# ALGORITHM SHEET Acoustical Transmission

MULTIACOU

Acoustical Transmission Loss Model for Multiphysics Building Simulation

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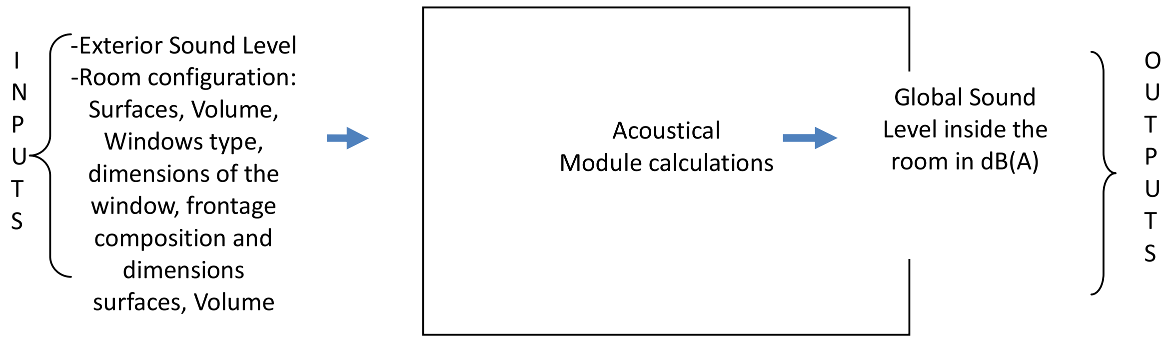
## 1. General description

The purpose of routine MULTIACOU is to assess the sound level inside a room by determining first the acoustical transmission loss for different window types and for different rates of apertures. The information diagram of this routine is presented in Figure 1.




## 2. Developper

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## 3. Nomenclature

| | Description | *Units* | *Min* | *max* |
|---|---|---|---|---|
| **Input variables** | | | | |
| **Control system** | | | | |
| Opening ratio | Windows opening ratio | % | 0 | 100 |
| | | | | |
| **Parameters** | | | | |
| **Room configuration** | | | | |
| Absorbing materials inside the room | Properties of absorption $\alpha_i$ and surface $S_i$ of each component inside the room | $\alpha_i$ $S_i\,(m^2)$ | *0* | *1* |
| Vr | Space volume | $m^3$ | | |
| Tr | Reverberation Time inside the room | *S* | *0.1* | *5* |
| $L_{out}$ | Exterior Global Sound Level | *dB(A)* | | |
| **Opening Configuration** | | | | |
| Opening Type | Windows type selected if<br>=1: French window<br>=2: sash window<br>=3: England window<br>=4: Italian window<br>=5: Sliding window | - | | |
| c1eff, c2eff… | Effective opening surfaces coefficient<br>c5eff = 1 if window type=5… | $m^2$ | | |
| Frontage composition | Composition and surface $S_{fi}$ of each component of the frontage | $R_{structurali}$ *(dB(A))* $S_{fi}$ en $m^2$ | | |
| **Output variables** | | | | |
| $R_{totali}$ | Transmission Loss coefficient for each 1/3 octave i | dB(A) | | |
| $R_{totalG}$ | Global transmission loss coefficient | dB(A) | | |
| $L_{in}$ | Global Sound Level inside the room | dB(A) | | |

## 4. Mathematic description

### 4.1 Physical model

When the opening size is smaller than the acoustic wavelength, it is typically referred to as a "leak"; the term "opening" is generally used for larger opening sizes. In literature, the term "aperture" is used for both leaks and openings. It must be also underlined that the modeling of the sound transmission loss of window apertures has been rarely considered in literature.

As described by Hongisto[1] for doors, sound transmission through windows and frontage is assumed to comprise two factors: structural (frontage + windows) transmission and aperture transmission, having sound transmission coefficients $\tau_{structural}$ and $\tau_{aperure}$ respectively.

$$\tau_{total} S_{total} = \tau_{structural} S_{structural} + \tau_{aperture} S_{aperture}$$

where $S_{structural}$ and $S_{aperture}$ are the areas of global structure (frontage+windows) and aperture respectively. The term "total" refers to the sum of aperture transmission and structural transmission (frontage+windows).

The global sound reduction index can then be deduced:

$$R_{total} = 10\log\left(\frac{1}{\tau_{total}}\right)$$

$$R_{total} = 10\log\left(\frac{S_{total}}{S_{strutual}\tau_{structural} + S_{aperture}\tau_{aperture}}\right) = 10\log\left(\frac{S_{total}}{S_{strutual}10^{-\frac{R_{strutural}}{10}} + S_{aperture}10^{-\frac{R_{aperture}}{10}}}\right)$$

Prediction of the structural sound reduction index of frontage, closed windows (simple, double panels separated by air cavity, by sound absorbing material…) has been discussed widely in literature and it is well known (a data base will be taken for the estimation of each component): a classical model will be used ($\tau_{structural} S_{structural} = \sum_{componenti} \tau_{structurali} S_{structurali}$ for components in parallel with $\tau_{structurali} = 10^{-\frac{R_{structurali}}{10}}$ ....)

However, the determination of $\tau_{aperture}$ is more complicated. In many building simulation tools, $\tau_{aperture}$ is taken equal to 1 which is very simplified and not verified by experimental results for small apertures. That is why $\tau_{aperture}$ must be better predicted.

$S_{aperture}$ will be multiplied by a coefficient between 0 and 1 (this coefficient will depend on the window type, it will be denoted cieff for the window type i) .It will account for the effective surface of aperture.

The Global $R_{totalG}$ is then calculated :

$$R_{totalG} = 10\log\left(\sum_{every\ 1/3\ octave\ i} 10^{\frac{R_{totali}}{10}}\right)$$

Then, by supposing that here is no lateral leaks (transmission loss only on the façade) and that the outside field is free (inside field is supposing to be diffuse):

$$L_{in} = L_{out} - R_{totalG} + 10\log\left(\frac{S\cos\theta}{A}\right) + 6$$

Where $\vartheta$ is the incidence angle of the emission wave. By default cos $\vartheta$ can be taken equal to one (normal incidence for example). *S* is the area of the façade.

*A* is the equivalent absorption area (Sabine's Theory) : $A = \sum_i \alpha_i S_i$

If no information is known *A* can be deduced by (Sabine's Theory): $A = \frac{0.16\ V_r}{T_r}$

## 4.2 Opening ratio more than 10%

For opening ratio more than 10 %, $\tau_{aperture}$ will be taken equal to 1 (this is verified experimentally).

## 4.3 Small rates of apertures

For small apertures, $\tau_{aperture}$=1 is not verified by experimental results. So, a more complicated model can be used.

Sgard *et al.*[2] recently published a review of existing models about sound transmission loss of small apertures, especially rectangular and slit-shaped apertures. It is summarized in the following.

Transmission through apertures with negligible thickness has been first studied by Bouwkamp[3], Spence[4] and Mulholland and Parbrook[5]. Then, several authors studied the acoustic transmission through finite thickness apertures. First, Gomperts[6,7] , Wilson and Soroka[8], Sauter and Soroka[9] assumed a plane wave field within the circular and/or rectangular aperture. Compertz[6,7] related the velocity potential in a circular or slit-shaped aperture to the velocity potential of spherical or cylindrical waves, respectively, to get the transmission coefficient in terms of trigonometric functions and “end corrections” associated to the aperture shapes. Wilson and Soroka[8], Sauter and Soroka[9], and Mechel[10] assumed the field in the aperture to be the sum of two plane waves propagating in opposite directions. Chen[11] investigated the prediction of the normal incidence and diffuse field transmission loss of slits. A combination of Rayleigh’s formula and a wave number transform of the fields were used to solve the problem. Park and Eom’s model[12] has been developed for the calculation of the oblique incidence sound transmission loss and reflection coefficient of a rectangular aperture of finite thickness taking into account the three-dimensional nature of the sound field within the aperture. Then, Serizawa and Hongo[13] proposed an exact solution for the normal incidence transmission loss of a rectangular aperture in a thick wall taking into account the 3D wave field in the aperture using Weber-Schafheitlin integrals.
Moreover, General numerical techniques such as boundary element methods can be used to predict the diffracted acoustic field by complicated shaped apertures. Huang and Chen[14] solved Helmholtz integral equation to calculate the sound diffracted through circular apertures in soft and hard plane baffles using boundary elements. At low frequencies, Furue[15] applied the Boundary Element Methods to calculate the sound field diffracted by the extremity of an unbaffled circular aperture excited by a point source.
Sgard *et al.*[2] also proposed a general and efficient numerical method based on a modal approach for predicting transmission loss of apertures with rectangular and circular cross sections for various geometrical configurations. Trompette *et al.*[16] complemented the work of Sgard *et al.*[2], which was essentially comparisons between existing models and numerical results, by performing new experimental validation tests for rectangular openings and slits. Results were found to be reliable over a wide frequency range and it was found that the modal approach correlates very closely with the experiments performed.
For all these reasons, Sgard *et al.*[2] model can be chosen here and applied to window apertures.
The model developed by Sgard *et al.*[2] is based on modeling the sound field within the aperture in terms of propagating and evanescent acoustic modes. Aperture radiation is considered by means of a modal radiation impedance matrix. The coupled problem is then solved in terms of modal contribution factors to obtain the transmission coefficient for any plane wave angle of incidence. The sound transmission coefficient for a plane wave with an angle of incidence $(\theta_i, \varphi_i)$ is given by

$$\tau(\theta_i, \varphi_i) = -\frac{\rho_0}{k_0 \cos\theta_i \rho_f^* \left|\hat{A}_i\right|^2 S} \Re\left( \sum_M N_M \hat{k}_M^* \hat{C}_M \hat{D}_M^* \right)$$

where the summation is performed over the aperture lateral modes. Modal coefficients $\hat{C}_M$ and $\hat{D}_M$ are related to modal radiation impedances, the area of the aperture, and the impedance of the fluid within the aperture. Coefficients $\hat{k}_M^*$ and $N_M$ are the modal wave number and the modal norm, respectively. $\hat{A}_i$ represents the amplitude of the incident plane wave. Further details can be found in Sgard *et al.*[2].

## 5. DATA BASE

A data base is pre-recorded into the model. Indeed, for each component of the frontage, the transmission loss of this component ($R_{structural}$) is know in function of the frequency.
Example: for a component “concrete 20cm”:

| Fc (Hz) | 100 | 125 | 160 | 200 | 250 | 315 | 400 | 500 | 630 | 800 | 1000 | . | . | . | . | . | 5000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R (dB(A)) | 22 | 24 | 27 | 22 | 27 | 34 | 39 | 46 | 54 | 59 | 63 | | | | | | 80 |

There are two columns: the first is for frequency, the second is for the $R_{structural}$ in dB(A)

Hollow concrete blocks of 10 cm coated on one side

| | |
|---|---|
| 100 | 38.0 |
| 125 | 37.0 |
| 160 | 35.0 |
| 200 | 33.0 |
| 250 | 34.0 |
| 315 | 35.0 |
| 400 | 36.0 |
| 500 | 37.0 |
| 630 | 38.0 |
| 800 | 41.0 |
| 1000 | 44.0 |
| 1250 | 46.0 |
| 1600 | 48.0 |
| 2000 | 50.0 |
| 2500 | 48.0 |
| 3150 | 51.0 |
| 4000 | 54.0 |
| 5000 | 56.0 |

Hollow concrete blocks of 12.5 cm coated on one side

| | |
|---|---|
| 100 | 39.0 |
| 125 | 38.0 |
| 160 | 36.0 |
| 200 | 35.0 |
| 250 | 35.0 |
| 315 | 37.0 |
| 400 | 39.0 |
| 500 | 41.0 |
| 630 | 43.0 |
| 800 | 44.0 |
| 1000 | 46.0 |
| 1250 | 48.0 |
| 1600 | 50.0 |
| 2000 | 51.0 |
| 2500 | 49.0 |
| 3150 | 52.0 |
| 4000 | 55.0 |
| 5000 | 57.0 |

Hollow concrete blocks of 15 cm coated on one side

| | |
|---|---|
| 100 | 39.0 |
| 125 | 38.0 |
| 160 | 37.0 |
| 200 | 37.0 |
| 250 | 38.0 |
| 315 | 39.0 |
| 400 | 41.0 |
| 500 | 44.0 |
| 630 | 46.0 |
| 800 | 48.0 |
| 1000 | 50.0 |

| | |
|---|---|
| 1250 | 52.0 |
| 1600 | 54.0 |
| 2000 | 56.0 |
| 2500 | 57.0 |
| 3150 | 54.0 |
| 4000 | 57.0 |
| 5000 | 58.0 |

Hollow concrete blocks of 17.5 cm coated on one side

| | |
|---|---|
| 100 | 41.0 |
| 125 | 39.0 |
| 160 | 39.0 |
| 200 | 39.0 |
| 250 | 41.0 |
| 315 | 44.0 |
| 400 | 47.0 |
| 500 | 50.0 |
| 630 | 52.0 |
| 800 | 53.0 |
| 1000 | 54.0 |
| 1250 | 55.0 |
| 1600 | 55.0 |
| 2000 | 57.0 |
| 2500 | 57.0 |
| 3150 | 54.0 |
| 4000 | 56.0 |
| 5000 | 58.0 |

Hollow concrete blocks of 20 cm coated on one side

| | |
|---|---|
| 100 | 43.0 |
| 125 | 42.0 |
| 160 | 42.0 |
| 200 | 43.0 |
| 250 | 46.0 |
| 315 | 48.0 |
| 400 | 50.0 |
| 500 | 53.0 |
| 630 | 55.0 |
| 800 | 56.0 |
| 1000 | 57.0 |
| 1250 | 58.0 |
| 1600 | 58.0 |
| 2000 | 59.0 |
| 2500 | 57.0 |
| 3150 | 55.0 |
| 4000 | 56.0 |
| 5000 | 58.0 |

Solid concrete blocks ( full or perforated ) 15 cm coated on one side

| | |
|---|---|
| 100 | 44.0 |
| 125 | 43.0 |
| 160 | 42.0 |
| 200 | 43.0 |
| 250 | 45.0 |

| | |
|---|---|
| 315 | 47.0 |
| 400 | 49.0 |
| 500 | 52.0 |
| 630 | 54.0 |
| 800 | 56.0 |
| 1000 | 58.0 |
| 1250 | 60.0 |
| 1600 | 62.0 |
| 2000 | 64.0 |
| 2500 | 65.0 |
| 3150 | 66.0 |
| 4000 | 68.0 |
| 5000 | 71.0 |

Solid concrete blocks ( full or perforated ) 17.5 cm coated on one side

| | |
|---|---|
| 100 | 45.0 |
| 125 | 44.0 |
| 160 | 44.0 |
| 200 | 45.0 |
| 250 | 48.0 |
| 315 | 50.0 |
| 400 | 52.0 |
| 500 | 55.0 |
| 630 | 57.0 |
| 800 | 59.0 |
| 1000 | 61.0 |
| 1250 | 63.0 |
| 1600 | 66.0 |
| 2000 | 68.0 |
| 2500 | 68.0 |
| 3150 | 70.0 |
| 4000 | 72.0 |
| 5000 | 74.0 |

Solid concrete blocks ( full or perforated ) 20 cm coated on one side

| | |
|---|---|
| 100 | 46.0 |
| 125 | 47.0 |
| 160 | 47.0 |
| 200 | 48.0 |
| 250 | 50.0 |
| 315 | 53.0 |
| 400 | 56.0 |
| 500 | 59.0 |
| 630 | 61.0 |
| 800 | 63.0 |
| 1000 | 65.0 |
| 1250 | 66.0 |
| 1600 | 68.0 |
| 2000 | 69.0 |
| 2500 | 71.0 |
| 3150 | 73.0 |
| 4000 | 75.0 |
| 5000 | 77.0 |

Concrete blocks made of lightweight aggregates 15 cm coated on one side

| | |
|---|---|
| 100 | 37.0 |
| 125 | 36.0 |
| 160 | 36.0 |
| 200 | 37.0 |
| 250 | 39.0 |
| 315 | 42.0 |
| 400 | 44.0 |
| 500 | 47.0 |
| 630 | 50.0 |
| 800 | 52.0 |
| 1000 | 55.0 |
| 1250 | 58.0 |
| 1600 | 60.0 |
| 2000 | 62.0 |
| 2500 | 64.0 |
| 3150 | 65.0 |
| 4000 | 64.0 |
| 5000 | 62.0 |

Concrete blocks made of lightweight aggregates 20 cm coated on one side

| | |
|---|---|
| 100 | 39.0 |
| 125 | 39.0 |
| 160 | 40.0 |
| 200 | 41.0 |
| 250 | 44.0 |
| 315 | 46.0 |
| 400 | 48.0 |
| 500 | 50.0 |
| 630 | 52.0 |
| 800 | 55.0 |
| 1000 | 57.0 |
| 1250 | 60.0 |
| 1600 | 62.0 |
| 2000 | 64.0 |
| 2500 | 66.0 |
| 3150 | 67.0 |
| 4000 | 66.0 |
| 5000 | 64.0 |

Solid concrete blocks 10 cm coated on one side

| | |
|---|---|
| 100 | 40.0 |
| 125 | 39.0 |
| 160 | 38.0 |
| 200 | 39.0 |
| 250 | 40.0 |
| 315 | 41.0 |
| 400 | 43.0 |
| 500 | 45.0 |
| 630 | 48.0 |
| 800 | 50.0 |
| 1000 | 52.0 |
| 1250 | 54.0 |
| 1600 | 56.0 |

| | |
|---|---|
| 2000 | 58.0 |
| 2500 | 61.0 |
| 3150 | 64.0 |
| 4000 | 67.0 |
| 5000 | 69.0 |

Solid concrete blocks 12.5 cm coated on one side

| | |
|---|---|
| 100 | 42.0 |
| 125 | 41.0 |
| 160 | 40.0 |
| 200 | 40.0 |
| 250 | 42.0 |
| 315 | 44.0 |
| 400 | 46.0 |
| 500 | 49.0 |
| 630 | 51.0 |
| 800 | 53.0 |
| 1000 | 55.0 |
| 1250 | 57.0 |
| 1600 | 60.0 |
| 2000 | 62.0 |
| 2500 | 63.0 |
| 3150 | 65.0 |
| 4000 | 67.0 |
| 5000 | 70.0 |

Aerated concrete blocks of 15 cm coated on one side

| | |
|---|---|
| 100 | 32.0 |
| 125 | 31.0 |
| 160 | 30.0 |
| 200 | 29.0 |
| 250 | 29.0 |
| 315 | 30.0 |
| 400 | 32.0 |
| 500 | 34.0 |
| 630 | 37.0 |
| 800 | 40.0 |
| 1000 | 42.0 |
| 1250 | 45.0 |
| 1600 | 48.0 |
| 2000 | 50.0 |
| 2500 | 52.0 |
| 3150 | 53.0 |
| 4000 | 52.0 |
| 5000 | 50.0 |

Aerated concrete blocks of  20 cm coated on one side

| | |
|---|---|
| 100 | 35.0 |
| 125 | 34.0 |
| 160 | 34.0 |
| 200 | 34.0 |
| 250 | 35.0 |
| 315 | 35.0 |
| 400 | 36.0 |

| | |
|---|---|
| 500 | 38.0 |
| 630 | 41.0 |
| 800 | 44.0 |
| 1000 | 46.0 |
| 1250 | 48.0 |
| 1600 | 50.0 |
| 2000 | 52.0 |
| 2500 | 53.0 |
| 3150 | 53.0 |
| 4000 | 52.0 |
| 5000 | 52.0 |

Aerated concrete blocks of 25 cm coated on one side

| | |
|---|---|
| 100 | 38.0 |
| 125 | 37.0 |
| 160 | 36.0 |
| 200 | 37.0 |
| 250 | 39.0 |
| 315 | 40.0 |
| 400 | 41.0 |
| 500 | 42.0 |
| 630 | 45.0 |
| 800 | 48.0 |
| 1000 | 50.0 |
| 1250 | 52.0 |
| 1600 | 53.0 |
| 2000 | 54.0 |
| 2500 | 52.0 |
| 3150 | 51.0 |
| 4000 | 53.0 |
| 5000 | 55.0 |

Hollow bricks of 10 cm coated on one side

| | |
|---|---|
| 100 | 37.0 |
| 125 | 36.0 |
| 160 | 35.0 |
| 200 | 33.0 |
| 250 | 32.0 |
| 315 | 32.0 |
| 400 | 33.0 |
| 500 | 35.0 |
| 630 | 37.0 |
| 800 | 39.0 |
| 1000 | 41.0 |
| 1250 | 43.0 |
| 1600 | 45.0 |
| 2000 | 47.0 |
| 2500 | 49.0 |
| 3150 | 50.0 |
| 4000 | 50.0 |
| 5000 | 48.0 |

Hollow bricks of 12 cm coated on one side

| | |
|---|---|
| 100 | 38.0 |

| | |
|---|---|
| 125 | 38.0 |
| 160 | 35.0 |
| 200 | 33.0 |
| 250 | 32.0 |
| 315 | 32.0 |
| 400 | 33.0 |
| 500 | 35.0 |
| 630 | 37.0 |
| 800 | 39.0 |
| 1000 | 41.0 |
| 1250 | 43.0 |
| 1600 | 45.0 |
| 2000 | 47.0 |
| 2500 | 49.0 |
| 3150 | 50.0 |
| 4000 | 50.0 |
| 5000 | 48.0 |

Hollow bricks of 15 cm coated on one side

| | |
|---|---|
| 100 | 41.0 |
| 125 | 40.0 |
| 160 | 38.0 |
| 200 | 35.0 |
| 250 | 35.0 |
| 315 | 37.0 |
| 400 | 39.0 |
| 500 | 41.0 |
| 630 | 43.0 |
| 800 | 45.0 |
| 1000 | 47.0 |
| 1250 | 49.0 |
| 1600 | 50.0 |
| 2000 | 51.0 |
| 2500 | 52.0 |
| 3150 | 52.0 |
| 4000 | 51.0 |
| 5000 | 50.0 |

Hollow bricks of 20 cm coated on one side

| | |
|---|---|
| 100 | 42.0 |
| 125 | 44.0 |
| 160 | 46.0 |
| 200 | 45.0 |
| 250 | 44.0 |
| 315 | 44.0 |
| 400 | 47.0 |
| 500 | 48.0 |
| 630 | 49.0 |
| 800 | 50.0 |
| 1000 | 52.0 |
| 1250 | 53.0 |
| 1600 | 54.0 |
| 2000 | 56.0 |
| 2500 | 56.0 |

| | |
|---|---|
| 3150 | 55.0 |
| 4000 | 52.0 |
| 5000 | 48.0 |

Perforated bricks of 22 cm coated on one side

| | |
|---|---|
| 100 | 41.0 |
| 125 | 40.0 |
| 160 | 39.0 |
| 200 | 43.0 |
| 250 | 46.0 |
| 315 | 49.0 |
| 400 | 51.0 |
| 500 | 53.0 |
| 630 | 54.0 |
| 800 | 55.0 |
| 1000 | 56.0 |
| 1250 | 56.0 |
| 1600 | 57.0 |
| 2000 | 58.0 |
| 2500 | 59.0 |
| 3150 | 60.0 |
| 4000 | 61.0 |
| 5000 | 62.0 |

Solid bricks 11 cm

| | |
|---|---|
| 100 | 36.0 |
| 125 | 37.0 |
| 160 | 38.0 |
| 200 | 38.0 |
| 250 | 36.0 |
| 315 | 35.0 |
| 400 | 36.0 |
| 500 | 39.0 |
| 630 | 42.0 |
| 800 | 45.0 |
| 1000 | 48.0 |
| 1250 | 51.0 |
| 1600 | 54.0 |
| 2000 | 56.0 |
| 2500 | 58.0 |
| 3150 | 60.0 |
| 4000 | 61.0 |
| 5000 | 62.0 |

Solid bricks 22 cm

| | |
|---|---|
| 100 | 49.0 |
| 125 | 48.0 |
| 160 | 47.0 |
| 200 | 47.0 |
| 250 | 48.0 |
| 315 | 50.0 |
| 400 | 52.0 |
| 500 | 54.0 |
| 630 | 56.0 |

| | |
|---|---|
| 800 | 58.0 |
| 1000 | 60.0 |
| 1250 | 62.0 |
| 1600 | 64.0 |
| 2000 | 66.0 |
| 2500 | 67.0 |
| 3150 | 68.0 |
| 4000 | 69.0 |
| 5000 | 70.0 |

Single window , double glazing : Rw + Ctr = 29 dB

| | |
|---|---|
| 100 | 26.0 |
| 125 | 26.0 |
| 160 | 25.0 |
| 200 | 15.0 |
| 250 | 25.3 |
| 315 | 28.0 |
| 400 | 30.5 |
| 500 | 31.0 |
| 630 | 33.0 |
| 800 | 36.0 |
| 1000 | 37.0 |
| 1250 | 38.5 |
| 1600 | 40.0 |
| 2000 | 39.0 |
| 2500 | 37.0 |
| 3150 | 33.0 |
| 4000 | 35.0 |
| 5000 | 38.0 |

Single window , double glazing : Rw + Ctr = 31 dB

| | |
|---|---|
| 100 | 26.0 |
| 125 | 26.0 |
| 160 | 25.0 |
| 200 | 18.0 |
| 250 | 27.0 |
| 315 | 32.0 |
| 400 | 33.0 |
| 500 | 35.0 |
| 630 | 37.0 |
| 800 | 38.0 |
| 1000 | 38.0 |
| 1250 | 38.7 |
| 1600 | 40.0 |
| 2000 | 39.0 |
| 2500 | 37.0 |
| 3150 | 36.0 |
| 4000 | 38.0 |
| 5000 | 43.0 |

Single window , double glazing : Rw + Ctr = 34 dB

| | |
|---|---|
| 100 | 28.0 |
| 125 | 28.0 |
| 160 | 26.3 |

| | |
|---|---|
| 200 | 23.5 |
| 250 | 27.0 |
| 315 | 32.0 |
| 400 | 33.0 |
| 500 | 35.0 |
| 630 | 37.0 |
| 800 | 38.0 |
| 1000 | 38.0 |
| 1250 | 38.7 |
| 1600 | 40.2 |
| 2000 | 40.7 |
| 2500 | 40.0 |
| 3150 | 39.8 |
| 4000 | 42.0 |
| 5000 | 45.0 |

Single window , double laminated glazing : Rw + Ctr = 38 dB

| | |
|---|---|
| 100 | 30.0 |
| 125 | 30.0 |
| 160 | 30.0 |
| 200 | 30.0 |
| 250 | 37.0 |
| 315 | 39.0 |
| 400 | 40.0 |
| 500 | 41.0 |
| 630 | 41.0 |
| 800 | 40.0 |
| 1000 | 39.0 |
| 1250 | 40.0 |
| 1600 | 42.0 |
| 2000 | 44.0 |
| 2500 | 45.0 |
| 3150 | 42.5 |
| 4000 | 45.7 |
| 5000 | 48.0 |

Door solid core : Rw + C = 27 dB

| | |
|---|---|
| 100 | 22.0 |
| 125 | 24.0 |
| 160 | 26.0 |
| 200 | 28.0 |
| 250 | 30.0 |
| 315 | 31.0 |
| 400 | 31.0 |
| 500 | 31.0 |
| 630 | 29.0 |
| 800 | 28.0 |
| 1000 | 28.0 |
| 1250 | 26.0 |
| 1600 | 25.0 |
| 2000 | 25.0 |
| 2500 | 27.0 |
| 3150 | 29.0 |
| 4000 | 31.0 |

| | |
|---|---|
| 5000 | 33.0 |

Alveolar door for indoor distribution: Rw + C = 22 dB

| | |
|---|---|
| 100 | 20.0 |
| 125 | 21.0 |
| 160 | 22.0 |
| 200 | 23.0 |
| 250 | 23.0 |
| 315 | 24.0 |
| 400 | 24.0 |
| 500 | 24.0 |
| 630 | 24.0 |
| 800 | 24.0 |
| 1000 | 24.0 |
| 1250 | 23.0 |
| 1600 | 23.0 |
| 2000 | 22.0 |
| 2500 | 21.0 |
| 3150 | 20.0 |
| 4000 | 20.0 |
| 5000 | 21.0 |

Landing door : Rw + C = 38 dB

| | |
|---|---|
| 100 | 28.0 |
| 125 | 26.0 |
| 160 | 26.5 |
| 200 | 27.0 |
| 250 | 28.3 |
| 315 | 30.0 |
| 400 | 34.0 |
| 500 | 37.0 |
| 630 | 40.0 |
| 800 | 42.0 |
| 1000 | 42.0 |
| 1250 | 42.0 |
| 1600 | 42.0 |
| 2000 | 41.0 |
| 2500 | 40.0 |
| 3150 | 38.0 |
| 4000 | 40.3 |
| 5000 | 42.0 |

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# ALGORITHM SHEET Glare Module

MULTILIGHT

Glare Module for Multi-physics Building Simulation

August. 2014 version 1.0

CEA-INES
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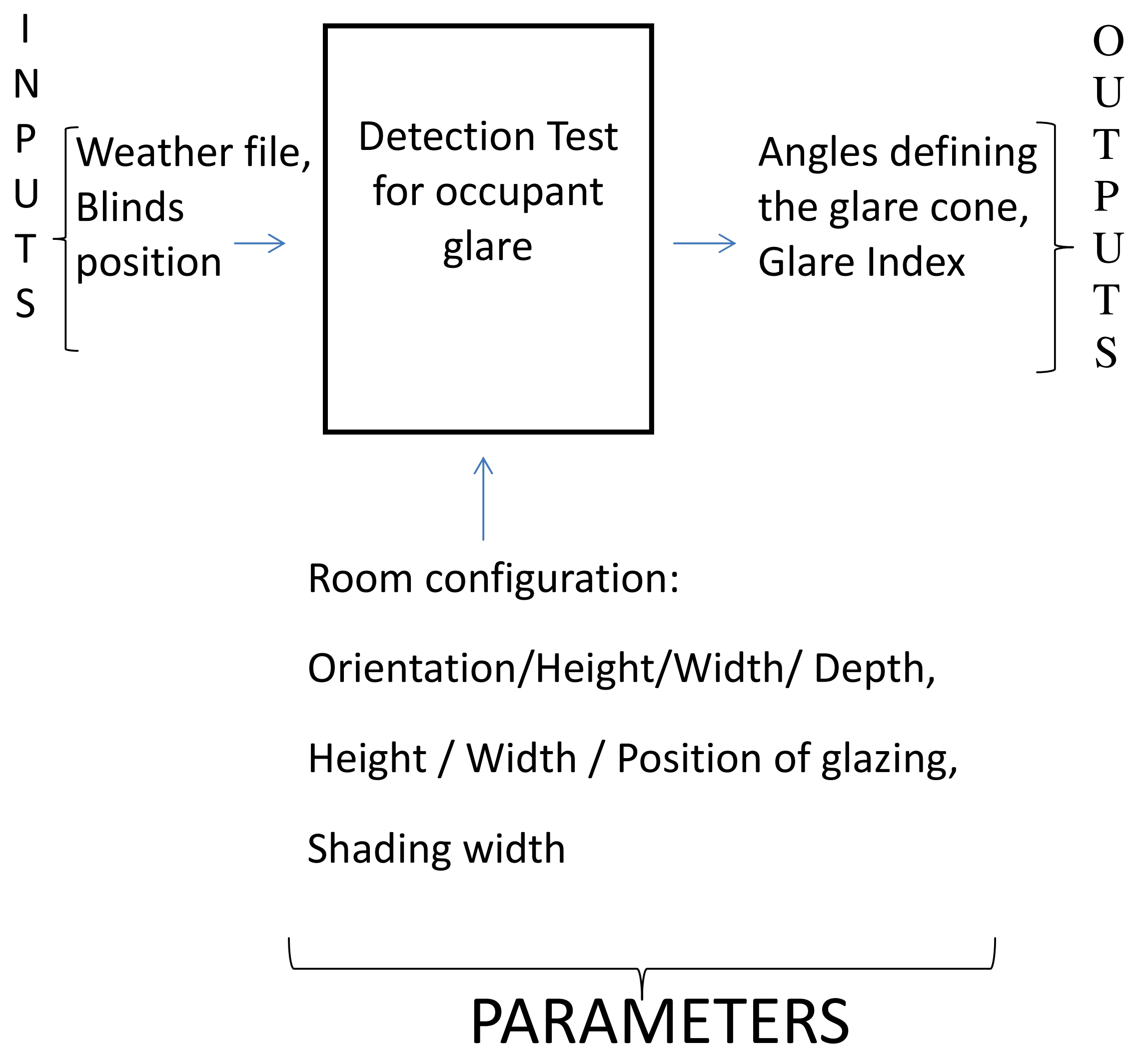
**1. Model description**



## 2. Nomenclature

| | Description | *Units* | *min* | *max* |
|---|---|---|---|---|
| **Input variables** | | | | |
| **Weather** | | | | |
| $a_s$ | Angle between the solar ray projection on the ground and the normal to the glazing | ° | | |
| $h_s$ | Solar height | ° | | |
| BP | Blind position | Open / 50% closed | | |
| **Parameters** | | | | |
| **Room configuration** | | | | |
| $D_r$ | Room depth | *m* | | |
| $W_r$ | Room width | *m* | | |
| $H_r$ | Room ceiling height | *m* | | |
| **Opening configuration** | | | | |
| $W_g$ | Glazing width | *m* | | |
| $H_g$ | Glazing height | *m* | | |
| $y_A$ | Coordinate 2 of A in (0 x y z) | *m* | | |
| $y_B$ | Coordinate 2 of B in (0 x y z) | *m* | | |
| $z_D$ | Coordinate 3 of D in (0 x y z) | *m* | | |
| $y_E$ | Coordinate 2 of E in (0 x y z) | *m* | | |
| $x_P$ | Coordinate 1 of P in (0 x y z) | *m* | | |
| $y_P$ | Coordinate 2 of P in (0 x y z) | *m* | | |
| $z_P$ | Coordinate 3 of P in (0 x y z) | *m* | | |
| **Shading configuration** | | | | |
| $W_s$ | Shading width | *m* | | |
| **Output variables** | | | | |
| $\theta_1$ | Horizontal angle 1 of the glare cone | ° | | |
| $\theta_2$ | Horizontal angle 2 of the glare cone | ° | | |
| $\beta$ | Vertical angle of the glare cone | ° | | |
| GI | Glare Index | *Yes/No* | | |

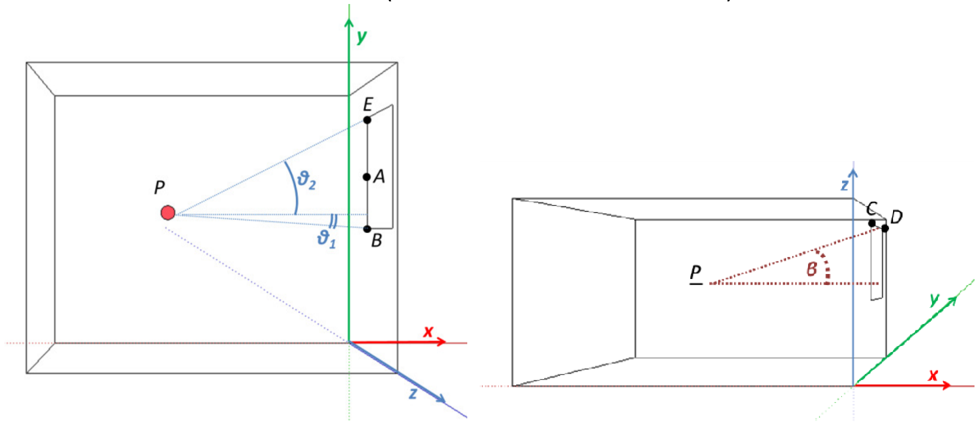
## 3. Model description

### Occupant glare detection test

The aim of the calculation model below is to determine if the occupant placed at the office centre, facing the opening, has to undergo glare or not.

The occupant will be dazzled when the sun is in the “glare cone”; this cone angle is delimited by two boundaries: a "vertical" angle β and a "horizontal" angle θ.

The user will be dazzled if the solar radiation (i.e. solar altitude and azimuth) enters the cone.




*« Horizontal » angle ϑ*

A : Point in the middle of the window bottom ($x_A$, $y_A$, $z_A$).

P : Occupant position ($x_P$, $y_P$, $z_P$) – P is placed at the occupant eye level, in the middle of the room, 1.2m above the ground.

$a_s$ : Angle between the projection of the solar radius on the ground and the normal to the glass opening.

$h_s$ : Height of the sun.

$$\tan\theta_1 = \frac{y_P - y_B}{|x_P|}$$

With: $y_P = \frac{W_r}{2}$

$$y_B = y_A - \frac{W_g}{2} = \frac{W_r}{2} - \frac{W_g}{2}$$

$$|x_P| = \frac{D_r}{2} + W_s$$

$$\theta_1 = \tan^{-1}\left(\frac{W_g}{D_r + 2W_s}\right)$$

$$\tan\theta_2 = \frac{y_E - y_P}{|x_P|}$$

With: $y_E = y_A + \frac{W_g}{2} = \frac{W_r}{2} + \frac{W_g}{2}$

$$y_P = \frac{W_r}{2}$$

$$|x_P| = \frac{D_r}{2} + W_s$$

In our case (window centered on the facade), we have: $\theta_2 = \theta_1 = \tan^{-1}\left(\frac{L_f}{D_r + 2W_s}\right)$

The occupant will be dazzled if $|a_S| \leq \theta_1$.

*« Vertical » angle β*

$$\tan\beta = \frac{z_D - z_P}{|x_P|}$$

With: $z_D = z_A + H_g$ if blinds are open.

$z_D = z_A + \frac{H_g}{2}$ if blinds are 50% closed.

$$z_P = 1.2$$
$$|x_P| = \frac{D_r}{2} + W_s$$
There will be glare if $h_s \leq \beta$.

## 4. CODE

```
C     PARAMETERS
       DOUBLE PRECISION Za
       DOUBLE PRECISION Zp
       DOUBLE PRECISION Xp

C     INPUTS
       DOUBLE PRECISION Window_width
       DOUBLE PRECISION Wj
       DOUBLE PRECISION Wc
       DOUBLE PRECISION Window_height
       DOUBLE PRECISION Zenith
       DOUBLE PRECISION Azimuth
       DOUBLE PRECISION Orientation

C    OUTPUTS
       DOUBLE PRECISION Ebloui

C    INTERMEDIATE VARIABLES
       DOUBLE PRECISION Pi, beta_sup, beta_inf, theta_sup, theta_inf
       DOUBLE PRECISION hauteur_soleil, azimuth_corr
pi=3.14159265358979323846

       !Angle par rapport à la verticale

       beta_sup=atan((Za+Window_height-Zp)/(Xp+Wc))*(180/pi)


       beta_inf=atan((Za+Window_height-Zp)/(Xp+Wc))*(180/pi)-
      &atan((Za-Zp)/(Xp+Wc))*(180/pi)

       !Angle par rapport à l'horizontale


       theta_sup=orientation+atan(Window_width*0.5/(Xp+Wj))*(180/pi)


       theta_inf=orientation-atan(Window_width*0.5/(Xp+Wj))*(180/pi)

       ! Hauteur du soleil

       hauteur_soleil=90-Zenith

       ! Azimuth Corrected

       Azimuth_corr=Azimuth+180


         ! Calculs éblouissement


          if (beta_sup .lt. 0) then

             Ebloui=0
```

```
    else

       if (hauteur_soleil .eq. 0)  then

         Ebloui=0

       else

           if (Zp .gt. Za) then


               if ((hauteur_soleil .lt. beta_sup) .and.
&(Azimuth_corr .gt. theta_inf) .and.
&(Azimuth_corr .lt. theta_sup)) then

               Ebloui=1

               else

               Ebloui=0
               end if
           else

               if ((hauteur_soleil .lt. beta_inf) .and.
&(Azimuth_corr .gt. theta_inf) .and.
&(Azimuth_corr .lt. theta_sup)) then

               Ebloui=1

               else

               Ebloui=0

               end if

           end if
    end if
    end if
```

# ALGORITHM SHEET Natural Lighting Module

MULTILIGHT

Natural Lighting Module for Multi-physics Building Simulation

August. 2014 version 1.0

CEA-INES
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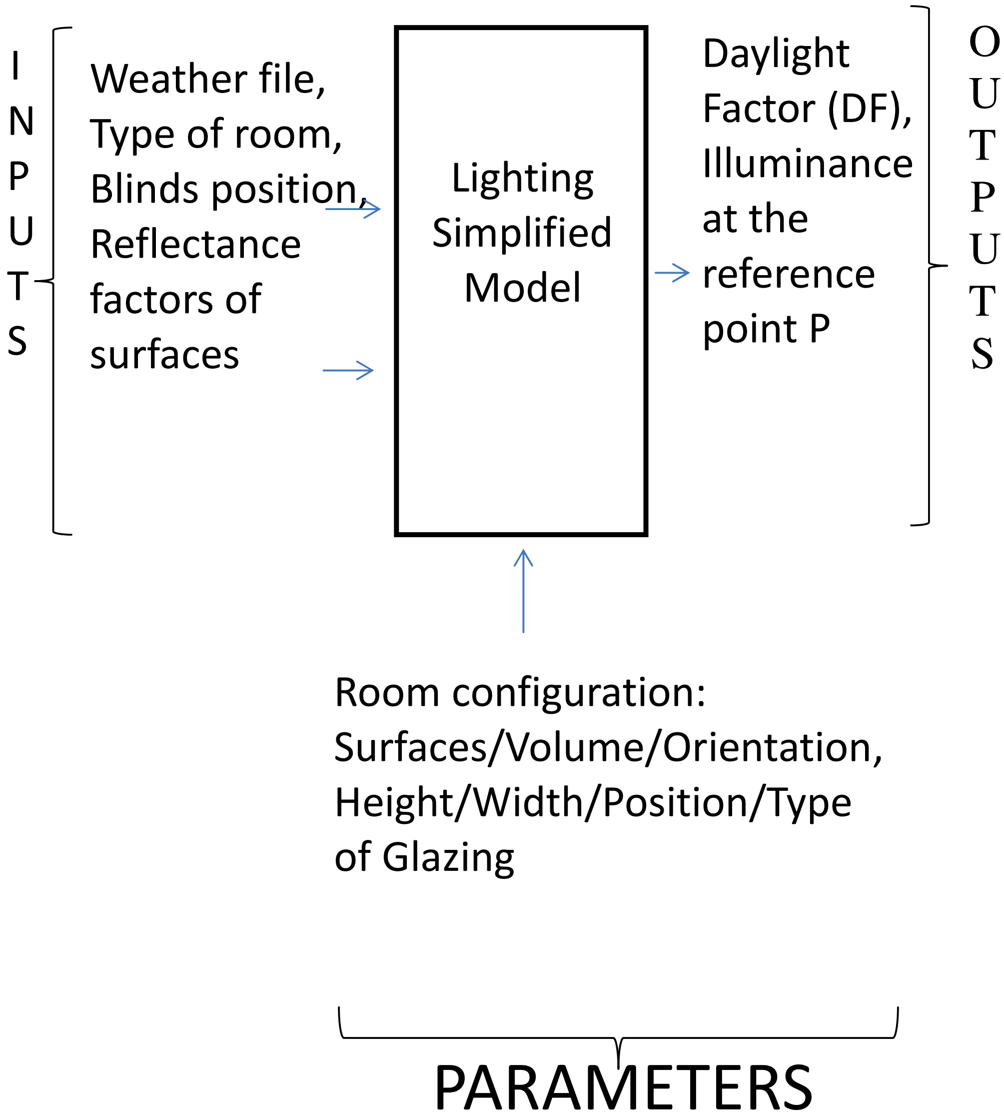
1. **MODEL description**



## 2. Nomenclature

| | Description | *Units* | *min* | *max* |
|---|---|---|---|---|
| **Input variables** | | | | |
| BP | Blind position | *Open / 50% closed* | | |
| z | Site altitude | *m* | | |
| $h_s$ | Solar height | ° | | |
| G | Global Horizontal Irradiance | *W/m²* | | |
| $D_h$ | Horizontal Diffuse Irradiance | *W/m²* | | |
| $I_0$ | Extra-terrestrial Normal Incidence Irradiance | *W/m²* | | |
| I | Normal Incidence Direct Irradiance | *W/m²* | | |
| $T_d$ | Surface Dew Point Temperature | *°C* | | |
| **Parameters** | | | | |
| **Room configuration** | | | | |
| $D_r$ | Room depth | *m* | | |
| $W_r$ | Room width | *m* | | |
| $H_r$ | Room ceiling height | *m* | | |
| $H_{strip}$ | Height between the top of the window and the room ceiling | *m* | | |
| A | Total area of the inner walls (floor, walls and ceiling, including openings) | *m²* | | |
| $z_D$ | Coordinate 3 of D in (0 x y z) | *m* | | |
| $z_E$ | Coordinate 3 of E in (0 x y z) | *m* | | |
| $z_P$ | Coordinate 3 of P in (0 x y z) | *m* | | |
| R | Average weighted reflection factor of the inner walls (floor, walls and ceiling, including openings) | | *0* | *1* |
| $R_{FW}$ | Average weighted (depending on surfaces) reflection factor of the ground and surfaces of walls located below the opening center (with exclusion of the wall containing the opening) | | *0* | *1* |
| $R_{CW}$ | Average weighted (depending on surfaces) reflection factor of the ceiling and surfaces of walls above the opening center (with exclusion of the wall containing the opening) | | *0* | *1* |
| $R_{ground}$ | Ground reflection coefficient | | *0* | *1* |
| $R_{walls}$ | Walls reflection coefficient | | *0* | *1* |
| $R_{ceiling}$ | Ceiling reflection coefficient | | *0* | *1* |
| $S_{tot\ FW}$ | Surfaces of ground and walls located below the opening center (with exclusion of the wall containing the opening) | *m²* | | |
| $S_{tot\ CW}$ | Surfaces of ceiling and walls above the opening center (with exclusion of the wall containing the opening) | *m²* | | |
| $W_{case\ x}$ | Calculation depth for the daylight factor which takes into account: the shading depth and the reference point P position | *m* | | |
| **Opening configuration** | | | | |
| LT | Glazing lighting transmission | | | |
| $A_w$ | Glazing surface | *m²* | | |
| $H_g$ | Glazing height | *m* | | |
| $W_g$ | Glazing width | *m* | | |

| | | | | |
|---|---|---|---|---|
| $k_1$ | Reduction factor (of DF) related to the glazing light transmission | *%* | | |
| $k_2$ | Reduction factor (of DF) related to the opaque parts of windows | *%* | | |
| $k_3$ | Reduction factor (of DF) related to the glazing dust/dirt | *%* | | |
| **Opening configuration case 1** | | | | |
| $L_b$ and $L_d$ | Glazing width lying to the right of the reference point projection on the façade | *m* | | |
| $H_{bd}$ | Distance between the glazing top and the reference point projection on the façade | *m* | | |
| $H_d$ | Distance between the glazing bottom and the reference point projection on the façade | *m* | | |
| **Opening configuration case 2** | | | | |
| $L_b$ et $L_d$ | Glazing width lying to the right of the reference point projection on the façade | *m* | | |
| $H_b$ | Distance between the glazing top and the reference point projection on the façade | *m* | | |
| $H_d$ | Distance between the glazing bottom and the reference point projection on the façade | *m* | | |
| **External configuration** | | | | |
| $W_s$ | Shading width | *m* | | |
| C | Coefficient depending on external obstructions | | | |
| **Weather data** | | | | |
| Ω | Atmospheric Precipitable Water | *cm* | | |
| $\theta_Z$ | Solar Zenith Angle | *Rad/°* | | |
| $I_G$ | Global Horizontal Illuminance | *Lux* | | |
| Δ | Sky brightness | | | |
| m | Relative optical mass | | | |
| ε | Sky clearness | | | |
| $a_i$, $b_i$, $c_i$, $d_i$ | Coefficients related to ε | | | |
| **Output variables** | | | | |
| *c* | Correction factor | | | |
| $D_c$ | Direct component of DF | *%* | | |
| $D_e$ | External component of DF | *%* | | |
| $D_i$ | Internal component of DF | *%* | | |
| DF | Daylight Factor | *%* | *0* | *100* |
| E | Illuminance at reference point P | *Lux* | | |

## 3. MODEL description

The Daylight Factor (DF) at a selected point of a space is determined by the split flux methods.
In our case, the calculation will be carried out in the center of the room, at the work plan level (i.e. 80cm).
The calculation allows us to determine separately the three components of the daylight factor:
- Direct (step 1)
- External Reflected (step 2)
- Internal Reflected (step 3).

$$DF = c\,(D_c + D_e + D_i)$$

With: c: the correction factor which takes into account the glazing type, the windows cleanliness, the frame size.

### Calculation of the direct component (Dc)

The principle is to use aspect ratios h/d and W/d (Fig. 1) to perform an analytical calculation of the respective contributions of the different portions of the opening.

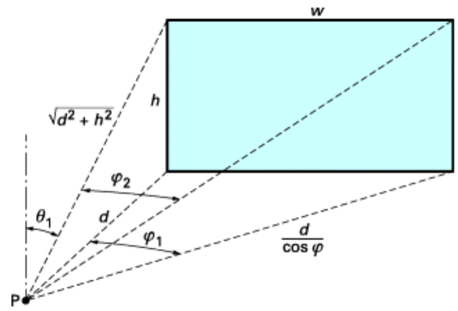



**Fig. 1 : Angle system settings**

Interior illuminance at a point P, located perpendicular to the lower corner of a vertical rectangular opening is defined by:

$$E_P = \oint_0^{\varphi_1} \left( \oint_{\theta_1(\varphi)}^{\frac{\pi}{2}} L\,(\theta,\ \varphi\,)(\cos\theta \sin\theta) d\theta \right) d\varphi \qquad \text{(Eq.1)}$$

With the luminance $L_\theta$ given, in the case of a CIE overcast sky, by the equation:

$$L_\theta = \frac{1}{3} L_z (1\ + 2\ \sin\theta) \qquad \text{(Eq.2)}$$

$L_\vartheta$ : luminance at angular height θ above the horizon

$L_z$ : sky luminance at zenith.

For a CIE type of sky, the illuminance E on the horizontal plane without any obstruction is expressed in Lux for a zenith luminance $L_z$ expressed in candela/m²:

$$E\ = \frac{7\pi\, L_Z}{9} \qquad \text{(Eq.3)}$$

The double integral of equation 1, after division by the illumination away from any obstruction (equation 3), provides the direct component of DF, at point P considered:

$$D_C = \frac{3}{14\pi}\tan^{-1}\left(\frac{W}{d}\right) - \frac{3}{14\pi}\frac{1}{\sqrt{\left(\frac{h}{d}\right)^2+1}}\tan^{-1}\frac{\frac{W}{d}}{\sqrt{\left(\frac{h}{d}\right)^2+1}} + \frac{2}{7\pi}\sin^{-1}\left(\frac{\frac{W\,h}{d\,d}}{\sqrt{1+\left(\frac{W}{d}\right)^2}\sqrt{1+\left(\frac{h}{d}\right)^2}}\right) - \frac{2}{7\pi}\left(\frac{\frac{W\,h}{d\,d}}{\left(\left(\frac{h}{d}\right)^2+1\right)\sqrt{1+\left(\frac{h}{d}\right)^2+\left(\frac{W}{d}\right)^2}}\right)$$

(Eq.4)

Depending on the position of the glass surface and of the reference point P, the equation is applied to each wall (with a glass surface) of the studied room: by addition (glass area) and subtraction (opaque surface). Thus, the contribution of the opening is determined; the contributions of the different windows are added at the reference point considered.

Fig. 2 shows how to determine the direct component of DF in the case of a reference point P offset from the opening. In this case,

$$D_C(Q) = D_C(PQRS) - D_C(PR) - D_C(RS) + D_C(R) \qquad \text{(Eq.5)}$$

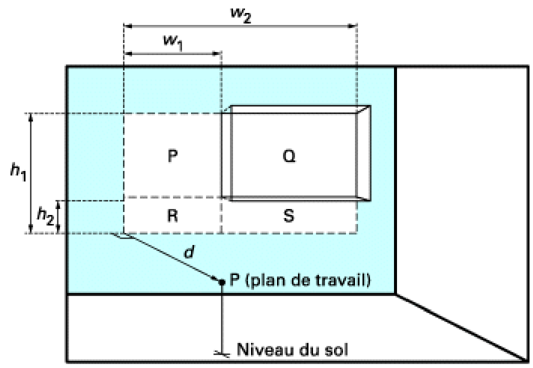


Fig. 2 : Example of direct component calculation for a particular case

➔ Calculation of the direct component for test cases defined:

Two types of offices have been defined:

- 1 office with dimensions 2.5 * 5 * 2.5m (Ceiling Height)
- 1 office with dimensions 4 * 4 * 2.5m (Ceiling Height)

Three glazing surfaces:

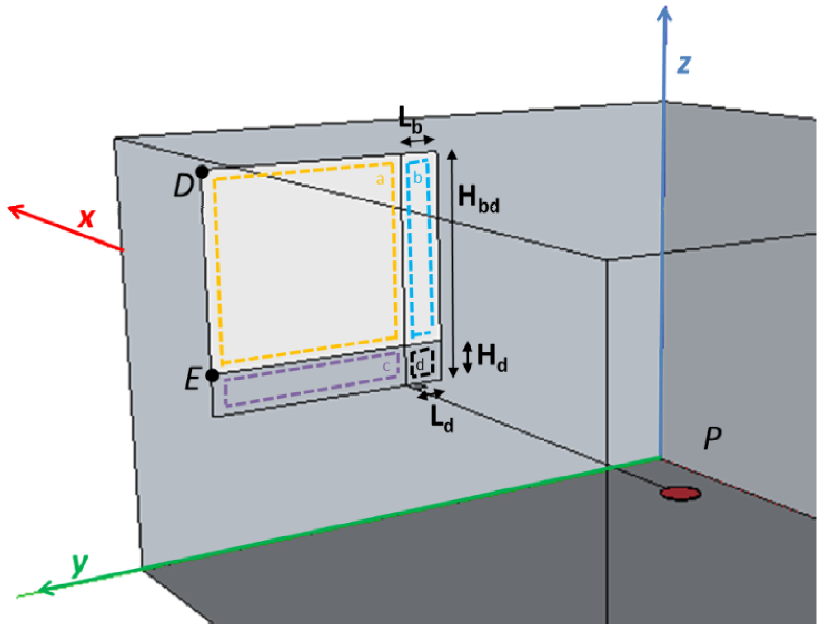
- 30% of glazing surface (1.4 * 1.4 ht) → Configuration 1
- 50% of glazing surface (2.1 * 1.6 ht) → Configuration 2
- 70% of glazing surface (2.5 * 1.75 ht) → Configuration 3

*IMPORTANT*
The windows are in the middle of the façade.
The upper edge of the glazing does not necessarily coincide with the top of the room.
The reference point P is the center of the room.

The two types of office and three windows configurations give us two cases of calculation explained below.

*Case 1*

The window bottom is located above or at the reference point level (i.e. 0.8m).
a and b are glazed surfaces; c and d opaque surfaces.




As well as for the specific case presented above (Figure 2 - Equation 5), for our case study 1, the direct component is expressed as follows:

$D_c\,(ab) = D_c\,(bd) - D_c\,(d) + D_c\,(ac) - D_c\,(c)$ (Eq.6a)

Moreover, in all three glazing configurations, the windows are in the middle of the façade ; then, we have: $D_c\,(ac) = D_c\,(bd)$ et $D_c\,(c) = D_c\,(d)$

$D_c\,(ab) = 2D_c\,(bd) - 2D_c\,(d)$ (Eq.6b)

$$D_C(bd) = \frac{3}{14\pi}\tan^{-1}\left(\frac{L_b}{W_{case1}}\right) - \frac{3}{14\pi}\frac{1}{\sqrt{\left(\frac{H_{bd}}{W_{case1}}\right)^2 + 1}}\tan^{-1}\frac{\frac{L_b}{W_{case1}}}{\sqrt{\left(\frac{H_{bd}}{W_{case1}}\right)^2 + 1}} + \frac{2}{7\pi}\sin^{-1}\left(\frac{\frac{L_b}{W_{case1}} \times \frac{H_{bd}}{W_{case1}}}{\sqrt{1 + \left(\frac{L_b}{W_{case1}}\right)^2}\sqrt{1 + \left(\frac{H_{bd}}{W_{case1}}\right)^2}}\right) - \frac{2}{7\pi}\left(\frac{\frac{L_b}{W_{case1}} \times \frac{H_{bd}}{W_{case1}}}{\left(\left(\frac{H_{bd}}{W_{case1}}\right)^2 + 1\right)\sqrt{1 + \left(\frac{H_{bd}}{W_{case1}}\right)^2 + \left(\frac{L_b}{W_{case1}}\right)^2}}\right)$$

With: $L_b = \frac{W_g}{2}$

$W_{case1} = \frac{D_r}{2} + W_s$

$H_{bd} = z_D - z_P$ If blinds are opened.

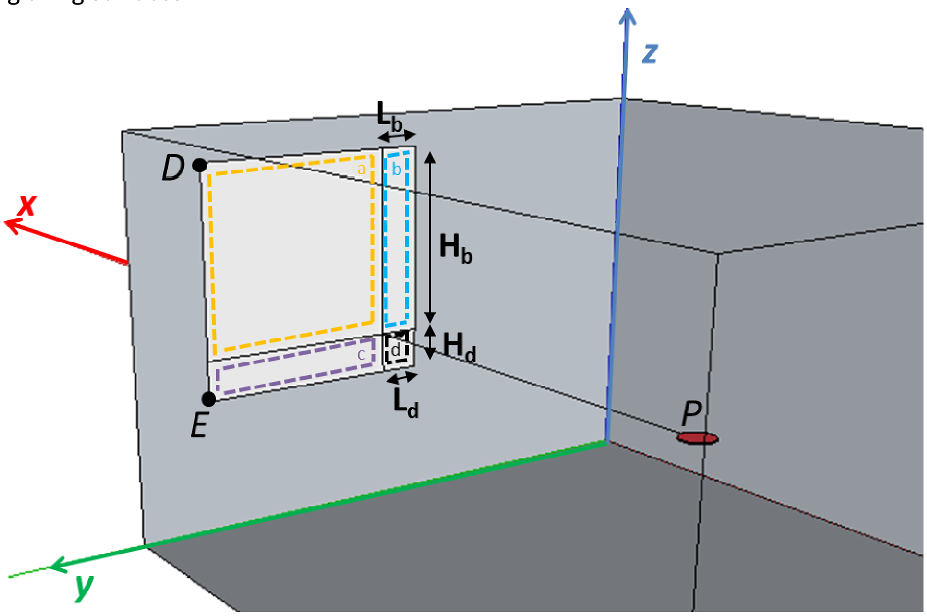
$H_{bd} = \frac{H_g}{2} + z_D - z_P$ If blinds are 50% closed.
$z_P = 0.8m.$

$$D_C(d) = \frac{3}{14\pi}\tan^{-1}\left(\frac{L_d}{W_{case1}}\right) - \frac{3}{14\pi}\frac{1}{\sqrt{\left(\frac{H_d}{W_{case1}}\right)^2 + 1}}\tan^{-1}\frac{\frac{L_d}{W_{case1}}}{\sqrt{\left(\frac{H_d}{W_{case1}}\right)^2 + 1}} + \frac{2}{7\pi}\sin^{-1}\left(\frac{\frac{L_d}{W_{case1}} \times \frac{H_d}{W_{case1}}}{\sqrt{1 + \left(\frac{L_d}{W_{case1}}\right)^2}\sqrt{1 + \left(\frac{H_d}{W_{case1}}\right)^2}}\right) - \frac{2}{7\pi}\left(\frac{\frac{L_d}{W_{cas1}} \times \frac{H_d}{W_{cas1}}}{\left(\left(\frac{H_d}{W_{case1}}\right)^2 + 1\right)\sqrt{1 + \left(\frac{H_d}{W_{case1}}\right)^2 + \left(\frac{L_d}{W_{case1}}\right)^2}}\right)$$

With: $L_d = \frac{W_g}{2}$
$W_{case1} = \frac{D_r}{2} + W_s$
$H_d = z_E - z_P$ and $z_P = 0.8m.$

These equations allow the calculation of the direct component of DF in the first case (case 1).

*Case 2*
The bottom of the window is below the reference point level (i.e. 0.8m).
a, b, c et d are glazing surfaces.




As well as for the particular case presented above (Figure 2 - Equation 5), for our case study 2, the direct component is expressed as follows:
$D_c$ (abcd) = $D_c$ (a) + $D_c$ (b) + $D_c$ (c) + $D_c$ (d) (Eq.7a)

With $D_c$ (a) = $D_c$ (b) et $D_c$ (c) = $D_c$ (d), because of the glazing position in the façade center.
Then, $D_c$ (abcd) = 2$D_c$ (b) + 2$D_c$ (d) (Eq.7b)

$$D_C(b) = \frac{3}{14\pi}\tan^{-1}\left(\frac{L_b}{W_{case2}}\right) - \frac{3}{14\pi}\frac{1}{\sqrt{\left(\frac{H_b}{W_{case2}}\right)^2+1}}\tan^{-1}\frac{\frac{L_b}{W_{case2}}}{\sqrt{\left(\frac{H_b}{W_{case2}}\right)^2+1}}$$
$$+\frac{2}{7\pi}\sin^{-1}\left(\frac{\frac{L_b}{W_{case2}}\times\frac{H_b}{W_{case2}}}{\sqrt{1+\left(\frac{L_b}{W_{case2}}\right)^2}\sqrt{1+\left(\frac{H_b}{W_{case2}}\right)^2}}\right)$$
$$-\frac{2}{7\pi}\left(\frac{\frac{L_b}{W_{case2}}\times\frac{H_b}{W_{case2}}}{\left(\left(\frac{H_b}{W_{case2}}\right)^2+1\right)\sqrt{1+\left(\frac{H_b}{W_{case2}}\right)^2+\left(\frac{L_b}{W_{case2}}\right)^2}}\right)$$

With: $L_b = \frac{W_g}{2}$

$W_{case2} = \frac{D_r}{2} + W_s$

$H_b = z_D - z_P$ If blinds are opened.

$H_b = z_D - \frac{H_g}{2} - z_P$ If blinds are 50% closed.

$z_P = 0.8m.$

$$D_C(d) = \frac{3}{14\pi}\tan^{-1}\left(\frac{L_d}{W_{case2}}\right) - \frac{3}{14\pi}\frac{1}{\sqrt{\left(\frac{H_d}{W_{case2}}\right)^2+1}}\tan^{-1}\frac{\frac{L_d}{W_{case2}}}{\sqrt{\left(\frac{H_d}{W_{case2}}\right)^2+1}}$$
$$+\frac{2}{7\pi}\sin^{-1}\left(\frac{\frac{L_d}{W_{case2}}\times\frac{H_d}{W_{case2}}}{\sqrt{1+\left(\frac{L_d}{W_{case2}}\right)^2}\sqrt{1+\left(\frac{H_d}{W_{case2}}\right)^2}}\right)$$
$$-\frac{2}{7\pi}\left(\frac{\frac{L_d}{W_{case2}}\times\frac{H_d}{W_{case2}}}{\left(\left(\frac{H_d}{W_{case2}}\right)^2+1\right)\sqrt{1+\left(\frac{H_d}{W_{case2}}\right)^2+\left(\frac{L_d}{W_{case2}}\right)^2}}\right)$$

With: $L_d = \frac{W_g}{2}$

$W_{case2} = \frac{D_r}{2} + W_s$

$H_d = z_P - z_E$ and $z_P = 0.8m.$

These equations allow the calculation of the direct component of DF in the second case (case 2).

Calculation of the external reflected component (De)

When natural light access is limited by external obstructions, it is necessary to calculate the external reflected component (De). Visible obstructions are considered from the reference point (P) such as sky parts with luminance corresponding to a fraction of the obstructed sky. The De component corresponding to the obstructed area is calculated in a first time as a direct component (Dc); it is then weighted by the surface average reflection factor forming the mask (Fig. 3).

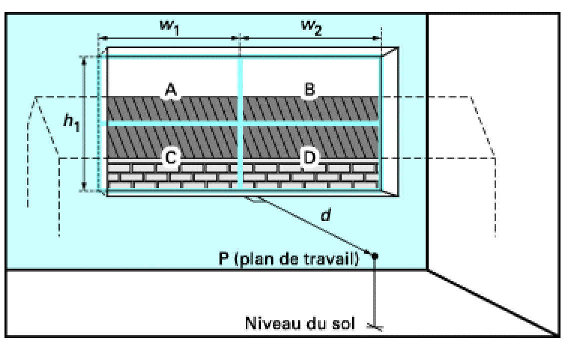



**Fig. 3 : Masked portion of sky (C and D) by the reflectance (%) of the corresponding surface**

The reflected external component (De) of the daylight factor is obtained, at point P, by weighting the luminance value of the masked portion of sky (C and D) by the reflectance (%) of the corresponding surface:

$D_e = CD \times \rho$ (Eq.8)

In our study, no distant mask is considered; so: $D_e = 0$.

## Calculation of the internal reflected component (Di)

Di is the amount of light reflected by the local inner walls decreases with the distance to the opening. In this method, it is considered that the average value of the internal reflected component follows the following empirical law in the largest part of the space: $D_i = (0.85 \times A_W) \times \frac{(C\,R_{FW} + 5\,R_{CW})}{A\,(1-R)}$ (Eq.9)

With:

- $A_W$ : Window surface (in m²)
  - $A_w = H_g \times W_g$

- C : Coefficient depending on external obstructions.

  We take the assumption of a continuous obstruction angular height W above the horizon (measured in the middle of the window)

  $C = 40 - \frac{W}{2}$ (Eq.10)
  - In our study cases, $C = 40$ (no obstructions).

- $R_{FW}$ : Weighted average reflection factor (depending on surfaces) of the ground and wall surfaces located below the opening middle (with the exclusion of the opening wall)

*If blinds are 100% opened*

$$R_{FW} = \frac{R_{sol} \times W_r \times D_r + R_{walls} \times \left(H_r - \frac{H_g}{2} - H_{strip}\right) \times (2D_r + W_r)}{S_{tot\ FW}}$$

With

$$S_{tot\ FW} = W_r \times D_r + \left(H_r - \frac{H_g}{2} - H_{strip}\right) \times (2D_r + W_r)$$
$$H_{strip} = H_r - z_D$$

*If blinds are 50% opened*

$$R_{FW} = \frac{R_{sol} \times W_r \times D_r + R_{walls} \times \left(H_r - \frac{3H_g}{4} - H_{strip}\right) \times (2D_r + W_r)}{S_{tot\ FW}}$$

With

$$S_{tot\ FW} = W_r \times D_r + \left(H_r - \frac{3H_g}{4} - H_{strip}\right) \times (2D_r + W_r)$$
$$H_{strip} = H_r - z_D$$

- $R_{CW}$ : Weighted average reflection factor (depending on surfaces), of the ceiling and wall surfaces located above the opening middle (with the exclusion of the opening wall)

*If blinds are 100% opened*

$$R_{CW} = \frac{R_{ceiling} \times W_r \times D_r + R_{walls} \times \left(\frac{H_g}{2} + H_{strip}\right) \times (2D_r + W_r)}{S_{tot\ CW}}$$

With

$$S_{tot\ CW} = W_r \times D_r + \left(\frac{H_g}{2} + H_{strip}\right) \times (2D_r + W_r)$$
$$H_{strip} = H_r - z_D$$

*If blinds are 50% opened*

$$R_{CW} = \frac{R_{ceiling} \times W_r \times D_r + R_{walls} \times \left(\frac{3H_g}{4} + H_{strip}\right) \times (2D_r + W_r)}{S_{tot\ CW}}$$

With

$$S_{tot\ CW} = W_r \times D_r + \left(\frac{3H_g}{4} + H_{strip}\right) \times (2D_r + W_r)$$
$$H_{strip} = H_r - z_D$$

- A : Inner walls total area (including floor, walls and ceiling, including openings) (in $m^2$)
    - $A = 2W_rD_r + 2H_rD_r + 2H_rW_r$

- R : Average weighted reflection factor (floor, walls and ceiling, including openings).
    - $R = \frac{R_{floor}\, W_r\, D_r + R_{ceiling}\, W_r\, D_r + R_{walls} \times \left(H_r \times (2D_r + 2W_r) - W_g \times H_g\right) + R_f\, W_g\, H_g}{A}$

*N.B.* The reflection coefficients of the walls are:

- Ceiling : 70%
- Walls : 50%
- Floor : 20%

## Calculation of the correction factor (c)

c is the correction factor which takes into account the glazing type, the windows cleanliness and the frame size.

For the c calculation, Belgian standard NBN L13-002 was taken as reference. This standard is much more accurate concerning the correction factor than the French standard NF EN 15193.

$$c = k_1 \times k_2 \times k_3$$

In our case,

- The glazing lighting transmission (LT) will be entered by the user. The reduction factor $k_1$ is related to the glazing transmission. The table below shows the correction factor value to be applied based on the known glazing transmission factor.

| Facteurs de transmission du vitrage à incidence normale $\tau_N$ | Facteurs moyens de transmission du vitrage $\tau = 0{,}995\ \tau_N - 0{,}035$ | $k_1$ |
|---|---|---|
| 0,90 | 0,86 (vitrage clair 2 à 3 mm) | 1,00 |
| 0,84 | 0,80 | 0,93 |
| 0,74 | 0,70 | 0,81 |
| 0,64 | 0,60 | 0,70 |
| 0,54 | 0,50 | 0,58 |
| 0,44 | 0,40 | 0,47 |
| 0,34 | 0,30 | 0,35 |

- The glazing cleanliness is considered with the attenuation coefficient $k_3$. The NBN L13-002 standard gives the correction factor values related to the dust to be taken into account depending on the room type and on the environment.

| Conditions extérieures | | Conditions intérieures | | Inclinaison du vitrage par rapport à l'horizontale | | |
|---|---|---|---|---|---|---|
| Localisation | Degré de salissement de la surface extérieure du vitrage | Nature de l'activité | Degré de salissement de la surface intérieure du vitrage | 0 à 30° | 45 à 60° | 75 à 90° |
| région rurale ou zone suburbaine | faible | propre | faible | 0.80 | 0.85 | 0.9 |
| | | sale | élevé | 0.55 | 0.60 | 0.7 |
| zone urbaine ou résidentielle | moyen | propre | faible | 0.70 | 0.75 | 0.8 |
| | | sale | élevé | 0.40 | 0.50 | 0.6 |
| zone industrielle | élevé | propre | faible | 0.55 | 0.60 | 0.7 |
| | | sale | élevé | 0.25 | 0.35 | 0.5 |

- The scale factor $k_2$ takes into account the opening proportional to the frame surface. This ratio value is generally of 70%. It can also be directly calculated.

## Evaluation of the indoor illuminance based on the DF

### Determination of the Global Horizontal Illuminance $I_G$

$I_G = G \times [a_i + b_i \times \Omega + c_i \times \cos\theta_Z + d_i \times \ln(\Delta)]$ (1) – Perez, R, et al. (1990)

With: $\Omega = e^{(0.07 \times T_d - 0.075)}$

$\theta_Z = (90 - h_s) \times \frac{2\pi}{360}$ (Avec $h_s$ en °)

$\Delta = \frac{Dh \times m}{I_0}$

With m by Kasten and Young (1989) – Approximation valid for z < 4000m.

$m = \left(1 - \frac{z}{10000}\right) \frac{1}{\cos(\theta_Z) + 0.50572 \times (96.07995^\circ - \theta_Z)^{-1.6364}}$

The coefficients $a_i$, $b_i$, $c_i$ and $d_i$ values are function of the sky brightness ε.

$\varepsilon = \frac{\frac{Dh + I}{Dh + 1.041 \times \theta_Z^3}}{1 + 1.041 \times \theta_Z^3}$

The ε calculation allows the identification of the studied sky clarity: from 1 to 8.

| ε between | ε category | Sky category |
|---|---|---|
| [1.000 – 1.065] | 1 | Overcast |
| [1.065 – 1.230] | 2 | |
| [1.230 – 1.500] | 3 | |
| [1.500 – 1.950] | 4 | |
| [1.950 – 2.800] | 5 | |
| [2.800 – 4.500] | 6 | |
| [4.500 – 6.200] | 7 | |
| [6.200 – MAX] | 8 | Clear |

Depending on the sky type, we would have the following coefficients values for $a_i$, $b_i$, $c_i$ et $d_i$.

| Category ε | $a_i$ | $b_i$ | $c_i$ | $d_i$ |
|---|---|---|---|---|
| 1 | 96.63 | -0.47 | 11.50 | -9.16 |
| 2 | 107.54 | 0.79 | 1.79 | -1.19 |
| 3 | 98.73 | 0.70 | 4.40 | -6.95 |
| 4 | 92.72 | 0.56 | 8.36 | -8.31 |
| 5 | 86.73 | 0.98 | 7.10 | -10.94 |
| 6 | 88.34 | 1.39 | 6.06 | -7.60 |
| 7 | 78.63 | 1.47 | 4.93 | -11.37 |
| 8 | 99.65 | 1.86 | -4.46 | -3.15 |

### Determination of the illuminance at the reference point P

$E = I_G \times DF$

## References

PEREZ, R, *et al*. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy*, 1990, vol. 44, no. 5, p. 271-289.

François BOUVIER, Gilles COURRET, Bernard PAULE, Eclairage Naturel. Techniques de l'Ingénieur, 2008, C3315.

Kasten, E, Young, A. T., 1989: Revised optical air mass tables and approximation formula. Appl. Opt., 28, 4735-4738.

# 4. CODE

```
C   PARAMETERS
    DOUBLE PRECISION Rsol_lum
    DOUBLE PRECISION Rmurs_lum
    DOUBLE PRECISION Rplafond_lum
    DOUBLE PRECISION Rfen_lum
    DOUBLE PRECISION TL
    DOUBLE PRECISION clear_glass
    DOUBLE PRECISION scale_factor
    DOUBLE PRECISION Zp

C   INPUTS
    DOUBLE PRECISION Td
    DOUBLE PRECISION I
    DOUBLE PRECISION Dh
    DOUBLE PRECISION G
    DOUBLE PRECISION p_water
    DOUBLE PRECISION Zenith
    DOUBLE PRECISION Z
    DOUBLE PRECISION Hf
    DOUBLE PRECISION Lf
    DOUBLE PRECISION Hr
    DOUBLE PRECISION Lr
    DOUBLE PRECISION Wr
    DOUBLE PRECISION Za
    DOUBLE PRECISION Ebloui
    DOUBLE PRECISION Wc

C   OUTPUTS
    DOUBLE PRECISION Etotal, FLJ

C   INTERMEDIATE VARIABLES
    DOUBLE PRECISION zenithrad, pi, m, epsilon, delta, ai, bi, ci, di

C   intermediate variables
    DOUBLE PRECISION Lb, Zd, Wcas1, hbd, hbd_ebloui, ld, hd
    DOUBLE PRECISION Wcas2, hb, hd_ebloui, Dcb
    DOUBLE PRECISION Stot_fw, Stot_cw, Stot_fw_ebloui, Stot_cw_ebloui
    DOUBLE PRECISION Rtot_lum, A, Aw, Rfw, Rcw, Dir
    DOUBLE PRECISION Dc, Dcd, h_bandeau, C, deg, E



! Il y a deux cas différents:
        ! Cas 1: Le bas de la fenêtre se situe au dessus ou au niveau du point de référence
        ! Cas 2: Le bas de la fenêtre se situe sous le niveau du point de référence

  ! Variables d'entrée / Paramètres de la composante directe

  ! Lf = Largeur de la fenêtre
  ! Wr = Profondeur de la pièce
```

```
! Wc = Profondeur de la casquette
! Zp = Hauteur du plan où va être calculé l'éclairage
! Zd = Distance entre l'arête supérieure et le plafond
! Ze = Distance entre l'arête inférieure et le sol
! Hf = Hauteur de la fenêtre
! Ebloui = Eblouissement
! pi = nombre pi
! Dcb = Partie de la composante directe qui est liée à la lumière qui arrive au dessus du point p
! Dcd = Partie de la composante directe qui est liée à la lumière qui arrive en dessous du point p
! corr=correction due aux vitrages, propreté des fenêtres...

  ! COMPOSANTE REFLECHIE INTERNE

! Paramètres / Variables de la composante réfléchie interne

! Aw = Surface de la fenêtre
! C = Coefficient dépendant des obtructions extérieures
! R's_lum = Coefficients de réflexion (pourcentage)
! Rcw = Coefficient moyen pondéré des surfaces situées au dessus du centre de l'ouverture
! Rfw = Coefficient moyen pondéré des surfaces situées en dessous du centre de l'ouverture
! Lr = largeur de la pièce
! Rtot_lum = Coefficient moyen pondéré (y compris la surface vitrée)
! Ap = Surface des parois intérieures (y compris la surface vitrée)


! Calculs Composante directe

 ! Cas 1
  pi=3.141592
  Lb=Lf*0.5
  Zd=Za+hf
  Wcas1=Wr*0.5+Wc
  hbd=Zd-Zp
  hbd_ebloui=Zd-0.5*hf-Zp
  Ld=Lf*0.5
  hd=Za-Zp
  deg=180/pi

 ! Cas 2
  Wcas2=0.5*Wr+Wc
  hb=Zd-Zp
  hd_ebloui=Zd-0.5*hf-Zp



 ! Cas 1

  IF (Za .ge. Zp) THEN

   IF (Ebloui .eq. 0) THEN

   Dcb=((3.0/(14.0*pi))*atan(Lb/Wcas2))*deg-((3.0/(14.0*pi))*
 &(1/sqrt((Hbd/Wcas1)**2+1))*atan((Lb/Wcas2)/
 &(sqrt((Hbd/Wcas1)**2+1)))*deg)+((2.0/(7.0*pi))*asin((((Lb*Hbd)/
```

```
&(Wcas1**2))/(sqrt((1+(Lb/Wcas1)**2)*(1+(Hbd/Wcas1)**2)))))*deg)-
&((2.0/(7.0*pi))*(((Lb*Hbd)/(Wcas1**2))/(((Hbd/Wcas1)**2+1)*
&sqrt(1+(Hbd/Wcas1)**2+(Lb/Wcas1)**2))))

  ELSE

  Dcb=((3.0/(14.0*pi))*atan(Lb/Wcas2))*deg-((3.0/(14.0*pi))*
&(1/sqrt((Hbd_ebloui/Wcas1)**2+1))*atan((Lb/Wcas1)/(sqrt
&((Hbd_ebloui/Wcas1)**2+1)))*deg)+((2.0/(7.0*pi))*asin
&((((Lb*Hbd_ebloui)/(Wcas1**2))/(sqrt((1+(Lb/Wcas1)**2)*
&(1+(Hbd_ebloui/Wcas1)**2)))))*deg)-((2.0/(7.0*pi))*
&(((Lb*Hbd_ebloui)/(Wcas1**2))/(((Hbd_ebloui/Wcas1)**2+1)*
&sqrt(1+(Hbd_ebloui/Wcas1)**2+(Lb/Wcas1)**2))))

  END IF

  Dcd=((3.0/(14.0*pi))*atan(Ld/Wcas1))*deg-deg*((3.0/(14.0*pi))*
&(1/sqrt((Hd/Wcas1)**2+1))*atan((Ld/Wcas1)/(sqrt
&((Hd/Wcas1)**2+1))))+((2.0/(7.0*pi))*asin(((Ld*Hd)/(Wcas1**2))/
&(sqrt((1+(Ld/Wcas1)**2)*(1+(Hd/Wcas1)**2))))*deg)-(2.0/(7.0*pi))*
&(((Ld*Hd)/(Wcas1**2))/(((Hd/Wcas1)**2+1)*sqrt((1+(Hd/Wcas1)**2)*
&(1+(Ld/Wcas1)**2))))

  Dc=2*Dcb-2*Dcd

! Cas 2

 ELSE

  IF (Ebloui .eq. 0) THEN

  Dcb=((3.0/(14.0*pi))*atan(Lb/Wcas2))*deg-((3.0/(14.0*pi))*
&(1/sqrt((Hb/Wcas2)**2+1))*atan((Lb/Wcas2)/
&(sqrt((Hb/Wcas2)**2+1)))*deg)+((2.0/(7.0*pi))*asin((((Lb*Hb)/
&(Wcas2**2))/(sqrt((1+(Lb/Wcas2)**2)*(1+(Hb/Wcas2)**2)))))*deg)-
&((2.0/(7.0*pi))*(((Lb*Hb)/(Wcas2**2))/(((Hb/Wcas2)**2+1)*sqrt
&(1+(Hb/Wcas2)**2+(Lb/Wcas2)**2))))

  ELSE

  Dcb=((3.0/(14.0*pi))*atan(Lb/Wcas2))*deg-((3.0/(14.0*pi))*
&(1/sqrt((Hd_ebloui/Wcas2)**2+1))*atan((Lb/Wcas2)/(sqrt((Hd_ebloui/
&Wcas2)**2+1)))*deg)+((2.0/(7.0*pi))*asin((((Lb*Hd_ebloui)/
&(Wcas2**2))/(sqrt((1+(Lb/Wcas2)**2)*(1+(Hd_ebloui/Wcas2)**2)))))*
&deg)-((2.0/(7.0*pi))*(((Lb*Hd_ebloui)/(Wcas2**2))/(((Hd_ebloui/
&Wcas2)**2+1)*sqrt(1+(Hd_ebloui/Wcas2)**2+(Lb/Wcas2)**2))))

  END IF

  Dcd=((3.0/(14.0*pi))*atan(Ld/Wcas2))*deg-((3.0/(14.0*pi))*
&(1/sqrt((Hd/Wcas2)**2+1))*atan((Ld/Wcas2)/
&(sqrt((Hd/Wcas2)**2+1)))*deg)+((2.0/(7.0*pi))*asin((((Ld*Hd)/
&(Wcas2**2))/(sqrt((1+(Ld/Wcas2)**2)*(1+(Hd/Wcas2)**2)))))*deg)-
&((2.0/(7.0*pi))*(((Ld*Hd)/(Wcas2**2))/(((Hd/Wcas2)**2+1)*sqrt
```

```
&(1+(Hd/Wcas2)**2+(Ld/Wcas2)**2))))
  Dc=2*Dcb+2*Dcd
 END IF

! Calculs Composante Réfléchie Interne
 Aw=hf*Lf
 h_bandeau=hr-Zd
 Stot_fw=Lr*Wr+((hr-0.5*hf-h_bandeau)*(2*Wr+Lr))
 Stot_fw_ebloui=Lr*Wr+((hr-0.75*hf-h_bandeau)*(2*Wr+Lr))
 Stot_cw=Lr*Wr+((0.5*hf+h_bandeau)*(2*Wr+Lr))
 Stot_cw_ebloui=Lr*Wr+((0.5*hf+h_bandeau)*(2*Wr+Lr))
 A=(2*Lr*Wr)+(2*Hr*Wr)+(2*Hr*Lr)
 Rtot_lum=((Rsol_lum+Rplafond_lum)*Lr*Wr+(Rmurs_lum*(2*Hr*
&(Wr+Lr)-Lf*hf)+Rfen_lum*Lf*hf))/A


 IF (Ebloui .eq. 0) THEN
  Rfw=((Rsol_lum*Lr*Wr)+(Rmurs_lum*(hr-0.5*hf-h_bandeau)*
&(2*Wr+Lr)))/Stot_fw
 ELSE
  Rfw=((Rsol_lum*Lr*Wr)+(Rmurs_lum*(hr-0.75*hf-h_bandeau)*
&(2*Wr+Lr)))/Stot_fw_ebloui
 END IF
 IF (Ebloui .eq. 0) THEN
  Rcw=((Rplafond_lum*Lr*Wr)+(Rmurs_lum*(0.5*hf+h_bandeau)*
&(2*Wr+Lr)))/Stot_cw
 ELSE
  Rcw=((Rplafond_lum*Lr*Wr)+(Rmurs_lum*(0.75*hf+h_bandeau)*
&(2*Wr+Lr)))/Stot_cw_ebloui
 END IF
 A=(2*Lr*Wr)+(2*Hr*Wr)+(2*Hr*Lr)
```

```
    Rtot_lum=((Rsol_lum+Rplafond_lum)*Lr*Wr+(Rmurs_lum*
   &(2*Hr*(Wr+Lr)-Lf*hf)+Rfen_lum*Lf*hf))/A

  ! Calcul final Composante Réfléchie Interne

    C=TL*clear_glass*scale_factor

    Dir=((0.85*Aw)*(40*Rfw+5*Rcw))/(A*(1-Rtot_lum))

    FLJ=C*(Dir+Dc)/100

! Calculs Determination de l'éclairement extérieur Ig

    p_water=exp(0.07*Td-0.075)

    zenithrad=zenith*pi/180

    m=(1-Z/10000)*(1/(cos(zenithrad)+
   &(0.50572*(96.07995-zenith)**(-1.6364))))

    epsilon=((Dh+I)/(Dh+1.014*zenithrad**3))/
   &(1+1.041*zenithrad**3)

    delta=(Dh*m)/1361

    IF ((epsilon .gt. 0) .and. (epsilon .le. 1.065)) THEN

    ai=96.63
    bi=-0.47
    ci=11.50
    di=-9.16

    END IF

    IF ((epsilon .gt. 1.065) .and. (epsilon .le. 1.230)) THEN

    ai=107.54
    bi=0.79
    ci=1.79
    di=-1.19

    END IF

    IF ((epsilon .gt. 1.230) .and. (epsilon .le. 1.500)) THEN

    ai=98.73
    bi=0.70
    ci=4.40
    di=-6.95

    END IF

    IF ((epsilon .gt. 1.500) .and. (epsilon .le. 1.950)) THEN
```

```
ai=92.72
bi=0.56
ci=8.36
di=-8.31

END IF

IF ((epsilon .gt. 1.950) .and. (epsilon .le. 2.800)) THEN

ai=86.73
bi=0.98
ci=7.10
di=-10.94

END IF

IF ((epsilon .gt. 2.800) .and. (epsilon .le. 4.500)) THEN

ai=88.34
bi=1.39
ci=6.06
di=-7.60

END IF

IF ((epsilon .gt. 4.500) .and. (epsilon .le. 6.200)) THEN

ai=78.63
bi=1.47
ci=4.93
di=-11.37

END IF

IF (epsilon .gt. 6.2) THEN

ai=99.65
bi=1.86
ci=-4.46
di=-3.15

END IF

! Détermination de l'éclairement interne

E=G*(ai+(bi*p_water)+(ci*cos(Zenithrad))+di*log(delta))

! Determination de l’éclairement total interne

    Etotal=E*FLJ
```

# ALGORITHM SHEET Natural Ventilation

MULTINAT

Natural Ventilation Model for Multi-physics Building Simulation

June 2014 version 1.3

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## 1. GENERAL DESCRIPTION

The purpose of routine is to assess the air change rate in natural ventilation for different window types in single-sided and cross-ventilation mode. The information flow diagram of this routine is presented in Figure 1.

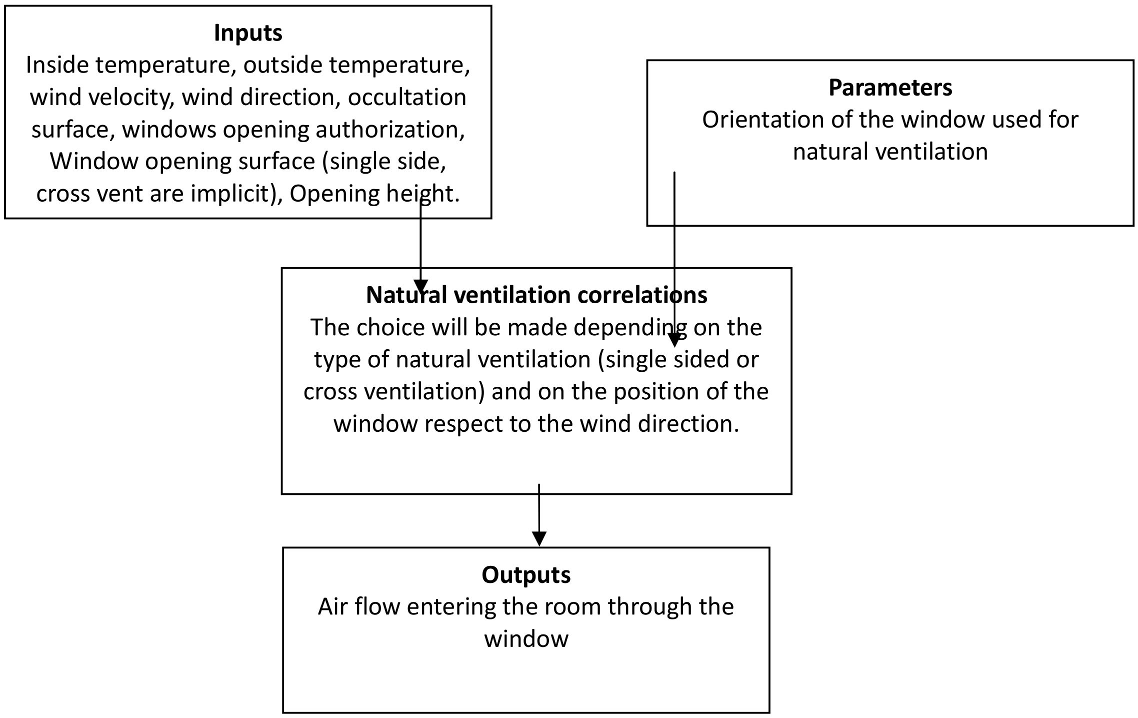


Figure 1. Flow diagram of the natural ventilation module

## 2. DEVELOPPERS

Name Marcel PERRET-GENTIL
Shuqing CUI
Pascal STABAT
Dominique MARCHIO

Organization CES, Mines Paristech

## 3. NOMENCLATURE

| | Description | *Units* | *min* | *max* |
|---|---|---|---|---|
| **Input variables** | | | | |
| **Weather data** | | | | |
| wind_vel | Wind speed | *m/s* | | |
| wind_dir | Wind direction | ° | 0 | *360* |
| Tout | Outside Temperature | °C | | |
| **Indoor temperature** | | | | |
| Tin | Average Indoor Temperature | °C | | |
| **Control inputs** | | | | |
| Sstore | Surface occupied by the roller blind. This input will modify directly the "eff_surf" according to the type of window. | % | 0 | 50 |
| Ouv | Window opening authorization | - | 0 | 1 |
| **Geometry Inputs** | | | | |
| Eff_surf | Opening area. If only one surface is provided the module will assume that the room is ventilated by single sided ventilation. However, if two surfaces are provided the module will assume that the room is ventilated by cross ventilation. | $m^2$ | | |
| Op_height | Opening height. | m | | |
| **Parameters** | | | | |
| **Orientation** | Enter here in degrees the orientation of the façade containing the window. The angle facing north will be taken as reference value (0°), increasing positively to the east. | ° (degrees) | 0 | 360 |
| **Room configuration** | | | | |
| Vr | Ventilated space volume | *$m^3$* | | |
| **Output variables** | | | | |
| Q_vent | Volume ventilation rate | $m^3/h$ | | |

## 4. MATHEMATICAL DESCRIPTION

### 4.1 Physical model

The common method used to predict the indoor change rate by natural ventilation is to determine which is the main impulsive force that allows the external air to enter the room. This two forces are the "buoyancy effect" due to the temperature difference between the room and the outside air, and the wind effect over the building due to the pressure difference within the two facades of the building.

This two parameters will vary according to the type of ventilation, which are: Single-sided ventilation and Cross-sided ventilation. The first one, the air exchange rate occurs by buoyancy and enters through a single window in one façade, whereas in Cross-sided ventilation the air enters by one façade and exits by the opposite side of the building, mainly driven by wind effects over the building's facades.

Extract from CEN 2007 [1]

## 4.2 Mathematical Expressions for Single-sided ventilation

**Leeward (if wind direction is greater than 90° and less than 270° regarding to the facade orientation)**

The correlations given by (M. Caciolo et al 2013) are used here. [2]

$$q = \frac{1}{3} \cdot S_{eff} \cdot C_d \cdot \sqrt{\frac{\Delta T \cdot \Delta T^{*} \cdot H_w \cdot g}{T_{av}}} \qquad (1)$$

where $C_d$ = 0.6 and $\Delta T^{*}$ is given by : $\Delta T^{*} = 1.355 - 0.179 \cdot v_{wind}$

Note that : $q = 0 \quad if \quad v_{wind} \geq 7.5\, {}^{m}/_{s}\ ,\ because\ \Delta T^{*} \leq 0 \quad (1^{*})$

This correlation is the result of empirical essays for wind velocities under 7.5 m/s, therefore is not valid for higher velocity values. For all the simulations, the assumption in (1*) will be used.

**Windward (if wind direction is less than 90° or greater than 270° regarding to the facade orientation)**

The correlations given by (M. Caciolo et al 2013) are used here. [2]

$$q = \frac{1}{3} \cdot S_{eff} \cdot C_d \cdot \sqrt{\frac{\Delta T \cdot \Delta T^{*} \cdot H_w \cdot g}{T_{av}}} + 0.0357 \cdot S_{eff} \cdot \left(v_{wind} - v_{wind,lim}\right) \quad (2)$$

where $C_d$ = 0.6 , $\Delta T^{*}$ and $v_{wind,lim}$ are given by

$$\Delta T^{*} = 1.234 - 0.49 \cdot v_{wind} + 0.048 \cdot v_{wind}^{2} \quad and \quad v_{wind,lim} = 1.23 \text{ m/s}$$

Note: This correlation has limit values for wind velocities, meaning that the calculation of the air flow rate will change according to the range of wind velocities. For this module the following changes may occur:

- If wind_vel ≤ 1.23 m/s, only the first term of (2) will be taken into account.
- If 1.23 m/s ≤ wind_vel < 4.5 m/s, both terms of (2) will be taken into account.
- If wind_vel ≥ 4.5 m/s, only the second term of (2) will be taken into account.

## 4.3 Mathematical Expression for Cross-Ventilation

The correlations given (P. Russeau et al.) [3] and (J. Seifert) [4] are used here.

$$q = C_d \cdot S_{eff} \cdot v_{wind} \sqrt{\Delta C_p} \qquad (3)$$

- The calculation of $\Delta C_p = C_{p1} - C_{p2}$ is also given in function of wind incident angle respect to the window's orientations.

– For an angle α≤90° or α≥270° (window on one side of the façade)

$$C_{p1} = 0.5994 - 0.1426|\sin\alpha| - 0.8055|\sin\alpha|^2 + 2.0149|\sin\alpha|^3 - 2.1972|\sin\alpha|^4$$

– For an angle $90° < \alpha < 270°$ (window on the other side of the façade)

$$C_{p2} = -0.333 - 0.1544|\sin\alpha| - 0.1128|\sin\alpha|^2$$

– The effective surface $S_{eff}$ is given by :

$$S_{eff} = \frac{S_1 S_2}{\sqrt{{S_1}^2 + {S_2}^2}} \qquad (4)$$

## 5. 5. ALGORITHM

The corresponding flow chart is given by

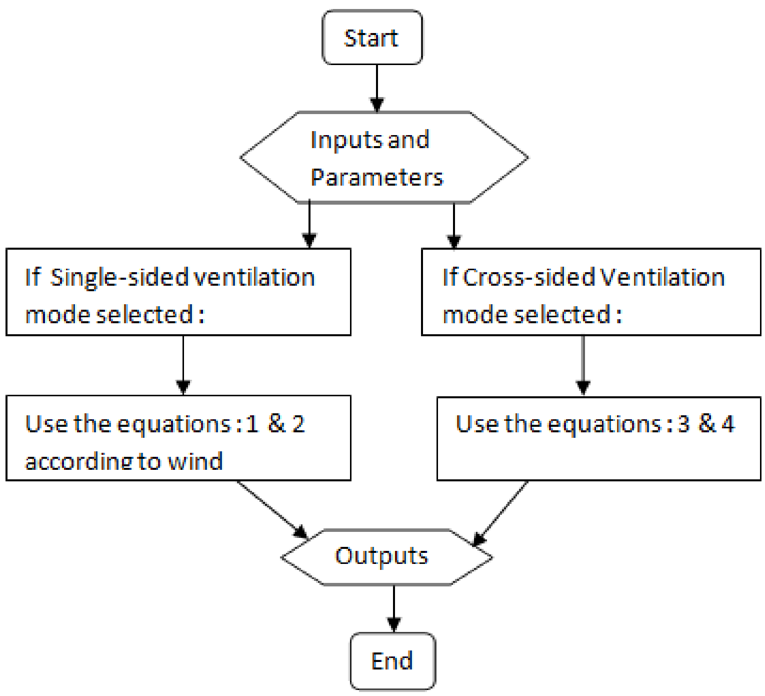


Figure 2. General algorithm of the natural ventilation module

## 6. CODE SOURCE (FORTRAN)

```
C     PARAMETERS
C     INPUTS
       DOUBLE PRECISION T_in
       DOUBLE PRECISION T_out
       DOUBLE PRECISION wind_dir
       DOUBLE PRECISION wind_vel
       DOUBLE PRECISION S1
       DOUBLE PRECISION S2
       DOUBLE PRECISION Houv
       DOUBLE PRECISION Orientation
```

```
C     OUTPUTS
       DOUBLE PRECISION Q_vent
C     INTERMEDIATE VARIABLES
       DOUBLE PRECISION Cd, g, delta_T, delta_Tau, delta_Tsous, V_lim
       DOUBLE PRECISION Tav, delta_Cpau, delta_Cpsous, Seff_cross
       DOUBLE PRECISION Dir_ventrad, delta_Cp, Seff_single
       DOUBLE PRECISION orientation_inf, orientation_sup, Q_vent_int

           !Intermediate Variables

        delta_T=abs(T_out-T_in)
        delta_Tsous=1.355-0.179*wind_vel
        delta_Tau=0.048*wind_vel**2-0.49*wind_vel+1.234
        g=9.81
        Cd=0.6
        Tav=0.5*(T_out+T_in)+273.15
        V_lim=1.37
        Dir_ventrad=(wind_dir*3.141592)/180.0
        delta_Cpsous=0.5994-0.1426*abs(sin(Dir_ventrad)) -
     &0.8055*abs(sin(Dir_ventrad)**2)+ 2.0149*abs(sin(Dir_ventrad)**3) -
     & 2.1972*abs(sin(Dir_ventrad)**4)
        delta_Cpau=-0.333-0.1544*abs(sin(Dir_ventrad)) -
     &0.1128*abs(sin(Dir_ventrad)**2)
        Seff_cross=(S1*S2)/sqrt(S1**2+S2**2)
        delta_Cp=delta_Cpsous-delta_Cpau
        Seff_single=S1+S2
        orientation_inf=orientation-90
        orientation_sup=orientation+90

!NATURAL VENTILATION CROSS
           !Natural ventilation (cross ventilation mode)
      IF ((S1 .gt. 0) .and. (S2 .gt. 0)) THEN

       Q_vent_int=Cd*Seff_cross*wind_vel*sqrt(Delta_Cp)

      ELSE
            !NATURAL VENTILATION SINGLESIDED
        !Generic Orientation
         ! Ventilation sous le vent

            IF  ((wind_dir .le. orientation_sup) .and.
     &(wind_dir .gt. orientation_inf)) THEN

                IF ((wind_vel .lt. 4.5) .and. (wind_vel .gt. 1.37)) THEN

                    Q_vent_int=(1.0/3.0)*Cd*Seff_single*sqrt
     &((delta_T*delta_Tau*Houv*g)/Tav) +
     &0.0357*Seff_single*(wind_vel-V_lim)

                    END IF

                    IF (wind_vel .gt. 4.5) THEN

                  Q_vent_int=0.0357*Seff_single*(wind_vel-V_lim)

                    END IF
                    IF (wind_vel .lt. 1.37) THEN

                Q_vent_int=(1.0/3.0)*Cd*Seff_single*
     &sqrt((delta_T*delta_Tau*Houv*g)/Tav)

                    END IF
```

```
        ELSE
        ! Ventilation Sous le vent

                IF (wind_vel .lt. 7.5) THEN
                Q_vent_int=(1.0/3.0)*Cd*Seff_single*
     &sqrt((delta_T*delta_Tsous*Houv*g)/Tav)
                ELSE
                Q_vent_int=0
                END IF

        END IF
  END IF
  Q_vent=Q_vent_int*3600
```

## 7. REFERENCES


[1] CEN (2007) Ventilation for buildings- Calculation methods for the determination of air flow rates in buildings including infiltration, EN 15242.

[2] M. Caciolo, S. Cui, P. Stabat, D. Marchio, Development of a new correlation for single-sided natural ventilation adapted to leeward conditions, Energy and Buildings, 60 (2013) 372-382.

[3] P. Rousseau, E. Mathews A new integrated design tool for naturally ventilated buildings, Energy and Buildings, 23 (1996) 231-236.

[4] J. Seifert, Y. Li, J. Axley, M. Rösler M Calculation of wind-driven cross ventilation in buildings with large openings, Wind Engineering, 94 (2006) 925-947.

# ALGORITHM SHEET Effective Opening Surface Calculation

MULTIFFS

Effective Opening Surface Calculation Model for Multiphysics Building Simulation

August. 2014 version

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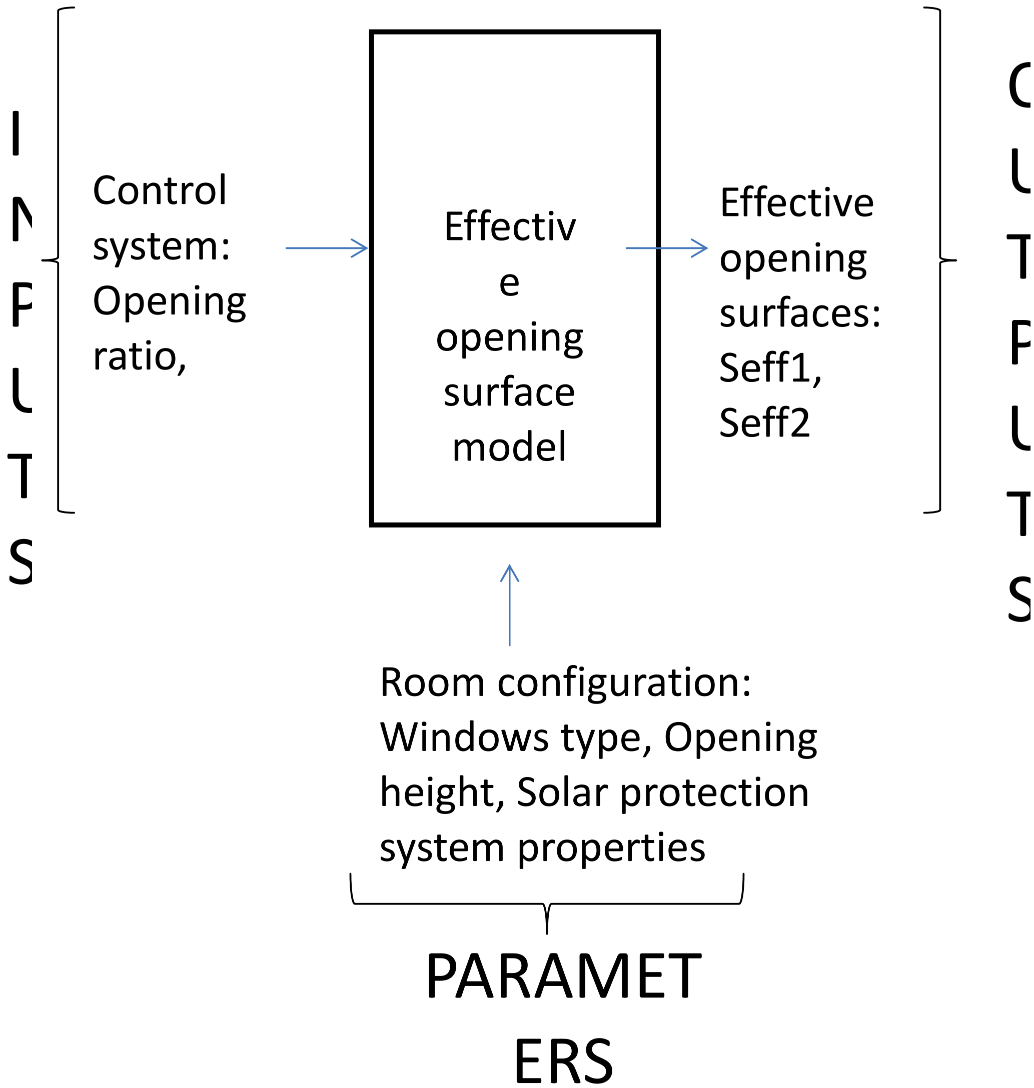
## 1. GENERAL DESCRIPTION

The purpose of routine MULTIFFS is to determine the effective opening surface of the windows. The information flow diagram of this routine is presented in following figure.




## 2. DEVELOPPERS

Name Shuqing CUI
Marcel Perret Gentil
Pascal STABAT
Dominique MARCHIO

Organisation CES, Ecole des Mines de Paris

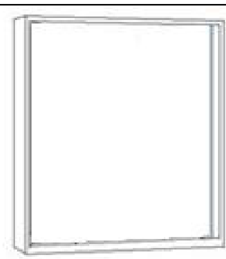
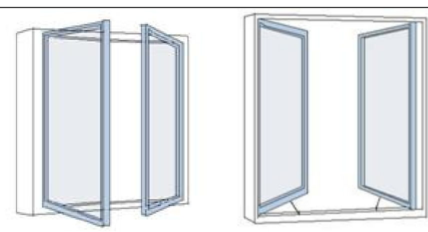
## 3. NOMENCLATURE

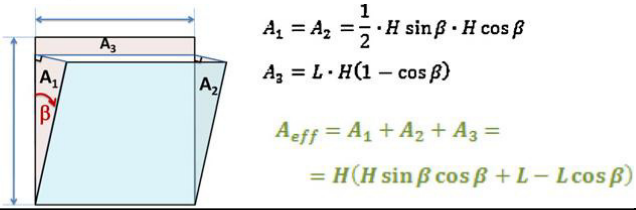
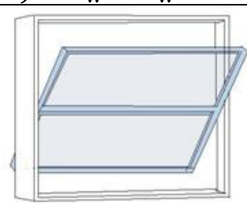
| | Description | *Units* | *min* | *max* |
|---|---|---|---|---|
| **Input variables** | | | | |
| **Control system** | | | | |
| Spratio | Solar protection ratio | % | 0 | 100 |
| Opratio | Opening surface ratio | % | 0 | 100 |
| | | | | |
| **Parameters** | | | | |
| **Room configuration** | | | | |
| Ventmd | Natural ventilation mode selection if<br>=1 single-sided<br>=2 cross-ventilation | | | |
| Sptp | Solar protection system type selection if<br>=0 none<br>=1 blade shutter<br>=2 slat shutter<br>… | | | |
| αfcd | Front Facade Orientation regarding to the north | ° | 0 | *359* |
| **Opening Configuration** | | | | |
| Opening Type | Windows type selected if<br>=1: casement window<br>=2: sash window<br>=3: England window<br>=4: Italian window<br>… | | | |
| Sw1, Sw2 | Maximum opening surface | $m^2$ | | |
| Hw1, Hw2… | Opening heights | *m* | | |
| Lw1, Lw2… | Opening length | *m* | | |
| Lovh | Overhang maximum length | *m* | *0* | |
| Hovh | Overhang height | *m* | | |
| Hdoo | Distance between overhang and opening upper edge | *m* | | |
| **Shutter Configuration** | | | | |
| **Blades shutter** | | | | |
| Numbld1, Numbld2… | Spacing numbers between blades over one opening | - | 0 | |
| αbld1, αbld2… | Blade inclination | ° | 0 | 90 |
| Hbld1, Hbld2… | Spacing height between blades | *m* | | |
| **Slats shutter** | | | | |
| Numslt1, Numslt2… | Slat numbers over one opening | - | 0 | |
| Numslty1, Numslty2… | Slats layers over one opening | - | 2 | |

| | | | | |
|---|---|---|---|---|
| Dslyt1, Dslyt2… | Spacing between slat layers | m | | |
| | | | | |
| **Output variables** | | | | |
| Sseff1, Sseff2… | Effective shutter spacing | $m^2$ | | |
| Sweff1, Sweff2… | Effective window surface | $m^2$ | | |
| Seffnv1, Seffnv2… | Effective opening surface for natural ventilation calculation | $m^2$ | | |
| Sefflit1, Sefflit2… | Effective opening surface for solar factor and transmission coefficient calculation | $m^2$ | | |
| Seffacou1, Seffacou2… | Effective opening surface for acoustical calculation | $m^2$ | | |

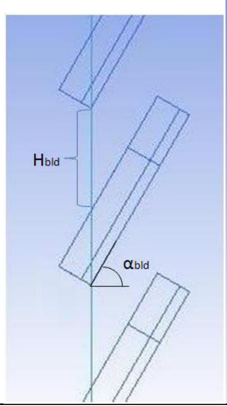
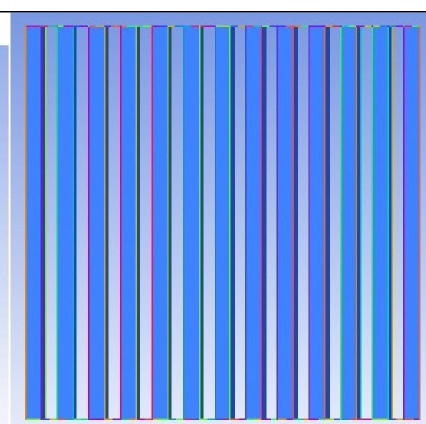
## 4. MATHEMATICAL DESCRIPTION

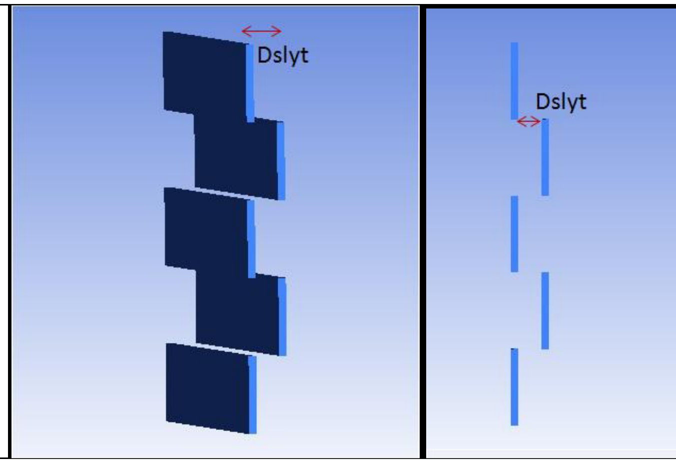
### 4.1 Effective window surface

| | |
|---|---|
| **Complete opening** |  |
| Description, characteristics | Aperture on the facade without window installed |
| Effective window surface | $Sweff = Sw$ (1) |
| **Casement window** |  |
| Description, characteristics | A window consists of two swinging glasses attached to the frame by one or multiple hinges fixed on the vertical sides. |
| Effective window surface | (2) |
| **Sliding window** |  |
| Description, characteristics | The mobile chassis slides horizontally in the frame |
| Effective window surface | $Sweff = Sw * Opratio$ (3) |

| | |
|---|---|
| **Top(bottom)-hung window** |    |
| Description, characteristics | The opening swings vertically with hinges activated on frame sides and fixed on frame bottom. |
| Effective window surface | $S_{weff} = \mathrm{H_w} * (\mathrm{H_w} * \sin(Opratio * 90) * \cos(Opratio * 90) + \mathrm{L_w} - \mathrm{L_w} * cos(Opratio * 90)$ (4) |
| **Side-pivot window** |  |
| Description, characteristics | A tilting window pivots on itself along a horizontal axis on the midpoint. |
| Effective window surface | $S_{weff} = \mathrm{H_w} * (0.5 * \mathrm{H_w} * \sin(Opratio * 90) * \cos(Opratio * 90) + \mathrm{L_w} - \mathrm{L_w} * cos(Opratio * 90)$ (5) |

## 4.2 Effective shutter spacing

| | |
|---|---|
| **Blades shutter** |    |
| Description, characteristics | The shutter consists of multiple parallel blades, similar to venetian louvers with variable blade thickness, height and inclination |

| | |
|---|---|
| Effective shutter spacing | $S_{seff} = \mathrm{H_{bld}} * \mathrm{L_w} * \mathrm{Numbld}$ (6) |
| **Slats shutter** |  |
| Description, characteristics | The shutter consists of multi-layer slats (Numslty=2 to 3): the slats are disposed horizontally or vertically on the window frame; the slats are side by side from a view in normal direction |
| Effective shutter spacing | IF Numslty =2<br>THEN<br>$S_{seff} = \mathrm{H_{bld}} * \mathrm{L_w} * \mathrm{Numbld}$ (7)<br><br>IF Numslty =3<br>THEN<br>$S_{seff} = \frac{\mathrm{H_{bld}^2} * \mathrm{L_w^2} * \mathrm{Numbld}^2}{\mathrm{S_w}}$ (8) |

### 4.3 Outputs for physical models

The effective opening surface for natural ventilation calculation (MULTINAT):

$\mathrm{Seffnv} = \frac{Sweff * Sseff}{Sw}$(1)

The effective opening surface for solar factor and transmission coefficient calculation (MULTISOL):

IF shutter materials are transparent THEN

$\mathrm{Sefflit} = \mathrm{Sw}$(2)

IF shutter materials are opaque THEN

$\mathrm{Sefflit} = \mathrm{Sseff}$(3)

The effective opening surface for acoustical calculation (MULTIACOU): $\mathrm{Seffacou}$

## 5. ALGORITHM

Calculate the effective window surface.

Calculate the effective shutter spacing

Calculate the effective opening surface.

## 6. CODE SOURCE

```
C   PARAMETERS
    DOUBLE PRECISION window_type
    DOUBLE PRECISION op_ratio
    DOUBLE PRECISION window_width
    DOUBLE PRECISION window_height
    DOUBLE PRECISION orientation
    DOUBLE PRECISION Wc
    DOUBLE PRECISION Wj
    DOUBLE PRECISION Room_height
    DOUBLE PRECISION Za
    DOUBLE PRECISION Room_width
    DOUBLE PRECISION Room_length
    DOUBLE PRECISION Room_volume_out

C   INPUTS
    DOUBLE PRECISION Ebloui

C   OUTPUTS
    DOUBLE PRECISION eff_surface, window_width_out, op_height
    DOUBLE PRECISION window_height_out, orientation_out, Wc_out
    DOUBLE PRECISION Wj_out, Room_height_out
    DOUBLE PRECISION Za_out, Room_width_out, Room_length_out
    DOUBLE PRECISION window_total_surf
! DESCRIPTION OF THE WINDOWS
      !Type 1 Sliding window (horizontally)
      !Type 2 Sliding window (vertically)
      !Type 3 Top/Botoom Hung window

    IF (window_type .eq. 1) THEN
      IF (ebloui .eq. 1) THEN
      eff_surface=window_height*window_width*op_ratio*0.5
      op_height=window_height*0.5
      ELSE
      eff_surface=window_height*window_width*op_ratio
      op_height=window_height
      END IF
    END IF

    IF (window_type .eq. 2) THEN
      IF (ebloui .eq. 1) THEN
```

```
    eff_surface=window_height*window_width*op_ratio
    op_height=window_height*op_ratio
    ELSE
    eff_surface=window_height*window_width*op_ratio
    op_height=window_height*op_ratio
    END IF
  END IF
  IF (window_type .eq. 3) THEN
    IF (ebloui .eq. 1) THEN
    eff_surface=window_height*(window_height*sin(op_ratio*90)*
&cos(op_ratio*90)+window_width-window_width*cos(op_ratio*90))
    op_height=window_height
    ELSE
    eff_surface=window_height*(window_height*sin(op_ratio*90)*
&cos(op_ratio*90)+window_width-window_width*cos(op_ratio*90))
    op_height=window_height
    END IF
  END IF
  window_total_surf=window_height*window_width
  Room_volume_out=Room_height*Room_width*Room_length
  window_height_out=window_height
  window_width_out=window_width
  Wc_out=Wc
  orientation_out=orientation
  Wj_out=Wj
  Room_height_out=Room_height

  Za_out=Za
  Room_width_out=Room_width
  Room_length_out=Room_length
```