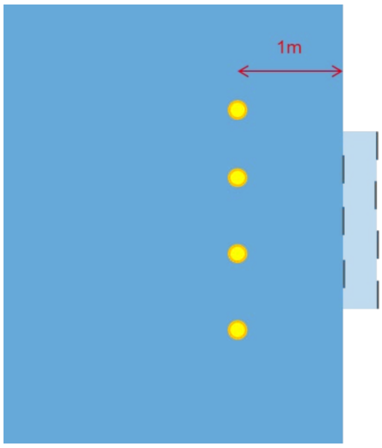


Figure 4-4. Dispositif expérimental - Emplacement des sondes intérieures (cercles jaunes) ; une mesure supplémentaire est prise à l'extérieur

Les mesures se sont déroulées en continu pendant plusieurs jours et les résultats représentatifs proviennent des journées de ciel couvert avec un éclairement extérieur diffus.

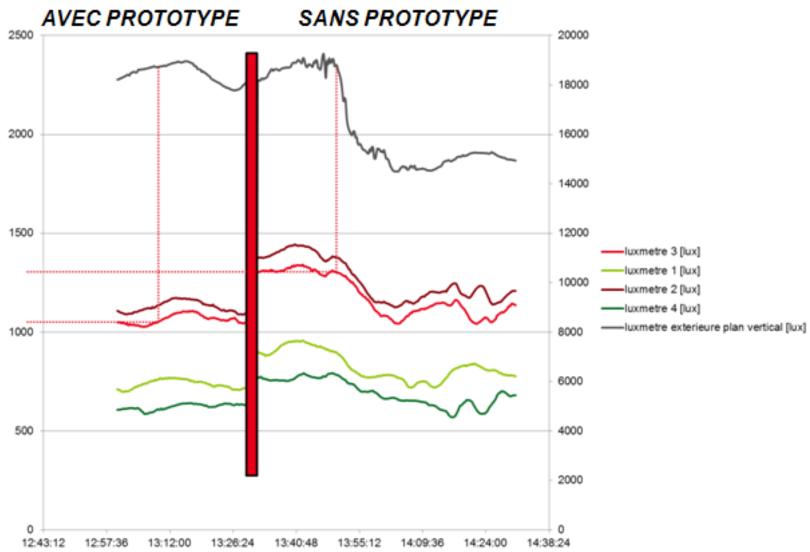


Figure 4-5. Mesures d'éclairement à l'intérieur de la cellule Hybcell avec et sans prototype

Comme le montre la Fig. 4-5, l'éclairement intérieur augmente d'environ 15% lorsque le prototype est enlevé de la fenêtre. Le prototype en plexiglas peut être considéré comme translucide; il n'est pas transparent.

Chapitre 5

Conception et gestion du système d'ouvertures vitrées

Dans ce chapitre, la problématique de conception et de gestion du système d'ouvertures vitrées est traitée au travers d'une approche multi-physique. Des modèles simplifiés représentant les différents aspects physiques de l'ouverture sont intégrés dans un outil de simulation. Ces modèles sont appliqués à des études paramétriques dans des bâtiments typiques afin d'évaluer la performance de la ventilation naturelle

- *mono-façade en tertiaire de jour*
- *et traversante en résidentiel de nuit*

en situation réelle avec contraintes acoustiques, d'éblouissement et d'éclairage pour le cas diurne. Ces études de simulations sont réalisées pour différents climats, configurations du bâtiment et scenarios d'occupation afin de comparer différentes stratégies de ventilation.

Dans une première partie, la nécessité d'une approche multi-physique du système d'ouvertures vitrées est rappelée. On décrit brièvement l'enchainement des modèles aérauliques choisis et validés aux précédents chapitres, des modèles acoustiques et d'éclairement proposés par les partenaires du projet OVI-SOLVE et enfin on définit les modèles de contrôle/commande envisagés dans cette étude.

Dans la deuxième partie, les caractéristiques des bâtiments et les paramètres de simulation à simuler sont listés. L'étude s'intéresse en premier lieu à l'influence de l'orientation et à la taille de la surface vitrée dans différents climats, l'impact du comportement de l'occupant résulte des scenarios d'occupation et des seuils de tolérance au bruit, à l'éblouissement et à l'inconfort thermique, etc.

Dans la troisième partie, à l'aide de l'outil de simulation, on évalue la réduction théorique du potentiel de refroidissement de ventilation naturelle lorsqu'on intègre les contraintes de confort et qu'on modélise des réactions comportementales complexes. On étudie enfin l'intérêt d'un volet acoustique (tel que conçu dans les chapitres précédents) pour maximiser la ventilation naturelle malgré le bruit extérieur et la tolérance acoustique des occupants. Les résultats sont présentés en nombre d'heures d'inconfort et en consommation électrique servant à l'éclairage artificiel. Les résultats débouchent sur des indicateurs de décision.

5.1. Implantation des différents modèles représentant la physique des phénomènes

5.1.1 Modèle multi-physique

Pour savoir si la ventilation naturelle peut conduire à de bonnes conditions de confort pendant l'été dans des bâtiments, il faut tenir compte des contraintes liées à l'ouverture de fenêtres telles que le bruit, le positionnement des stores et l'acceptation d'un sur-refroidissement etc..

Dans les précédents chapitres, les phénomènes aérauliques et thermiques ont été étudiés expérimentalement et les résultats d'essais acoustiques et lumineux ont été présentés. Ceux-ci permettent une représentation du système d'ouvertures vitrées: fenêtre ouverte ou fermée, avec ou sans volet, stores levés ou baissés.

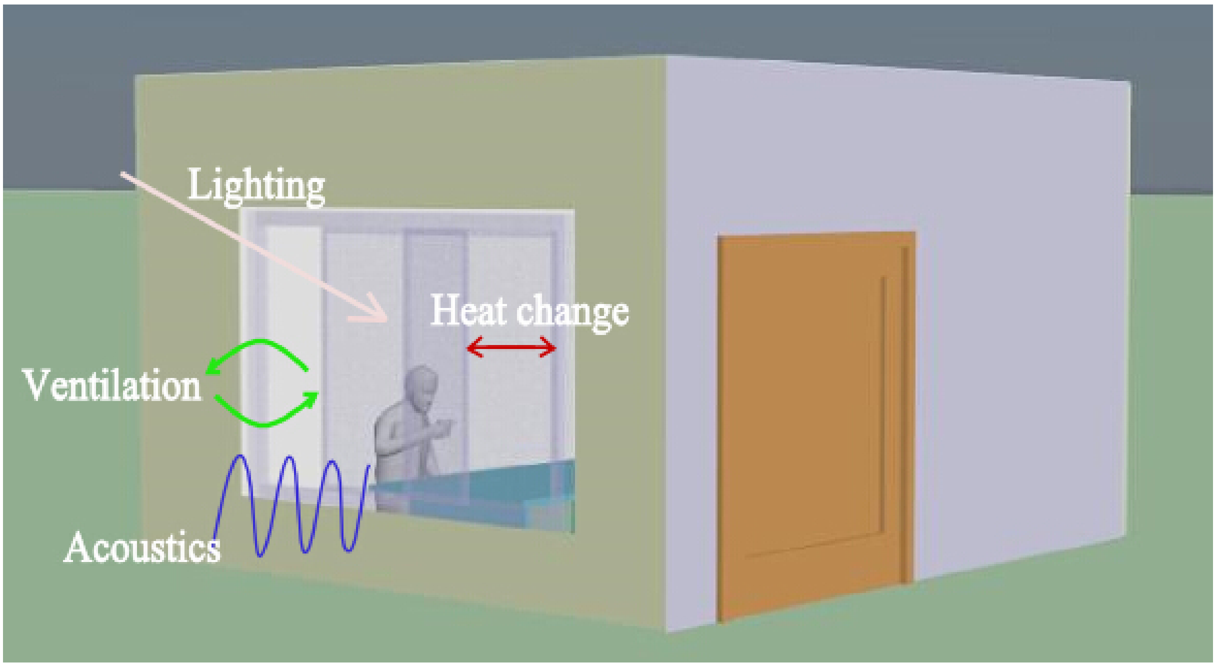


Figure 5-1. Modélisation multi-physique des phénomènes liés à l'ouverture vitrée

5.1.2 Environnement logiciel

Afin de constituer un outil à même de déterminer le meilleur dimensionnement des ouvertures en fonction du bâtiment et son climat et de définir un mode de gestion intelligente, il est nécessaire d'assembler tous les modèles sélectionnés ou développés pour chaque aspect physique et de contrôle. On dispose à présent de

a. Modélisation aéraulique basée sur les corrélations retenues.
b. Modélisation d'éclairage et du contrôle d'éblouissement.
c. Modélisation acoustique.
d. Modèles de contrôle plus ou moins exigeants qui tiennent compte des contraintes liées à l'ouverture des baies.

Les fiches détaillées de chaque module se trouvent en annexe 1 à 4 sous un format proche de celui de l'HVAC2 Toolkit afin de les rendre disponibles aux différents modélisateurs.

Après avoir codé et validé chaque module concernant les ouvertures vitrées (thermique, aéraulique acoustique et d'éclairage) individuellement, une intégration globale est réalisée afin de modéliser le comportement multi-physique des bâtiments utilisant la ventilation naturelle et la régulation des équipements (fenêtres, volets, stores, l'éclairage artificiel) pour garantir le respect des différentes contraintes de confort en les hiérarchisant.

Bien que les algorithmes puissent être implantés dans un autre environnement, le logiciel TRNsys 17 a servi de plateforme de développement. TRNsys est un logiciel extrêmement flexible avec une interface graphique facile à utiliser. Il sert à simuler le comportement des systèmes énergétiques du bâtiment en régime thermique dynamique.

TRNsys est constitué de deux parties différentes.

1. La première («the kernel» en anglais ou «le noyau» en français) gère les fichiers d'entrées, résout l'ensemble des équations en vérifiant la convergence et exporte les graphiques représentant les variables du système. Cette partie contient aussi les éléments déterminant les propriétés thermo-physiques, détermine des régressions linéaires et interpole des données d'entrée.
2. La deuxième partie est une bibliothèque de composants très complète qui permet de modéliser les différentes parties d'un système. La bibliothèque standard inclut près de 150 modèles dans des domaines très différents, allant des pompes à des bâtiments «multizones», des éoliennes à des panneaux photovoltaïques et des systèmes de climatisation ; en outre des modèles de calcul économique.

Pour constituer notre modèle global, on fait appel aux «types» de la bibliothèque TRNsys. Les modèles complémentaires que nous avons développés et présentés dans les fiches reportées en Annexe ont été créés sous la forme de types TRNsys. Le Type 56 (bâtiment) fait appel aux sorties des modules créés pour calculer la température intérieure dans le bâtiment et les consommations d'énergie. La figure 5.2 schématise le modèle global vu par l'interface TRNsys.

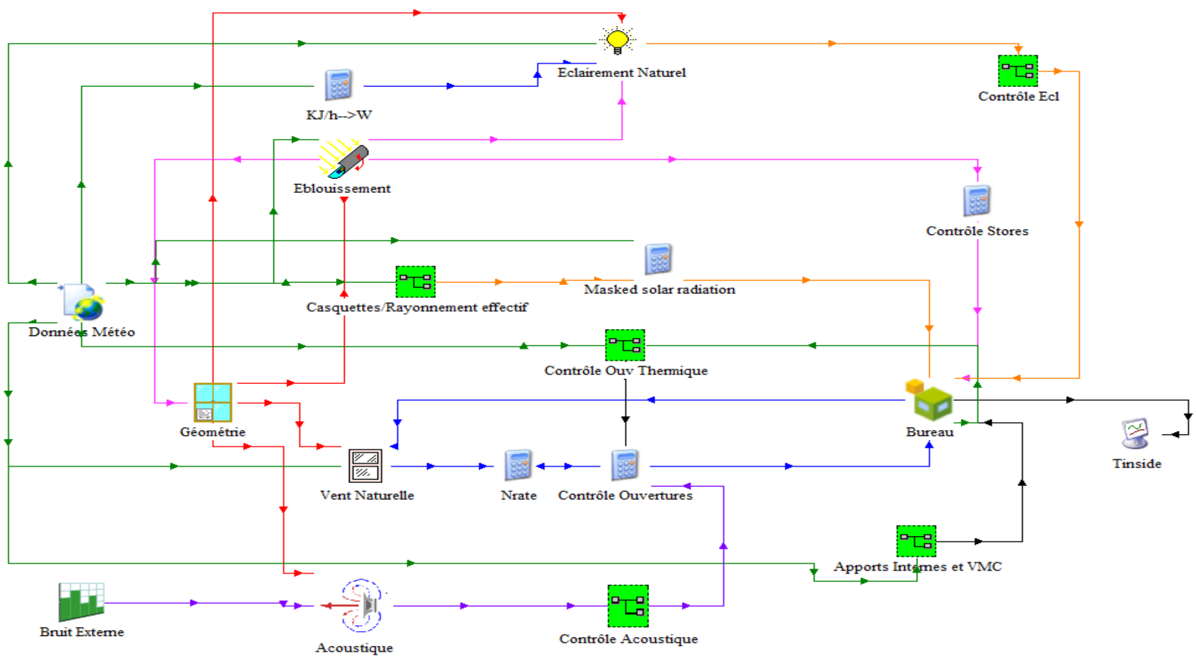


Figure 5-2. Modèle multi-physique d'ouvertures vitrées développé dans la plateforme TRNsys 17

5.2. Paramétrage des modèles

5.2.1 Paramètres qui varient pendant l'analyse

Ce chapitre a pour but prioritaire de répondre aux questions concernant le confort atteint pendant la période estivale (du 15 mai au 15 septembre) et les consommations électriques de l'éclairage artificiel. Les paramètres principaux qui ont été considérés pour l'analyse sont les suivants:

- La **zone géographique**, qui détermine les conditions extérieures de température et d'ensoleillement, ainsi que les caractéristiques du vent. Les climats examinés sont ceux de **Paris-Montsouris et Nice**. Les fichiers météorologiques sont issus de la base de données METEONORM et sont représentatifs du climat moyen sur 30 ans.
- **Typologie de bâtiment**, qui représente différents scenarios et problématiques de confort d'occupants. Les bâtiments étudiés sont un bureau individuel (12.5 m^2 par personne), un bureau de deux personnes (8 m^2 par personne), enfin une maison individuelle (21.3 m^2 par personne). Dans ce chapitre, quelques résultats pour le bureau individuel et la maison seront présentés. Les résultats de bureau de deux personnes seront présentés en annexe 5.
- **L'orientation de la façade** de la pièce, qui influence les apports solaires et l'angle d'incidence du vent. Pour cette analyse, les 8 orientations principales plus la direction au vent et sous le vent majoritaire dans le climat seront prises en compte. Le sud est l'orientation la plus favorable en matière d'éblouissement et la plus défavorable par rapport aux apports solaires, occasionnant donc le plus de surchauffe dans les bureaux pendant l'été. Ceci oblige d'ouvrir la fenêtre plus longtemps pour refroidir la pièce. L'ouest est l'orientation au vent majoritaire en région parisienne et favorise donc la ventilation naturelle.
- **Le taux de surface vitrée ou porosité de la façade lorsque les fenêtres sont ouvertes**, qui influence le débit d'air, les apports solaires, ainsi que la transmission lumineuse et, par conséquent, les apports internes dus à l'éclairage.
  Dans les bureaux, trois valeurs de taux de surface vitrée ont été choisies pour la ventilation mono-façade: 30 %, 50 % et 70 %. Par exemple, pour une surface de la façade du bureau individuel de surface 6.25 m^2, les trois surfaces vitrées sont donc:
  - 30 % soit une baie de 1.4m x 1.4m (1.96 m^2),
  - 50% soit une baie de 2.1m x 1.6m (3.36 m^2),
  - 70% soit une baie de 2.5m x 1.75m (4.38 m^2).

  Dans le cas de la maison avec ventilation nocturne où l'éclairage est moins important pour l'étude, la surface vitrée est fixée à 21%. Cette porosité est consistante avec les corrélations utilisées qui concernent la ventilation traversante.
- **L'inertie thermique**, qui influence le potentiel de refroidissement par la ventilation naturelle nocturne.
  Les deux niveaux retenus sont inertie moyenne et inertie lourde pour le bureau, selon la définition de la norme EN ISO 13786 (CEN, 2008). Dans l'article qui va suivre (limité en pages), seul le résultat en inertie lourde sera présenté en profondeur; il représente le cas le plus favorable. Le tableau 5.1 résume les caractéristiques des locaux retenus.

Tableau 0-1. Composition et caractéristiques thermiques des parois

Paroi	*Couche de matériaux (*)*	*Epaisseur cm*	*λ W/(mK)*	*ρ kg/m^3*	*c_P kJ/(m^{3}K)*	*U_{paroi} W/(m^{2}K)*
Paroi extérieure (isolation par l'extérieur)	Parois béton	20	1.4	2300	1000	0.15
	Polystyrène PSE 32	20	0.032	40	1450	
	Dalle béton	20	1.4	2300	1000	
Plancher / Plafond d'étage	Dalle béton	20	1.4	2300	1000	0.26
Cloisons (maison)	Placoplatre	1.3	0.35	1000	1000	0.61

	Laine minérale (λ=0.036)	5	0.036	100	1030	
	Placoplatre	1.3	0.35	1000	1000	

Les bureaux sont considérés d'être situés à l'étage intermédiaire, toutes les parois des bureaux simulées sauf celles qui contiennent les fenêtres sont considérées adiabatiques.

Les caractéristiques thermiques des parois dans la maison sont unies ayant une inertie lourde.

Les baies vitrées ont une menuiserie en aluminium avec double vitrage clair DV 4/16/4 faiblement émissif et rempli d'argon à 85 % (U_w = 1.4 W/ (m^2K), facteur solaire FS = 0.59 et taux de transmission lumineuse τ = 0.71).

5.2.2 Différentes variantes effectivement simulées

L'étude de différents cas vise à déterminer pour différentes configurations quand la ventilation naturelle peut garantir le confort thermique dans des bâtiments sans mettre en péril le confort acoustique et lumineux des occupants.

Pour ce faire, les variantes retenues dans la modélisation sont présentées dans Figure 5-3(bureau) et Figure 5-4 (maison individuelle) pour l'analyse paramétrique. Comme expliqué précédemment, l'article qui suit limite les résultats à une combinatoire réduite (2 climats seulement, etc..). L'ensemble des résultats apparait en annexe 5.

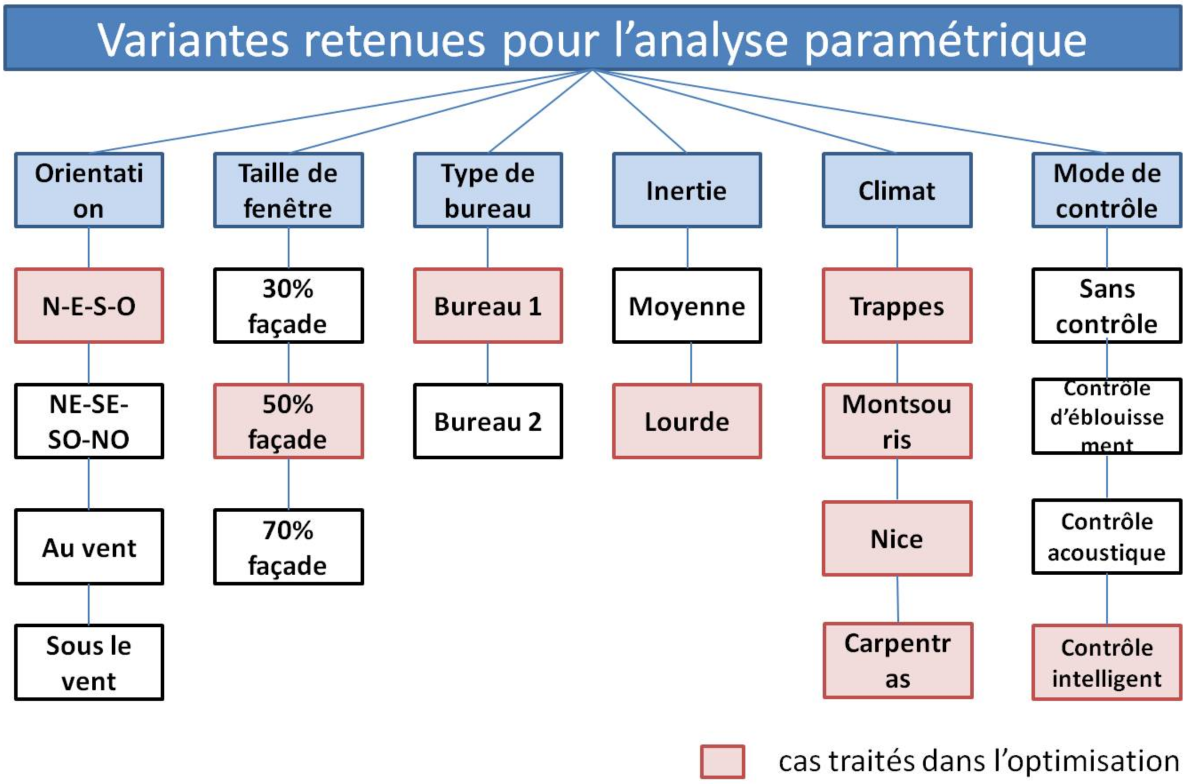


Figure 5-3. Ensemble des cas étudiés et des variables prises en compte dans l'analyse paramétrique pour le bureau

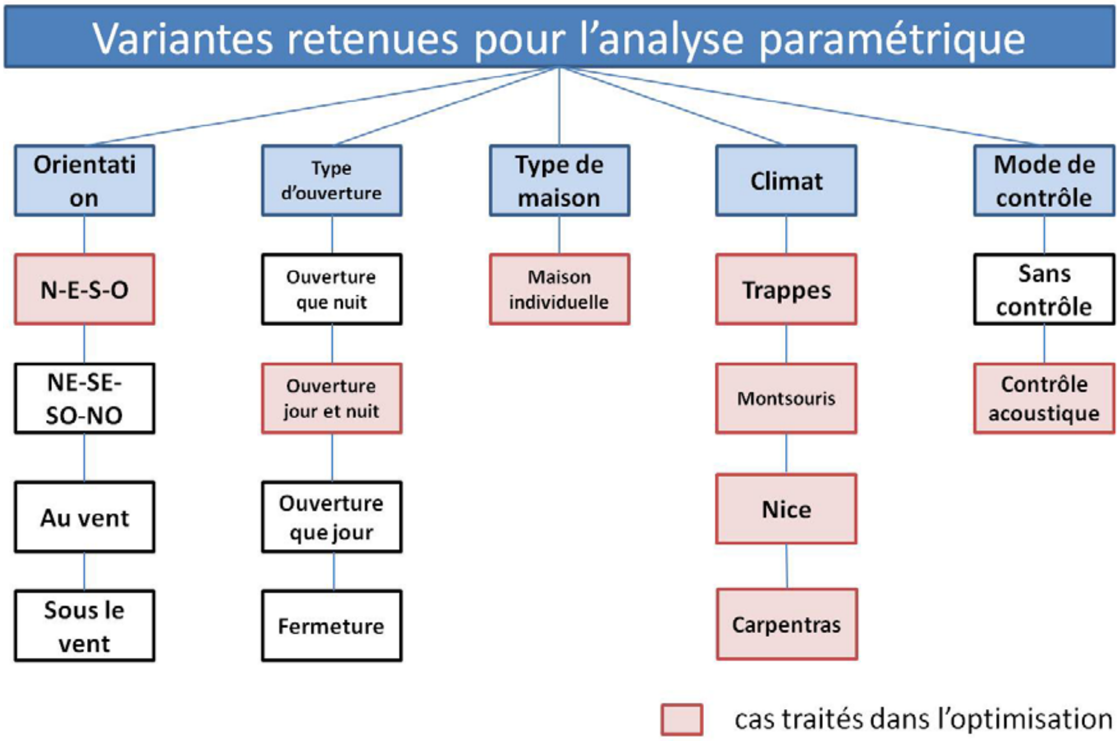


Figure 5-4. Ensemble des cas étudiés et des variables prises en compte dans l'analyse paramétrique pour la maison individuelle

Dans l'article reproduit ci-après et en cours de relecture par «Journal of Building Performance Simulation», on traite

- des bureaux individuels pour lesquels on recherche une gestion intelligente des ouvrants durant la période d'occupation en ventilation mono-façade, le pré-refroidissement nocturne étant autorisé.
- des maisons individuelles pour lesquelles on limite les contraintes physiques au problème du bruit en ventilation nocturne traversante.

5.3. Cas d'études et résultats de simulation

Revue scientifique publié dans « International Journal of Ventilaiton», accepté

A global modelling approach of natural ventilation with acoustic and daylighting constraints

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Abstract: Natural ventilation helps to cool buildings in summer without energy consumption, but its application may be restricted by acoustic and glare constraints. Here a modeling approach integrating different physical aspects was developed and connected to TRNSYS. Different control strategies of glazed openings were defined and simulations were performed with an office room and a detached family house. We find the natural ventilation potential is largely reduced due to acoustic and visual comfort constraints. An acoustic shutter, which facilitates more frequent window opening during occupancy by decreasing outdoor noise transmission, was equally studied in detail with the help of this modeling approach. The acoustic shutter improves the acoustic and thermal comforts for intelligent control strategy and is an attractive solution to enhance the natural ventilation potential under a moderate noisy environment.

Keywords: natural ventilation, multiple constraints, solar protection, acoustic shutter, indoor comfort, occupant behaviour

1. Introduction

With the growing awareness of energy consumption and environmental concerns, the European Union (EU) ambitiously aims to reduce CO_2 emissions by 80% -95% by 2050 compared to 1990 [European Commission 2011]. In the EU, buildings account for 40% of the final energy consumption and 36% of CO_2 emissions. The *Energy Performance of Buildings Directive* recast requires all new buildings have near-zero energy consumption by the end of 2020 [European Parliament and Council, 2010; Annunziata et al., 2013].A substantial proportion of energy consumption in buildings is caused by Heating, Ventilation and Air Conditioning (HVAC) systems. Though low-energy buildings are well-insulated for wintertime energy saving, they generally cause summertime overheating and thus aggravate cooling loads. Natural ventilation is a promising solution to reduction of cooling energy consumption in buildings [CIBSE 2005].

Natural ventilation can be achieved through window opening or dedicated devices based on wind or stack effect (e.g. wind catchers, chimneys, solar-induced ventilation)[Etheridge 2015].The simplest way for natural ventilation seems to be glazed opening. However, lighting and noise concerns must be considered in design of window openings.

Buildings in urban areas are often located near heavy traffic, so occupants usually close the windows completely in order to attenuate noise discomfort. When the sunlight directly enters the building and glares the occupants, they use solar protection devices, which inevitably reduce the open surface area. The window opening for natural ventilation is not only a multi-constraint problem, but also depends strongly on occupant behaviour. The interaction between occupants and window opening control has been extensively studied in order to improve indoor comfort [Roetzel et al., 2010][Yun et al., 2010][Rijal et al., 2008][Fabi et al., 2012][Yan et al., 2015].

Galasiu and Veitc [Galasiu and Veitc, 2006] reviewed the studies on occupant preferences to lighting condition shading and lighting control. An unrealistic modelling of lighting and shading controls can lead to misestimate of energy use and occupants' comfort satisfaction. Thus, comprehensive control approaches in building performance simulation (BPS) are needed [Parys et al., 2011].

In contrast today lighting, the impact of outdoor noise, a non-negligible factor [Warren 1984][Gunay et al., 2013),on natural ventilation performance has been barely studied. Barclay et al. [Barclay et al. 2012] studied the energy saving potential of natural ventilation integrating noise exposure, and found the cooling energy consumption by buildings in quiete environment decreased by more than 20% compared to noisy locations for a tolerance of 34dB. Some works have been conducted to develop noise attenuation devices [Wang et al. 2014][de Lima et al. 2011][Bibby and Hodgson 2013].

To our knowledge, no natural ventilation approach integrating noise, glare and daylighting constraints has been comprehensively explored so far. In this study, a global modelling approach of natural ventilation integrating different physical and control models was proposed and used to investigate the best trade-offs between thermal, acoustic, lighting and noise comforts. The models were implemented onTRNSYS17.0 [TRNSYS 2012] with building simulations, while the algorithms could also be used in other building simulation environments.

Section 2 describes the physical models and section 3 presents the control strategies of glazed openings defined according to occupants' discomfort tolerances.

Then the approach was applied into two case studies for intelligent control (Figure 1): (1) single-sided ventilation in an office room under a daytime scenario, and (2) cross-ventilation in a detached single-family house under a night scenario.

Simulation results are given to assess the impacts of glare and acoustic controls on natural ventilation potential.

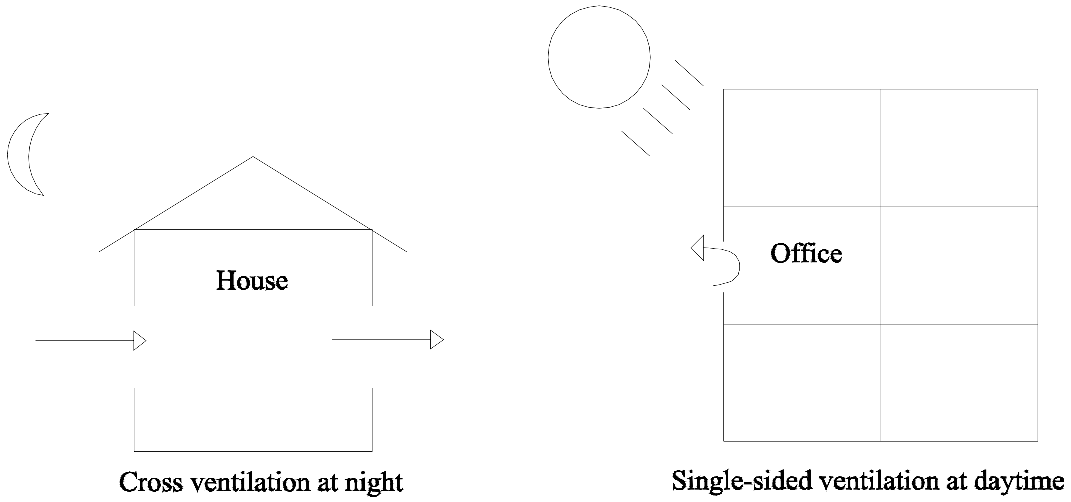

Figure 1.Case studies of simulation

Finally, the glazed opening surface for summertime comfort was optimized and the use of acoustic shutter to increase natural ventilation potential was discussed.

2. Physical Models

To fulfil the objective of this study, we developed three types of physical models:

- Ventilation model based on correlations;
- Acoustic model based on sound transmission and reflection;
- Glare and lighting models based on solar radiation and building geometry.

The physical models are briefly presented below, with details provided in annexes.

2.1 Ventilation model

Two configurations of natural ventilation were studied: single-sided ventilation and cross-ventilation. Algorithms based on empirical models were used to determine the airflow rate through window openings, which usually depends on environmental conditions such as wind direction and magnitude, indoor-outdoor temperature difference, and opening configuration.

The correlation for single-sided ventilation is based on a semi-empirical model inspired by the orifice model (Warren 1977). The semi-empirical model, which is set according to Computational Fluid Dynamics (CFD) tools and validated by in-situ experiments [Caciolo et al., 2011], represents both buoyancy effect and wind effect [Caciolo et al., 2013].The correlation for cross-ventilation is based on the study by Rousseau and Mathews [Rousseau and Mathews, 1996].

2.2 Acoustic model

The calculation algorithm of this model supposes a free outdoor acoustic field and a diffused indoor field [Sabine, 1929] [Hongisto, 2000], and only considers the facade transmission. Sound transmission reduction through windows and front walls was calculated using structural and aperture transmission coefficients [Hongisto, 2000], which were assessed according to window sizes and wall materials. Finally, the indoor noise level was derived from the data of outdoor noise and sound transmission reduction [Long, 2014].

2.3 Glare model

This model is based on geometrical calculation and solar radiation data, and determines whether people working on a desk in the room's centre are glared [ANR, 2015].The glaring is effective if the sun beam is in a pyramid, of which the apex is fixed on the desk and the base is the window.

2.4. Daylighting model

There are various numerical methods, from the simplest Daylight Factor (DF) method to the most sophisticated raytracing method. By comparing six daylight simulation methods, Reinhart and Herkel [Reinhart and Herkel, 2000] find the DF method performs well on fully and partially cloudy days, but underestimates the indoor illuminance on clear days. Considering simplicity and computation time, we select the DF method [CIBSE, 1999]. Its inaccuracy for clear days is limited if solar protection is lowered. The main model parameters are the size, orientation and type of window, position of shadings, and total vertical irradiance. The total horizontal irradiance was extracted from Meteonorm files [TRNSYS 2012], while the vertical global irradiance incident on the opening surface was derived from horizontal global irradiance. DF was calculated based on the geometry and reflective properties of the glazed and internal surfaces. The indoor illuminance was determined as the outdoor illuminance on the opening surface multiplied by the DF corrected by facade orientation [CIE 1973].

3. Control strategies of models

3.1 Overview of global model structure

Each physical model was coded and validated separately [ANR, 2015]. The models were coupled on TRNSYS to simulate the multi-physic aspects of natural ventilation. Then equipment control (windows, shadings, artificial lighting) was implemented to ensure the compliance with various constraints. The control models were interconnected and the interplays between them were pivotal in making the results consistent.

An overall flow diagram illustrating the interactions between the models is shown in Figure 2. This diagram is composed of four modules:

- Input module: It stores the inputs into the global model. Some inputs used for physical models are available in TRNSYS (weather file), and others are acquired from exterior data (e.g. urban noise scenario, occupancy schedule, geometries of windows and buildings).
- Physical module: It consists of five main physical models (green boxes in Figure 2).

- Control module: Main control models are presented in grey boxes in Figure 2. Window opening and closing decisions are made considering indoor acoustic and thermal conditions.
- Building module: It uses the Type 56 component of TRNSYS and simulates building energy using the parameters and intermediate variables from all physical and control models. The outputs include major indicators such as indoor temperature and energy consumption.

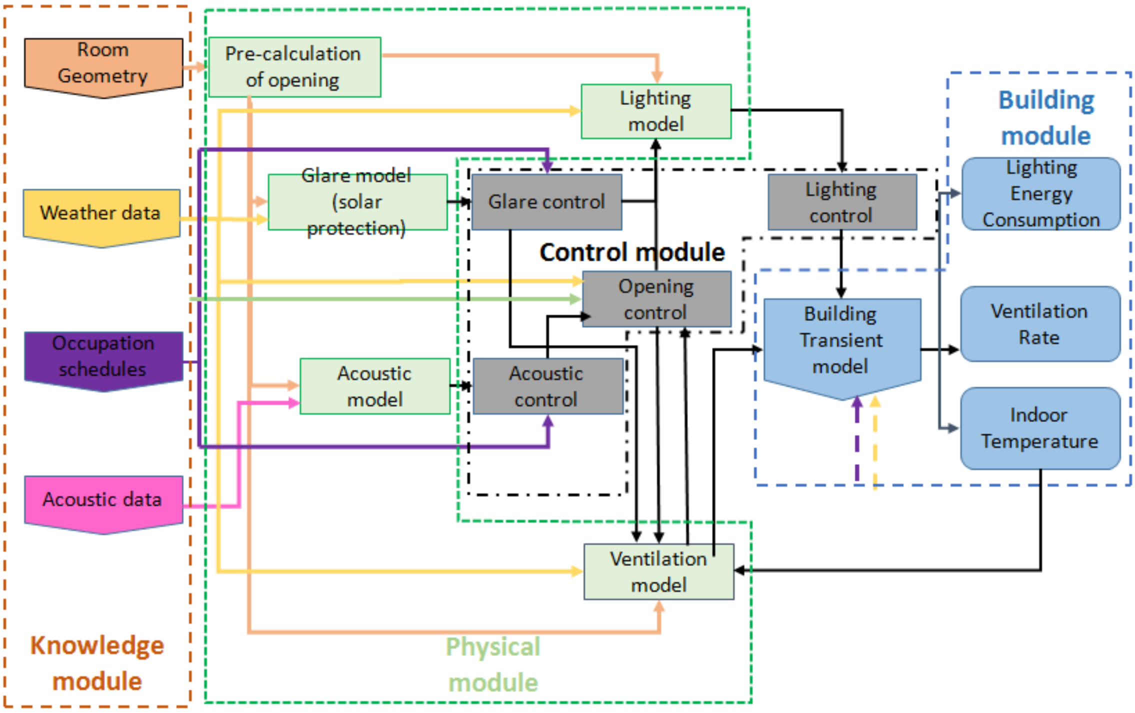

Figure 2.Interconnections of control models in the global model

As showed in Figure 2, the coloured arrows represent different data categories:

- Orange: features of windows and offices;
- Brownish yellow: weather data;
- Violet: occupancy scenarios;
- Rose: acoustic data.

The indoor temperature at a previous time step is marked by a black dotted arrow and used to calculate the air flow at the next time step.

Most of the control strategies are simulated on deterministic occupant behaviour models. This simplification is made due to two concerns. First, the practitioners can easily change the preset value in routine modelling and pre-design work. Second, there is no explicit arbitration model between thermal and acoustic comforts in field, so occupant behaviour patterns should be established, usually through long-term observation and field tests, but this is not the objective of this study.

3.2 Ventilation control

A simple ventilation control with only two modes of 'completely open' and 'completely closed' was chosen. As showed in the scenario (Figure 3), the temperature thresholds are established to avoid window opening when indoor temperatures are inappropriate for natural ventilation, and time hysteresis is introduced to avoid too frequent window opening/closing which are often unacceptable for occupants.

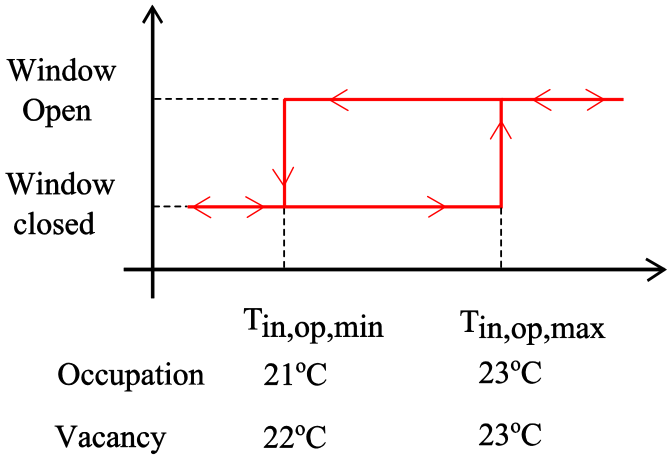

Figure 3. Window opening thresholds

The thresholds are changed according to occupancy and position (open or closed) of the window at the previous time step. The thermal control of window opening is planned as follows:

- Natural ventilation is allowed only when outdoor temperature is above 15°C during the occupancy period and above 13°C during the vacancy period, thus avoiding the discomfort due to too low temperature or over-cooling;
- Indoor temperature should be necessarily higher than outdoor temperature.

3.3 Acoustic Control

The acoustic control ensures sound comfort levels should be in the acceptable range for various indoor activities. The acoustic control together with ventilation control is used to make the decision of window opening. The acoustic control follows reversal logics(Figure 4):

- It would be applied only if the room is occupied;
- The window should be opened if the indoor temperature is too high;
- The window should be closed if the indoor noise level exceeds a threshold;
- The window opening order received from a thermal control model would be overridden if the acoustic condition is not fulfilled.

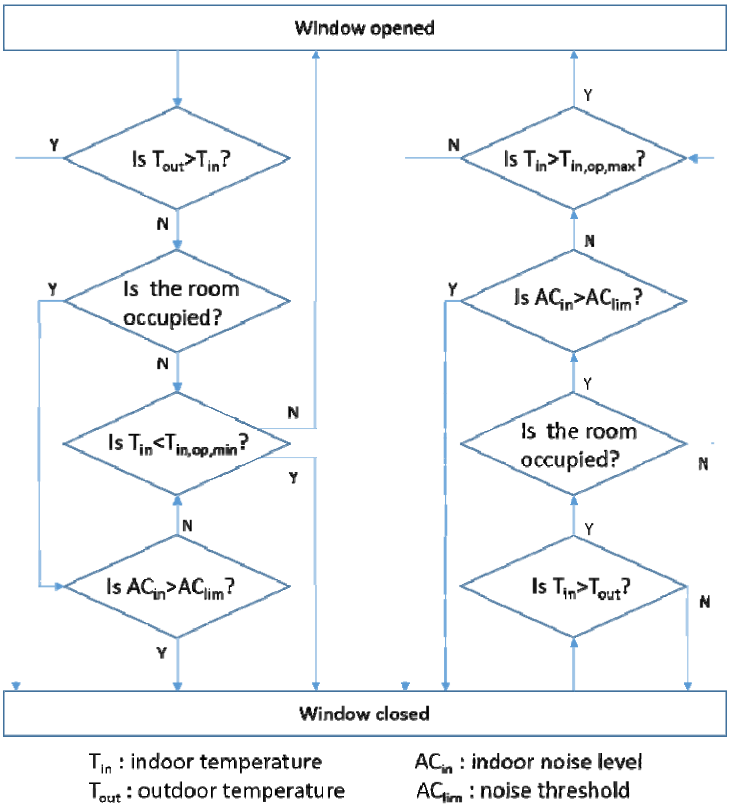

Figure 4. Control logics of window opening

3.4 Glare control

An opaque shading sunscreen is initially placed over the window. If the physical and user authorizations are both positive, the sunscreen will be lowered to a preset height, implying a reduction of air path for natural ventilation. During the vacancy period, the sunscreen is still in place to reduce solar gains if the window is closed.

3.5 Artificial lighting control

Lighting comfort in offices should be guaranteed throughout the occupation period. Appropriate facade orientation and an appropriate glazing size allow to make the largest use of daytime daylight. When the daylight resource is insufficient to maintain the occupants' visual comfort, this module sends an orderto turn on the artificial lighting.

3.6 Acoustic Shutter Protection

An acoustic protection device, a shutter is optional in the simulation. The characteristics of this shutter can be found in [Cui et al. 2013]. It is considered to be transparent and therefore does not directly impact lighting or glare control.

Figure 5. Example of transparent acoustic shutter

As showed in Figure 5, the shutter has been fabricated in plexiglass. It is considered to be transparent and therefore does not directly impact lighting or glare control. It reduces air change rate by 50% in average for both windward and leeward sides. It save rage reduction on passing noise is between 8 to 11 dB from50 to 4000 Hz which covers most street noise frequencies. Therefore the shutter is considered to lower the indoor noise by 10dB and reduce the air passing surface by 50% in the simulation.

4. Case study conditions

Two building configurations were chosen for simulations in TRNSYS with different control strategies presented in section 4.3: an office room with single-sided ventilation and a single-family detached house with cross-ventilation. Their locations, window sizes and orientations were parametrically analyzed.

4.1 Thermal Characteristics of the office room and the detached house

The office room (5 m long, 2.5 m wide and 2.5 m high) is located in the middle floor of a tall building. All walls except the facade are considered as adiabatic. The window sizes range from 30% to 70% of the facade surface. The room has heavy thermal inertia. The opaque part of its outer walls is well-insulated with 10 cm polystyrene. Each window is installed with an aluminium frame and low emissive glass. Indoor gain is 75W for one person and 110W for electrical equipment following a standard office schedule. Artificial lighting(72W) can be switched on only during the occupied period, which is 8:00-12:00 and 13:00-20:00.

The detached house only has one 32 m^2 bedroom zone and one 32 m^2 living room zone. The window surfaces are set to be 7m^2 in both zones. The windows in each zone are installed on the two sides of the house at 90^{o}to each other, which guarantees the cross-ventilation through the two zones. The house has similar thermal characteristics as the office. The indoor gains are 225W for three persons, 72W for artificial lighting, and 110W for electrical appliances in each room. The occupancy period is 8:00-20:00 in the living room zone and 20:00-8:00 in the bedroom zone. The lights and electrical appliances are turned on from 8:00-20:00 in the living room zone, and from20:00-24:00 and 6:00-8:00 in the bedroom zone.

The same closing/opening thresholds in thermal and acoustical constraints are applied to the office room and the detached house.

4.2 Environmental data

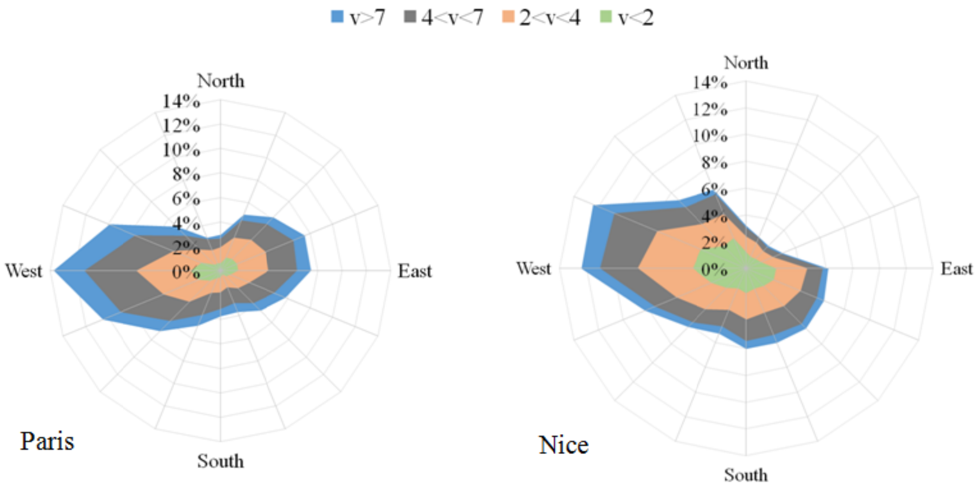

Figure 6. Wind direction and speed in two simulated locations

Figure 6 shows the speed and direction of summer winds in Paris and Nice, which represent an oceanic climate and a Mediterranean coast climate, respectively. The climate data at a time step of 1h were generated by a stochastic model from METEONORM in TRNSYS. Clearly, the west wind is dominant and the north wind is rare in both locations. The wind speed varies mostly between 1 and 6m/s.

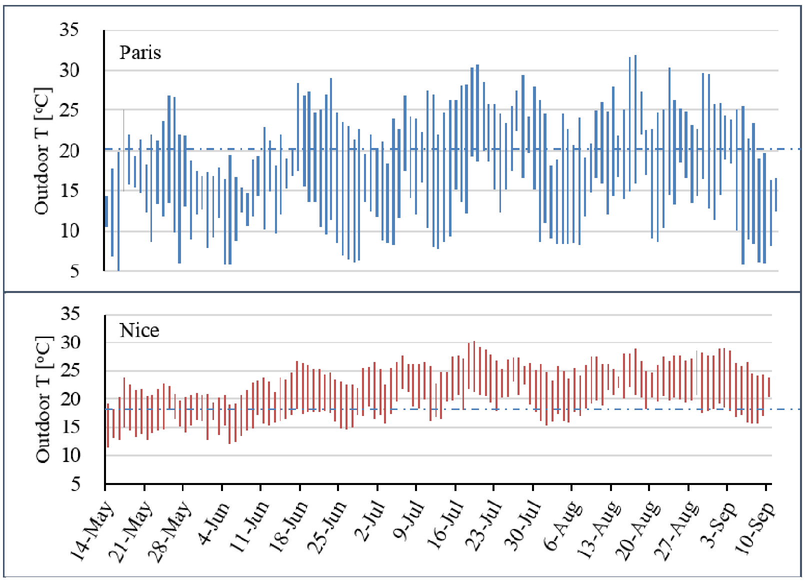

Figure 7. Temperature variations in two simulated locations

Figure 7 shows the daily temperature variations during summer. In Paris, the day-night temperature difference is often larger than 10 °C, while in Nice, the climate is more temperate with less temperature variation.

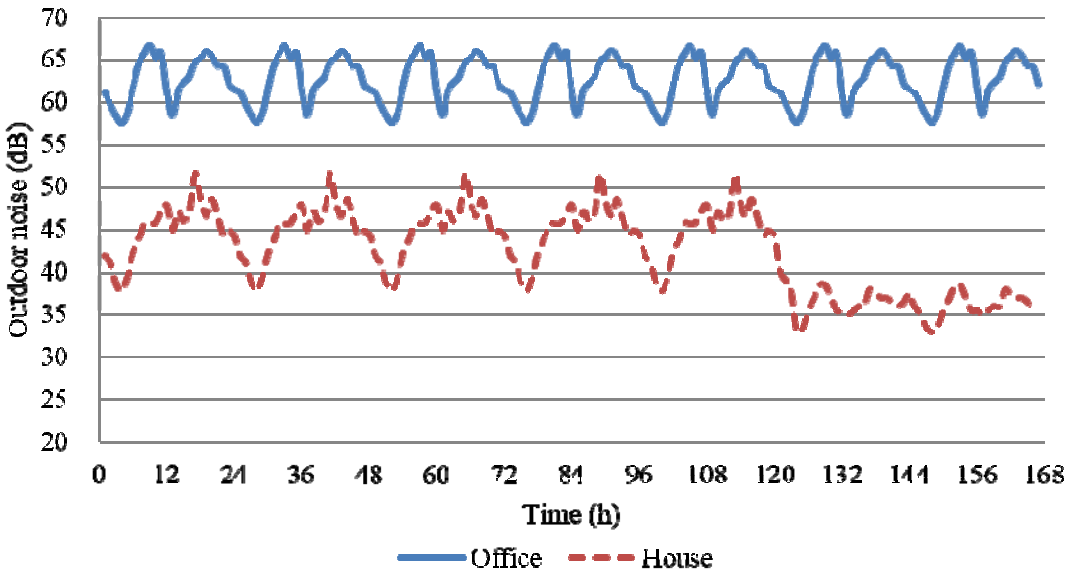

Figure 8. Outdoor noise profiles in one week

As showed in Figure 8, the outdoor noise profiles in one week are the same for the buildings in Paris and Nice, where offices are supposed to be located in urban areas and houses in suburban areas.

4.3 Characteristics of simulations

The simulations, which covered the summertime from 15 May to 15 September, were performed at a time step of 0.5 h. As natural ventilation may not always fulfil the cooling demands, the thermal discomfort should be quantified. Here, we selected Discomfort Degrees Hours (DDHs), which are defined as the temporal integration of differences between indoor temperature and comfort threshold (25 °C) during the occupancy.

This simple definition of DDH enables us to assess the general cooling effect of natural ventilation, though adaptive comfort temperatures are included in many standards [CIBSE, 2006] [CEN 15251] [ASHRAE, 2004].

Four window opening strategies are simulated:

- Strategywith natural ventilation in priority (VentPrior): Only the thermal constraint is applied. It provides the maximum obtainable cooling effect of natural ventilation.
- Strategy with lowered solar protection (Glare Ctrl): The opaque shading sunscreen is lowered by 50% of window height once glare is detected. Since the study with the detached house is focused only on acoustical and thermal comforts, the lighting scenarios are simplified such that the solar protection and artificial lighting controls are inactive. The lighting threshold was chosen according to the European standard [EN12464-1, 2011], which corresponds to 500 Lux for a person at work (sitting in front of a computer or reading documents on a desk).More-complicated daylighting models are available especially when complex solar protection devices and adaptive occupant behaviours are involved [Reinhart, 2004] [Bourgeois, 2006].

- Strategy with acoustical constraints (Acous Ctrl): The acoustic and ventilation controls are applied. In the following case studies, the noise threshold for the office is 40dB all the time (Table 1); but is40dB at daytime and 30dB at night for the detached house (Table 2).

Table 1. Acoustic scenario of the office

Office acoustic scenario	Weekday				Weekend
	8:00-12:00	12:00-13:00	13:00-18:00	18:00-8:00	0:00-24:00
Occupancy Threshold (dB)	40	40	40	40	40
Occupancy	Occ	Unocc	Occ	Unocc	Unocc

Table 2. Acoustic scenario of the detached house

House acoustic scenario	Daytime	Night
	8:00-20:00	20:00-8:00
Occupancy Threshold (dB)	40	30
Occupancy	Occ (livingroom)	Occ (bedroom)

- Strategy with intelligent control (Intel Ctrl): The thermal, acoustic and lighting constraints are all applied.

In the office, all four strategies were applied.

In the detached house, only 'VentPrior' and 'Acous Ctrl' were applied. Since the house's occupants can easily adapt to glare by moving contrary to office's occupants, no glare control is considered. Regardless of daylight level, the lamps are turned on as long as the room is occupied except from 0:00 to 6:00.

5. Results and Discussion

5.1 Simulation with the office room

5.1.1 Reference simulation

*Simulation of 'Window closed' (Clos).*The office room faces the south without solar protection and with 50% window surface ratio. A reference simulation (Table 3) enables a thermal analysis of the office room, which is equipped with only mechanical ventilation (constant at 0.7 vol/h) during the occupation period.

Table 3. Results from 'Window closed' simulation

Location	Average indoor temperature(°C)	DDH (°C*h)	Lighting energy consumption (kWh)
Paris	33.6	3845	75
Nice	34.5	6474	72

The average indoor temperature is 33.6 °C in Paris and 34.5 °C in Nice is obtained. The office room is partially uncomfortable regardless of the climate, suggesting cooling is necessary.

Simulation of VentPrior. Natural ventilation is authorized during both occupation (diurnal ventilation) and vacancy (nocturnal and weekend ventilation).

Table 4. Results from 'VentPrior' simulation

Location	Average indoor temperature(°C)	DDH (°C*h)	Lighting energy consumption (kWh)	Average air change rate (vol/h)	Openinghours(h)
Paris	23.0	104	74.0	11.5	1292
Nice	24.0	133	70.8	11.9	2251

As shown in Table 4, the average indoor temperature drops around 10°C and the DDHs almost disappear, which suggest the strong cooling effect of natural ventilation compared with the reference simulation where the window is always closed. These results, though very promising, are idealistic since the window opening constraints are neglected.

5.1.2 Comparison of simulation results

Simulations of other control strategies with different window sizes (30%, 50% and 70%) in Paris and Nice were also performed.

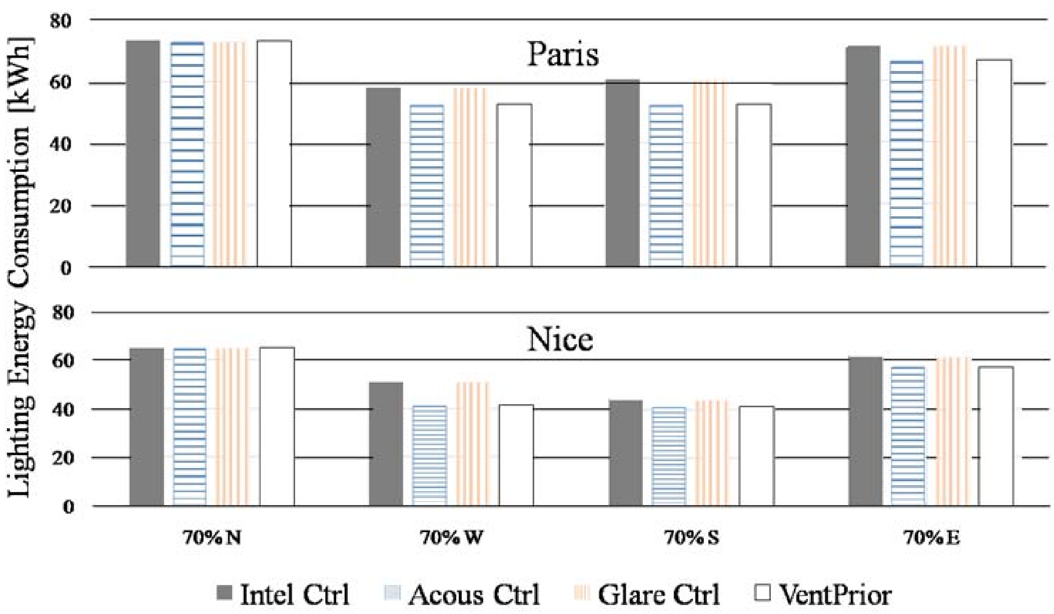

Figure 9. Lighting energy consumption for different orientations in both Paris and Nice, with a 70% window size

Figure 9 shows the lighting energy consumptions (LECs) for different control strategies and different window orientations, but only with the window size 70% because of similar results among window sizes. Only slight difference due to less solar gains is noticed between control strategies.
The LEC at west or south orientation is smaller compared with east and north orientations. Natural lighting reaches the threshold demand of 500 lux only around noon, so artificial lighting is turned on most of the time. On the contrary, at south, east and west orientations, the blinds are put down once glare is detected in strategies 'IntelCtrl' and 'Glare Ctrl'. Thus, artificial lighting is still needed and the LEC is slightly higher compared with the strategies without glare control ('AcousCtrl', 'VentPrior'). At the north orientation, no glare is detected and LECs remain the same among the control strategies.
LECs are higher in Paris than in Nice where sunny days are more frequent.

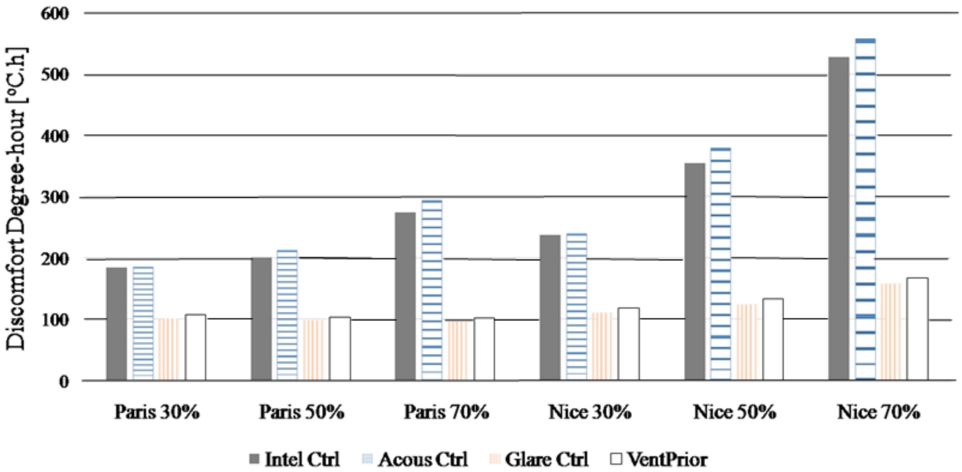

Figure 10. DDHs of different window sizes at southorientation in Paris and Nice

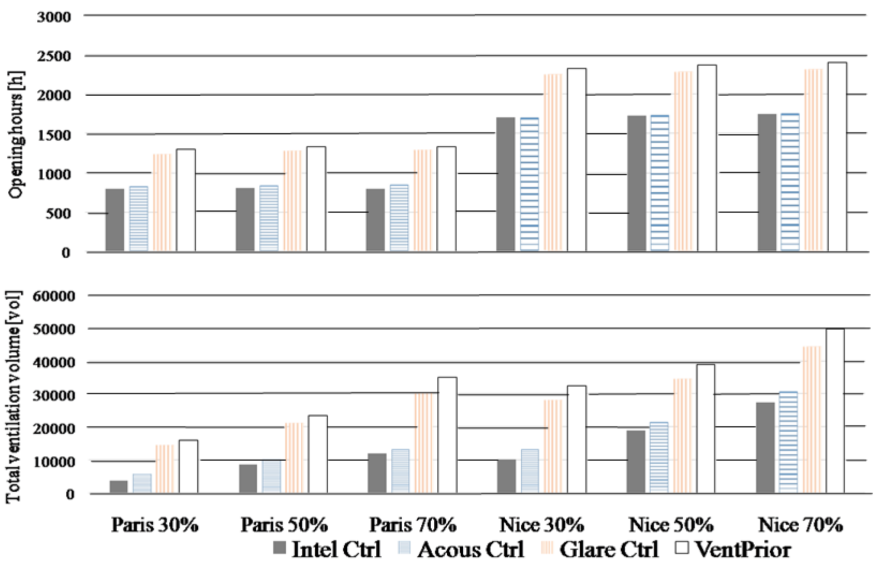

Figure 11. Opening hours (up) and ventilation volume (down) of different window sizes at south orientation in Paris and Nice

The DDHs vary largely depending on location, window size and control strategy. For instance, Figure 10 shows the DDHs of two offices in Paris and Nice with three window sizes at south orientation and all four control strategies. When window size and control strategy are both unchanged, the office in Paris generally has less DDHs than that in Nice.

A larger window makes the office more uncomfortable. As for the control strategies without acoustic constraint, the impact of window size on discomfort is slight since the solar gains are more or less compensated by the improved natural ventilation. In particular, the difference due to window sizes in the Paris office is negligible. However, if an acoustic control or intelligent control is applied, the window size strongly impacts the indoor comfort, indicating that the acoustic constraint strongly accentuates DDH.

DDH is related tothe ventilation volume. As showed in Figure 11, the total ventilation volume passing through a south-oriented window is maximized if no constraint is applied and minimized with the application of an intelligent control. The acoustic constraint may reduce more than 30%of window opening time and all ventilation volume.

5.1.3 Optimization of thermal comfort

The modelling tool could also be used to find out the optimum design for a more comfortable building. For instance, simulations with varying window sizes and orientations were carried out hereafter to identify the parameters that can minimize the DDH.

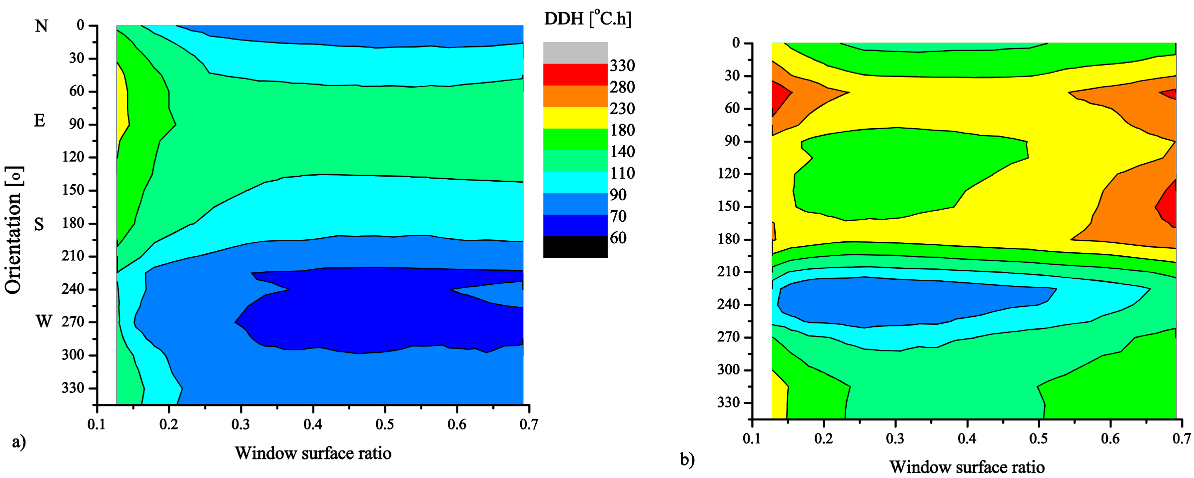

Figure 12. Variations of DDH with window size and orientation in Paris, (a) VentPrior; (b) IntelCtrl

Figure 12 shows the variations of DDH with window size and orientation in Paris with strategies 'VentPrior' and 'IntelCtrl'.

In the case of 'VentPrior', DDH decreases significantly when the window size increases from 13% to 40% of the facade, especially at the west orientation. The DDH drops over 80%in this orientation, which emphasizes the importance of natural ventilation in building cooling, irrespective of the duration when the outdoor temperature is above 25 °C. The variation of DDH with window size remains low when the window size exceeds 40% of the facade, indicating the natural ventilation and additional solar gains received by a large surface counterbalance each other. In Paris with a temperate oceanic climate, natural ventilation is an effective passive solution to summertime cooling needs. More specifically, when the window size is constant, the smallest DDH always occurs between orientation220and 300° (southwest), which suggests a comprehensive trade-off between natural ventilation and solar gains. Ventilation is the strongest at the orientation 240°, which is also the dominant wind direction (Figure 5). When the window orientation is close to the south, solar gains and DHH both increase. In this climate, the window orientation significantly impacts thermal discomfort, and therefore is a key parameter to be considered at the building design phase.

In the case of 'IntelCtrl', DDH is minimized when the window size is between 20% and 40% of the facade surface, which is the optimum window size under multi-physic constraints. By considering the noise and glare constraints, we think window opening is less frequent and overheating is slightly more frequent compared with strategy 'VentPrior'. The smallest DDH always occurs around the orientation 240°. Considering the two parameters, we think in order to optimize the thermal comfort, the best choice is probably a window of 30% size oriented at 240°when the strategy 'IntelCont' is applied in an office in Paris.

Similar simulations were conducted for Nice. The optimum zone tends to remain the same as the case in Paris, except for different degrees of DDH.

In comparison of the two control strategies, the natural ventilation potential can be largely reduced while respecting the noise and glare constraints. Therefore, thermal comfort is not significantly improved by enlarging the window surface, but by orientating the window to the windward direction.

5.1.4 Influence of acoustic shutter

Simulations were carried out to assess the necessity of using an acoustic shutter. The shutter was designed to reduce the outdoor noise while maintaining the natural ventilation acceptable. Results are showed in Figures 13 and 14.

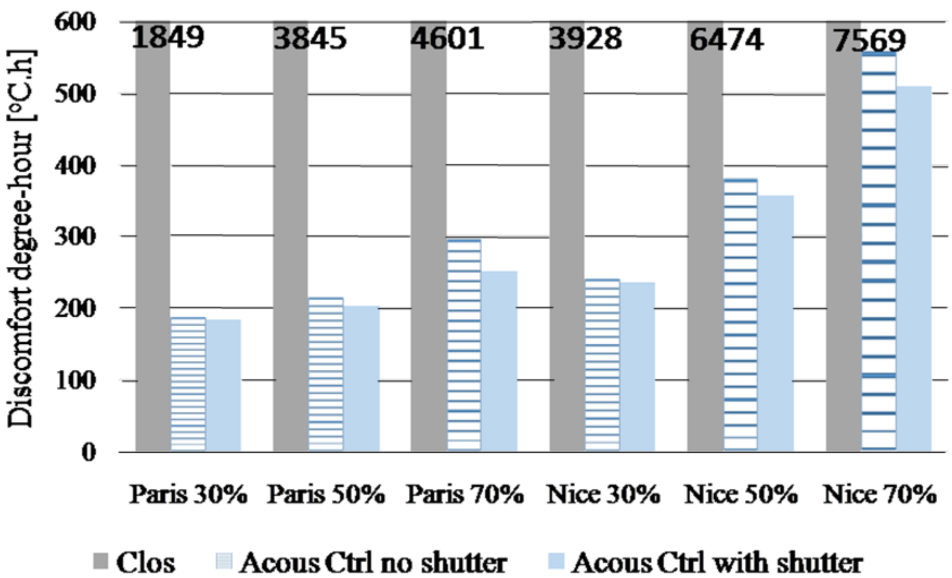

Figure 13. DDH for acoustic control with or without an acoustic shutter in Paris and Nice

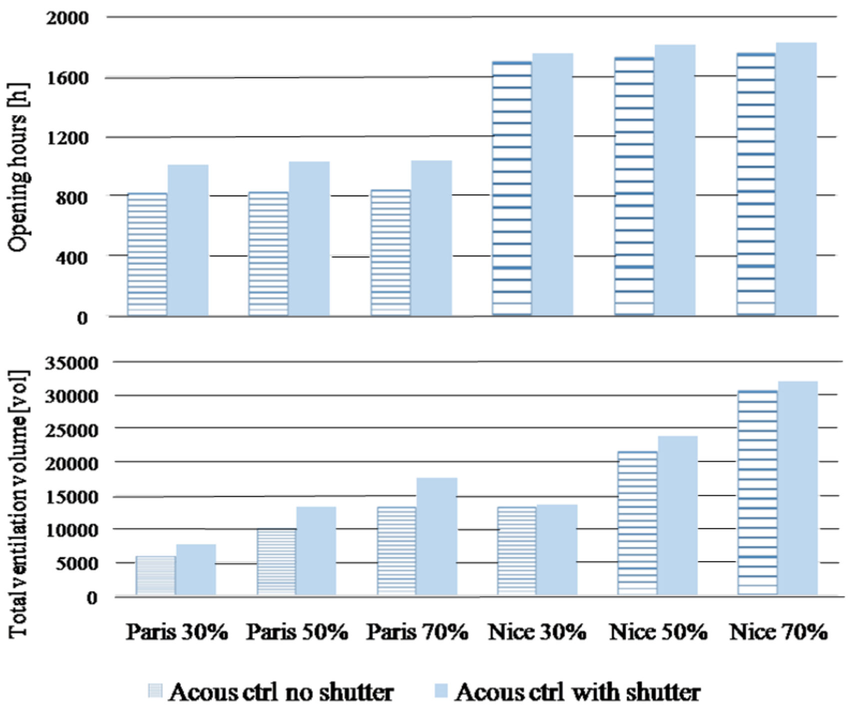

Figure 14. Opening hours (up) and ventilation volume (down) for acoustic control with or without an acoustic shutter in Paris and Nice

With the presence of an acoustic shutter, DDHs decrease in the strategy 'AcousCtrl'(Figure 13), while the opening hours and thus the total ventilation volume increase (Figure 14). The installation of acoustic shutters enables more frequent window opening even if the average air flow rate is low. Noise-sensitive occupants can benefit more from natural ventilation after the installation of an acoustic shutter.

A shutter over the window is an attractive solution because it reduces noise and improves ventilation performance at the same time. This advantage is especially evident in a moderately noisy environment. In a quiet environment (somehow equivalent to VentPrior), the window can always be opened. In a very noisy environment, however, a shutter with 10dB reduction does not bring much acoustic comfort, so the window could be always closed.

5.2 Simulations with the detached house

In this house, the number of occupants was set to be three. Only two zones were considered: a living room and a bedroom. The occupation schedule was different from that of the office. From 8:00 to 20:00, the living room zone was occupied while the bedroom zone was vacant; the situation from 20 to 8h was the opposite. Only 'Acous Ctrl' and 'VentPrior' were applied, since visual comfort was not a primary concern here. Each control strategy was applied simultaneously on the windows of both zones to provide cross-ventilation. The occupant and acoustic scenarios of the house are showed in Table 2. The ventilation volume was calculated from the air change volume passing through the two zones.

In the example presented hereafter, the window of the living room is south-oriented and occupies 20% of the wall surface.

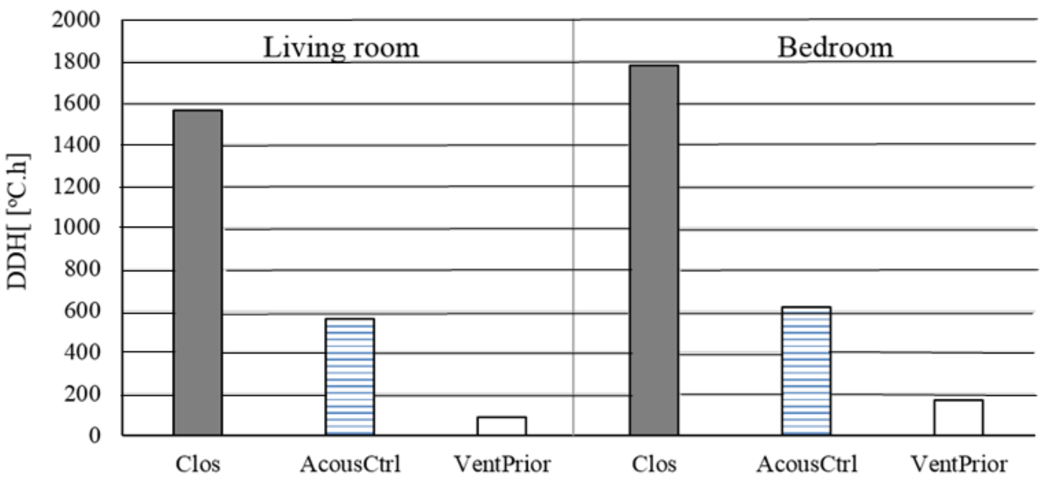

Figure 15. DHHs in the living room and bedroom in different control strategies in Paris

Figure 15 shows the daytime DDHs in the living room zone and night-time DDHs in the bedroom zone with strategies 'Clos', 'AcousCtrl' and 'VentPrior'. As for 'Clos', DDHs are unacceptable since the windows are always closed. As for 'AcousCtrl', DDHs are around 600 °C.h in both zones, which is already a big improvement on thermal comfort compared with 'Clos'. However, if the occupants aim to maximize ventilation, DDH in 'VentPrior' further decreases to less than 100 °C.hin the living room and less than 200 °C.h in the bedroom. There is no significant difference between night-time and daytime owing to the heavy thermal inertia of the building.

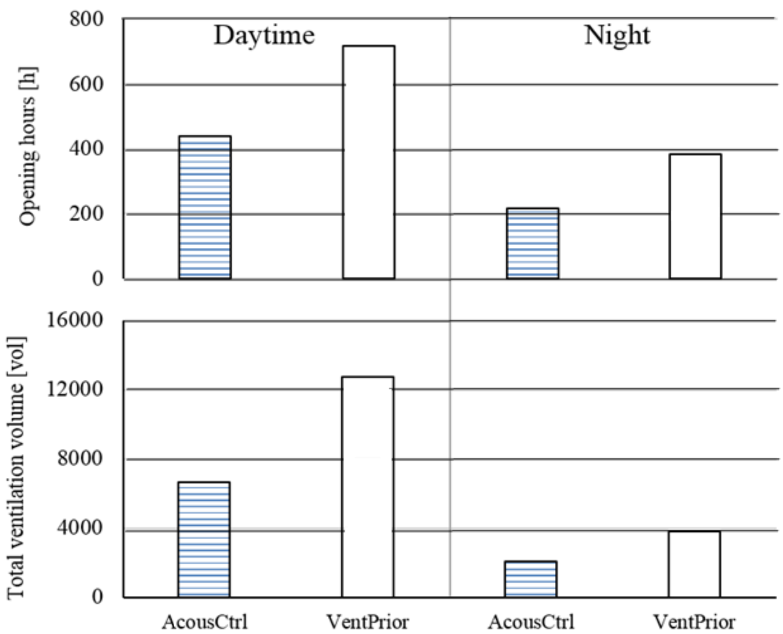

Figure 16. Opening hours and ventilation volume of the house in Paris under different control strategies

Figure 16 shows the opening hours and ventilation volume of the house during daytime and night. As for the VentPrior strategy, the occupants at sleeping time leave the window either closed or open permanently, which is unable to optimize the thermal-acoustic comfort and energy consumption. In comparison, with the AcousCtrl strategy, the natural ventilation potential is enhanced while the occupants are protected from night-time low temperature and outdoor noise. Thus, the benefit of automatic opening control at night is obvious in practice.

6. Conclusions and prospects

A global modelling approach with multi-constraint controls of glazed openings was developed. The control strategies proposed here can be applied by a full-auto or semi-auto system, and help to maximize the natural ventilation performance and thus improve indoor comfort. The algorithms were implemented in TRNsys, and the codes are available online as open source [OVISOLVE, 2015]. Simulations with a typical office room and a single-family detached house were carried out under different strategies. Conclusions are listed below.

- Thermal, acoustic and lighting comforts are impacted by orientation and size of window as well as building location.
- Acoustic constraint is a key influence factor of natural ventilation performance and depends strongly on noise acceptability from occupants.
- A balance among different constraints can be achieved by applying an intelligent control.
- Acoustic shutters can expand the application of natural ventilation in noisy environments even with a reduction of air path, which is counterbalanced partially by the possibility of more frequent window opening.

The proposed modelling approach integrating thermal, acoustic and daylighting constraints can be considered as a proof-of-concept representing the complexity of real-world natural ventilation and can be used to solve problems of glazed opening conception and control under various conditions. The refinement of lighting and acoustic models and the equipment control integrated in building energy simulation tools help to optimize the trade-offs between thermal, acoustic and lighting constraints and contribute to more reliable decision-making. Nevertheless, behavioural studies should be carried out to analyse the occupants' choices between noise and thermal discomforts.

Acknowledgment
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