SENSITIVITY ANALYSES ON THE DEFINITION OF WIND DRIVEN NATURAL VENTILATION POTENTIAL

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ABSTRACT

The most important parameters for designing wind-driven ventilation strategies are highlighted through a series of sensitivity analyses. A coupled approach using the freely available software package OpentTurns and a genetic algorithm is used to define the expecte range of variation for the importance indexes. The study focuses on whether the discharge coefficient for external openings or the opening area of internal doors is the most important parameter in determining global airflow rates in the kitchen. Different cases are considered through parametric simulation for a range of internal doors opening areas, which shows an inverse trend on both factors depending on the opening ratio (external over internal opening area).

INTRODUCTION

In the context of energy efficient buildings, ventilation is becoming the main source of energy consumption. Thus, the specification of ventilation rates, i.e. airflows in each volume, requires more precision than in the past.

The internal air flow mass need to be adjusted such that thermal comfort in summer and air quality in winter is ensured. These two objectives are to be maintained while reducing global energy consumption. The use of heating ventilation and air conditioning systems (HVAC) has been widely used up till now. These allow the above objectives to be met but can dramatically increase the energy needs. Concerning HVAC coupled with heat recovery systems, this can significantly reduce the energy needs but it is not always applicable. New buildings can easily integrate such systems with minimal investment but considering refurbishment, this might be not possible without major modifications and investment. Aside from energy consideration, fully mechanical ventilation introduces a health problem in case of fans or trap malfunction since the entire building envelope is less permeable with these systems. A rapid increase in air pollutant (carbon dioxide among other contaminants) can be observed without any ventilation [EPA (1990)].

For these reasons, and following environmental design concepts, natural ventilation is being more considered than in previous decades. Considering natural ventilation in the French context, designers will have to prove its efficiency with regard to airflow rates in the kitchen [arrêté 1982] and building global energy consumption [RT2012]. Thus, designing natural ventilation is a complex task since it involves some highly variable parameters. Indeed, and among internal / external temperature differences, external wind velocity and incidence, designer needs to make choices for airflow/pressure laws for each orifice considered and for the occupation scenarios.

As variable aspects, among others, the airflow/pressure laws include the well-known discharge coefficient. It is usually taken as constant for all the whole range of opening areas that might be considered. Another variable aspect is the occupation scenario. This implies strong changes in the internal airflow network. Indeed, considering internal doors as closed or partially opened leads to strong changes in the internal pressure losses and thus in the internal airflow rates and directions (internal distribution).

In order to help designer concerning theses two aspects, sensitivity analyses have been performed considering variable values of discharge coefficient and variables areas of internal doors. A classical one-storey building is considered for this study. The external pressure field is determined using wind tunnel measurements while the internal pressure field and thus internal airflow patterns are determined from a nodal code called MATHIS.

The test case is presented in a first part, followed by the methodology used for sensitivity analyses. Results, discussion and conclusion are then proposed.

CASE STUDIED

The studied case is a single family dwelling of 84m² with eight internal volumes. All living places (all rooms except the central corridor) are equipped with openings connected to the outside (external openings). Figure 1 presents a scheme of the internal architecture. Openings are represented in bold lines.

No openings are present on the gable walls, leading to some wind incidences being critical. Indeed, for wind incidence facing gable walls, the external pressure fields are very similar on both sides of the model resulting in a very low driving force for ventilation.

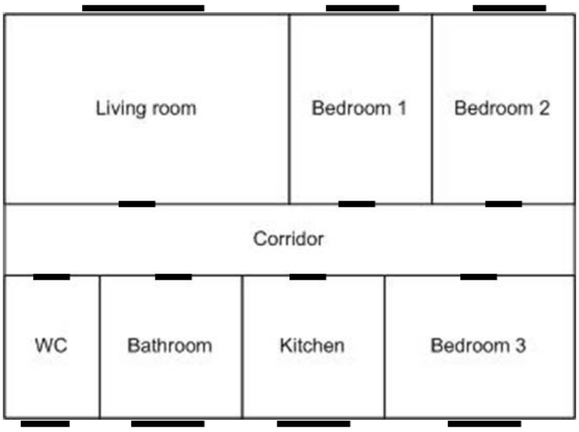


Figure 1. Internal architecture of the studied one storey dwelling.

The model has been scaled down at 1/10 and positioned in a wind tunnel. The maximum blockage ratio is less than 2.5%, so there is no need to correct for blockage effects.

A calibrated holes approach is used to represent every opening in the model. It allows varying the area without changing the airflow vs. pressure law of the opening. Static pressure is measured next to each openings facing either outside the model or between two internal volumes. The measurement uncertainties are estimated at +/-1Pa. A more detail presentation of the model, acquisition system, and global methodology can be found in Faure et Le Roux (2011). Figure 2 and Figure 3 present the scaled model and the internal architecture being equipped.

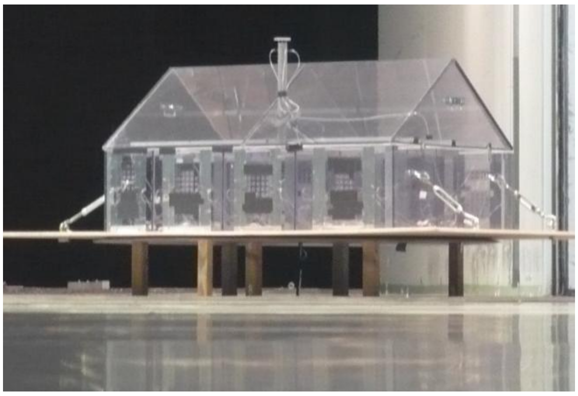


Figure 2. Model positioned in the wind tunnel.

Experimental results have shown the independence of external pressure field to external openings areas. Configurations of opening ratios (external/internal opening for each volume) from 0.2 to 17 have shown no major differences on the external pressure field. Thus, only one set of external pressure fields is used in this study for all the cases.

The external pressure field has been used as boundary conditions for a nodal code called MATHIS. Comparisons of internal pressure field and velocity ratios (local velocities upon upstream wind velocity) were done to validate MATHIS [Demouge et al. 2011].

All the results presented in this study use MATHIS to generate the internal pressure fields and thus the airflow rates using one set of external pressure fields.

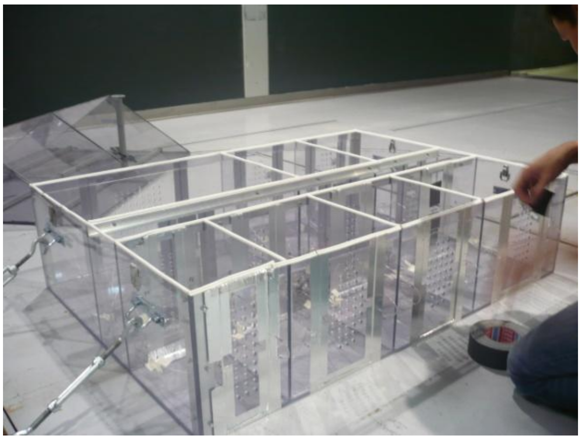


Figure 3. Internal architecture being equipped

In this study, only a few wind incidences are considered. Two incidences are normal to longest walls (wall with external openings), respectively 0° and 180° and one incidence with little acting forces (incidence on gable walls): 80°. Incidence 0° corresponds to wind facing the living room. The wind velocity is kept constant and equal to 15m/s. The external openings remained constant through all the simulation and equal to the smallest section in Faure et LeRoux (2011).

The parameters considered for the sensitivity analyses and the methodology are presented in the following part.

METHODOLOGY

In this part, the parameters chosen for study, using sensitivity analyses, are detailed in a first section. The methodology used for sensitivity analyses is then presented.

Studied parameter

Assuming incompressible, one-dimensional and steady flows through openings, the Bernoulli equation expresses the airflow rate vs. pressure difference law with the following generic form (expression (1)).

$$Q = C_D A\left(\frac{2|\Delta P|}{\rho}\right)^n \quad (1)$$

where Q is the volumetric flow rate (m^3/s), A is the opening area (m²), ρ is the fluid density (kg/m^3), ΔP is the static pressure difference (Pa), C_D is the discharge coefficient ($(m.s^{-1})^{1-2n}$) and n the exponent of the power law which is considered as quadratic (n = 0.5). In this case, the discharge coefficient C_D is a dimensionless parameter.

Expression (1) shows a linear dependency of the discharge coefficient C_D and the opening area A on the airflow rate Q. This would imply that these two parameters have both the same importance in the airflow rate definition. The uncertainties on both are not equal. Indeed, the first one, the discharge coefficient is known to take several values depending on several parameters, while the second one, the opening area, can dramatically change depending on the occupant behaviour. Besides, and considering wind-driven natural ventilation, the discharge coefficient will have a great impact on airflow passing through external opening (the ones for internal doors can be considered as constant), while occupant would change more often internal section areas (opening or closing doors between internal volumes) than external openings. The effect of one or the other might be not trivial since the first one impact the amount of mass entering the building while the second plays an important role in the internal pressure losses and therefore on the internal airflow.
Thus, the studied parameters are discharge coefficient of external openings and internal doors opening sections.

Discharge coefficients have been in the scope of many studies in the past. This empirical parameter is introduced to take into account streamlines contraction and viscous pressure losses. Its value has been defined experimentally from 0.6 to 0.65 in still air [Etheridge, 1996].
Researchers have focused on the impact of wind incidence, upstream velocity, and opening aspect ratios [Wang et al., 2011; Costola et al., 2008; Karava et al., 2007; Chiu et al., 2007; Chu et al., 2009; Salliou et al., 2012, among others]. Despites the numerous studies published in the literature, no general trends could be defined. Values from 0.3 up to 1 were reported depending on the orifice Reynolds number, wind incidence, turbulence, aspect ratios, etc. Its linear influence implies that 20% of error on the discharge coefficient implies 20% or error on the airflows, which is not compatible with energy efficient building design. Thus, the discharge coefficients of every external opening of the test case were considerer to vary independently within a range of [0.5-0.7], which represents the most expectable values of discharge coefficient (+/-15% around to conventional value of 0.6) . This means seven parameters since the test case has seven external opening sections. Some discussions will be proposed hereafter on the impact of a specific range of variation for sensitivity analyses.
The others parameter considered in the sensitivity analyses concerns internal doors opening sections.
French standard imposes doors to present residual openings even if closed in order to ensure airflow between separated volumes. These have to present opening height to be in order of 1cm for living rooms and bedrooms and of 2cm for water rooms (kitchen bathrooms and toilets). For the present study, different cases were considered. In a first step, these sections were considered to be close to the standard recommendation within a range of 0.01m² to 0.02 m² for living rooms. This range corresponds to opening height of 1.1cm to 2.2cm for a 90cm door large. The water rooms were considered to have opening section within a range of 0.02m² to 0.03m². This range corresponds to opening height of 2.2cm to 3.3cm for a 90cm door large. These configurations able to consider what effect a small amount of variation within the internal section or a small variation of the discharge coefficient would lead to and therefore on what parameter should the designer focus on in order to reach the requirement.
Another configuration has been considered with internal doors closed or opened, thus presenting openings section within a range of 0.01m to 2m². The ranges of variation of the discharge coefficient are the same as before for this configuration.

Table 1 summarises the studied configurations.

Table 1
Configurations for sensitivity analyses

Conf.	Wind Incidence	Range of external Cd value	Range of internal openings section
Cfig1	0°	0.5-0.7	0.01-0.02 m² 0.02-0.03 m²
Cfig2	180°	0.5-0.7	0.01-0.02 m² 0.02-0.03 m²
Cfig3	80°	0.5-0.7	0.01-0.02 m² 0.02-0.03 m²
Cfig4	80°	0.5-0.7	0.01-2 m²

For all simulation, the airflow rate in kitchen was systematically considered as the output. Thus, the impact of the factors presented in the following is with regards to the airflow rate in the kitchen.

Sensitivity analyses methodology

Sensitivity analyse is realized in this study with the assumption of a linear relationship between the considered output and the different input, also called factors or parameters. Thus, the model expressed in expression (2) will be first estimate. In order to evaluate the reliability of the linear assumption, the model will be evaluated considering the global regression coefficient R^2 and the predictive coefficient Q2. Expressions of these coefficients are presented respectively through the expression (3) and (4). The regression coefficient R^2 corresponds to the error on the residues over the model-fitting step and the predictive coefficient Q2 correspond to the residues over another sample of inputs and outputs of p size.

$$\hat{Y} = b_0 + \sum_i b_i X_i \quad (2)$$

$$R^2 = 1 - \frac{\sum_i^n (Y_i - \hat{Y}_i)^2}{\sum_i^n (\overline{Y} - Y_i)^2} \quad (3)$$

$$Q2 = 1 - \frac{\sum_i^p \left(Y_i^p - \hat{Y}\left(X^{p(i)}\right)\right)^2}{\sum_i^p \left(\overline{Y^p} - Y_i^p\right)^2} \quad (4)$$

If the model is linear, the standard regression coefficients (SRC's) can be used as sensitivity index since they represent the indexes of the variance of factor X_i over the output variance. SRC's are calculated through expression (5) below.

$$SRC_i = b_i^2 \frac{V(X_i)}{V(\hat{Y})} \quad (5)$$

The linear assumption remain a first step in sensitivity analyses and if the studied model does not match this assumption, more complex indexes, such as Sobol indexes would need to be used.
More details about sensitivity indexes can be found in Saltteli et al. 2008.

The different samples of inputs and the corresponding outputs are generated using the software OpenTurns [OpenTurns, 2012].
It can be coupled to any other code that can be launch from input data file. The coupling is done through wrapper files in which the studied parameters are specified. Each of them can be represented through different statistical distribution laws. The user can specify the sample size for the global study (number of simulation) and the way the sample of input is generate. Many functions are available to study both uncertainties propagation and sensitivity analyses. The indices of importance for each parameter can be calculated from the classical standard regression coefficients (SRC's) for linear model up to the Sobol Indices for any model. OpenTruns is used here for sample definition and computing SRC's on large sample. The studied parameters are following a normal law distribution for the present study. Input samples are generated through Monte Carlo method of dimensions 10^6.

In order to define some uncertainties on SRC's coefficient, smaller sample (taken from the one define by OpenTruns) were used to compute b_i regression coefficients (see relation (2)) using genetic algorithm in the Matlab Environment (Houck et al. 1996). Genetic algorithm will continue updating the regression coefficient values b_i until the cost function is minimised. This last is expressed as the difference between the output Y and the estimate output $\hat{Y}$.
Genetic algorithms are valuable in order to estimate the model representation uncertainties. Indeed, genetic algorithm will converge to the best set of regression coefficients values according to an initial population. By doing the same simulation 500 times, one will get 500 different sets of regression coefficient values that gives approximatively the same global residues (cost function minimisation process). The corresponding distribution is then used to define regression coefficient uncertainties.
Figure 4 shows some results of a b_i coefficient for the 500 models generated. A Gauss curves have been over plotted on the data in order to have representative mean and standard deviation values. This last were then used to define error bar on the SRC's coefficient by considering the regression coefficient within a +/- standard deviation confident range.

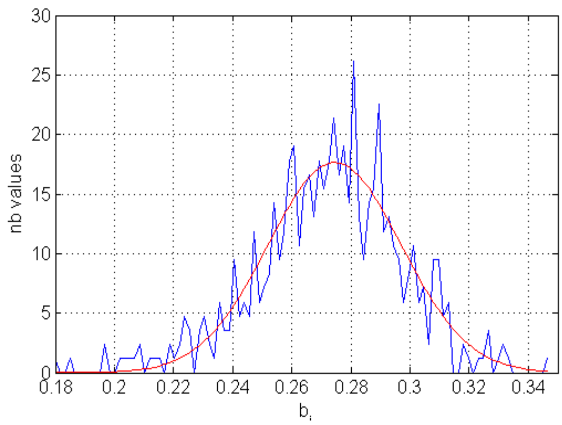


Figure 4. b_i distribution of 500 simulation using genetic algorithm to estimate model expressed in relation (2) and Gaussian distribution over plotted.

The results presented in the next section are obtained following the same protocol for every configuration:

- Simulation of 10^6 results from Monte Carlo input of sample (with OpenTurns).
- Computation of SRC's on large sample (10^6). (with OpenTurns).
- Estimation of the model regression coefficient and standard deviation of each coefficient b_i. With smaller sample (3000 data of Y = f(X), with Matlab).

- Definition of the R² and Q2 value for another sample of 50000 values of inputs and corresponding outputs.
- Comparison of the SRC's values obtained using least square methodology over 10^6 simulations and the SRC's as the genetic algorithm approach
- Estimation of the main important parameters for the considered output.

RESULTS

In this section, the results of several configurations are presented. The 14 parameters are identified as presented in the table 2.

For each configuration, the 14 parameters are systematically presented. The importance to the output is identified through the SRC's value. The highest the SRC's value, the most important is parameter for the considered output (egg. the airflow rate in the kitchen).

Table 2
Configurations for sensitivity analyses

Parameter n°	Cd	Parameter n°	Opening section
1	Bed 1	8	Bed 1
2	Bed 2	9	Bed 2
3	Bed 3	10	Bed 3
4	Liv. room	11	Liv. room
5	Kitchen	12	Kitchen
6	Bathroom	13	Bathroom
7	Toilet	14	Toilet

Figure 5 presented the results for the Cfig 1. The R² and Q2 values are presented at the top of the figure.

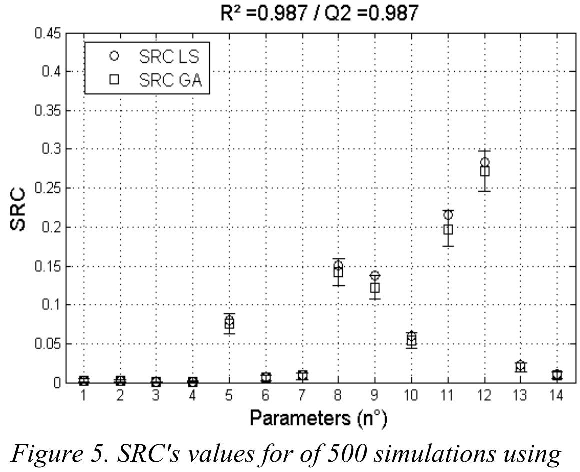


Figure 5. SRC's values for of 500 simulations using genetic algorithm (SRC GA) and using least square approach on 10^6 simulations (SRC LS) for Cfig. 1

The assumption of linear model is in this case confirmed with both values of R² and Q2. The SRC can thus be used as sensitivity indexes. The SRC's, for this case show the main influence of opening section areas (parameters n°8, 9, 11 and 12). The external opening discharge coefficient in the kitchen (parameter n°5) is still, up to 8%, responsible of the variance of the airflow rate in the kitchen. By order of importance, the living room and both bedrooms n° 1 and 2 have more influence than the discharge coefficient. For this specific wind incidence, this last three volumes are positioned on the windward side and if either one of the three internal opening present more important area, it leads directly to more possible airflow rate in the kitchen. The order of importance is due to the higher internal pressure for the living room since the external opening is more important while the difference of the two bedrooms lies in the external pressure coefficient. The bedroom n°2's external pressure coefficient is the lowest due to its position on the right hand of the model. The SRC's computed over large sample are always within the range of uncertainties of SRC's compute over much smaller sample. This reinforces the validity of using genetic algorithm to compute sensitivity analyses.

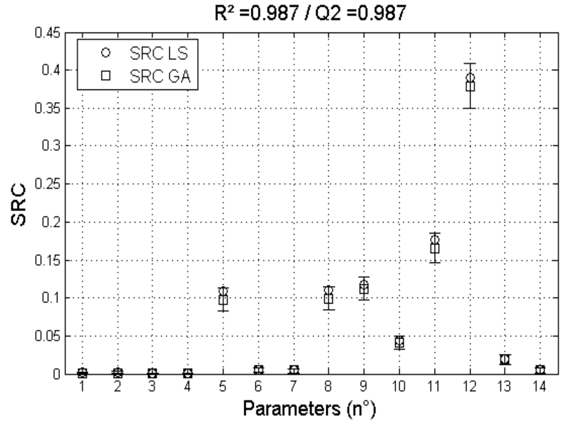


Figure 6. SRC's values for of 500 simulations using genetic algorithm (SRC GA) and using least square approach on 10^6 simulations (SRC LS) for Cfig . 2

The opposite wind incidence case (Cfig. 2), is presented in Figure 6. The linear assumption is still valid with the same amount of confidence than for the previous case. The main differences are the lowest influences of the three previous mentioned rooms (living room and bedrooms 1 and 2) and the inversion between bedroom 1 and bedroom 2. The former is due to the opposite position of the main acting force. Indeed, airflow is generated by pushing forces on the windward side and pulling forces on the leeward side. For this model, the pulling forces are lower than the pushing force, resulting in a less importance of the escaping doors and a greater impact of the kitchen discharge coefficient and the kitchen door opening area. The order of importance between the two bedrooms is inversed due to external pressure coefficients which are lower (resulting in stronger pulling forces) on sides than on the centre of the model.

Figure 7 presents the results of Cfig 3 which has a wind incidence close to the gable walls normal. This incidence leads to the smallest acting forces in the ventilation process. Indeed, pressure field on both sides of the model are quite close from each other resulting in little ventilation potential (Faure et LeRoux (2011). This configuration is shown to be also linear as the values of R^2 and Q2 are very close to unity. The area of the kitchen door still remain the most important parameter but the living room door section influence has been dropped in a lower position than the kitchen discharge coefficient and has nearly the same importance as the bedroom n°3 door section which is on the same side of the kitchen.

The two door sections of bedrooms n°1 and 2 have more importance in this specific case while the discharge coefficient remains appreciatively in the same importance for the three cases.

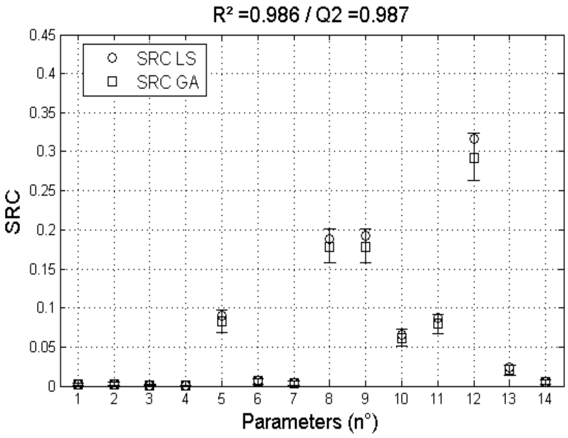


Figure 7. SRC's values for of 500 simulations using genetic algorithm (SRC GA) and using least square approach on 10^6 simulations (SRC LS) for Cfig . 3

The differences observed in this case are mainly due to external pressure coefficients. These present negative values on the living room external opening as for the kitchen, the bedroom n°3, the bathroom and the WC while external pressure is close to 0 for the two first bedrooms. The effect of the living room is reduced due to the negative pressure value as for the kitchen. Depending on internal opening sections, the acting forces on these two volumes are always in opposite direction.

As an illustration of the observation above, Figure 8 presents the external pressure coefficient of the 7 volumes for the three wind incidences studied previously.

The first three configurations had for aim to identify whereas a little change in the standard opening areas had more effect than classical error on the discharge coefficient.

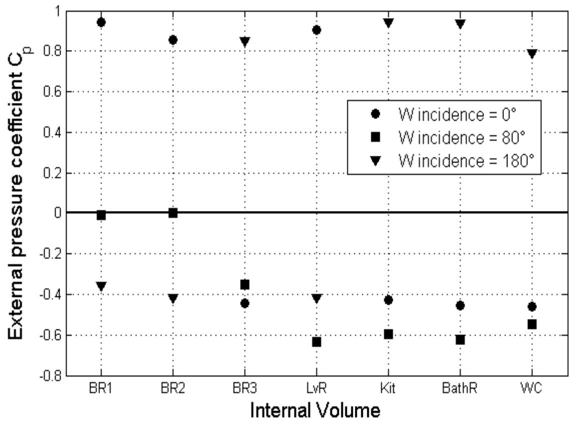


Figure 8. External pressure coefficients for the 7 internal volumes and three wind incidences.

Those previous cases made the assumption of internal doors as closed or almost closed. For considering complete opened doors, the configuration 4 has been also studied. Results, for this configuration, are presented in Figure 9.

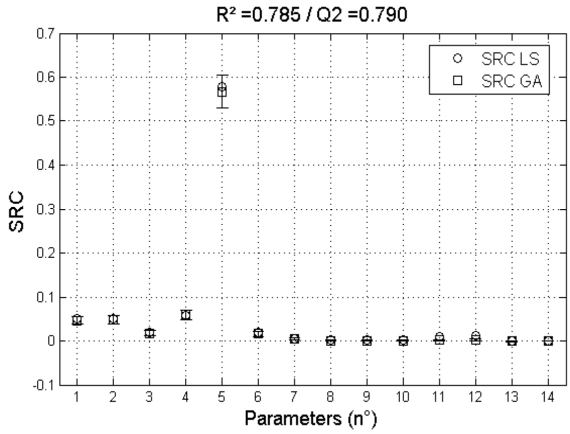
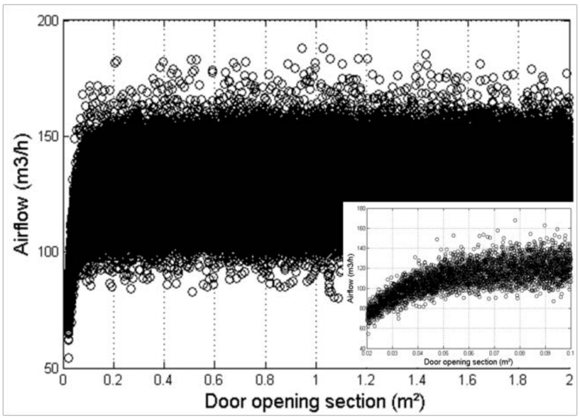


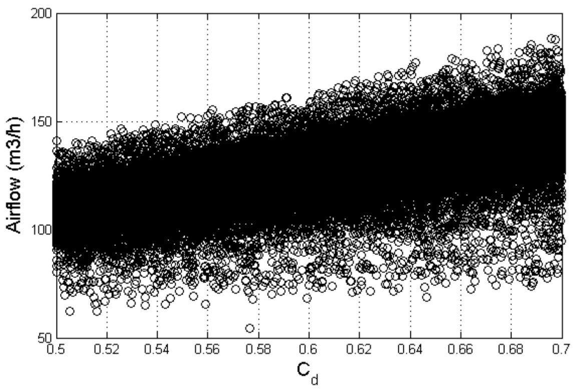
Figure 9. SRC's values for of 500 simulations using genetic algorithm (SRC GA) and using least square approach on 10^6 simulations (SRC LS) for Cfig . 4

For this case, the assumption of linear model is not as verified as for the previous cases. Values of R^2 and Q2 are slightly less than 0.8 which is still acceptable for global importance evaluation but it is worth noting that more than 20% of the outputs variance is not explained by SRC's analyses.
The results are surprising since, while the kitchen door opening sections was the dominant parameter for the previous cases, all doors opening section are negligible in this last case. By consequence, the discharge coefficient has gain in importance and the one for the external opening in the kitchen explains almost 60% of the output variance.

By analysing the scatter plot of doors opening sections over the output, it can be seen that the range of variation of the opening section is too large and make the effect negligible. Figure 10 below shows the scatter plots of the output upon the kitchen door opening section and the discharge coefficient. A zoom from 0.02 to 0.1m² is over plotted on the same figure for the former.



(a)



(b)

Figure 10. Scatter plot of the airflow in the kitchen upon the kitchen door opening section (a). A zoom is over plotted with opening section from 0.02 to 0.1m², and upon the kitchen discharge coefficient (b).

From Figure 10, it is clear that the effect of doors opening section are limited to small section from 0.02 to 0.1m² (fig.10 (a)) while influence seems to be constant for the complete range of variation of the discharge coefficient (fig.10 (b)). Above these opening sections, airflow rates are governed by other parameter such as discharge coefficient but also on the opening section of other openings. This threshold value of 0.1m² is a function of external opening section and would be certainly be greater for larger external opening section. Figure 10 explains also the non linearities of the model for this specific case.

Opposite observation would have been concluded if the range of variation of the discharge coefficient were greater for little internal opening section range of variation. Theses cases highlight the influence of other parameter as the opening ratios of the influence of one or another parameter.

In order to identify the most important parameter for ventilation design, it should be proceed step by step by considering different range of variation for the opening section areas. Their effect, and as it is for the discharge coefficient, is nonlinear because it is related to the pressure difference. Indeed, if the area is too important, the pressure difference on both sides of the opening will be equal and thus, any change in the discharge coefficient or in the opening area will not change the airflow rates through the opening.
This can be observed by computing successively the SCR's for case with different range of variation for the opening areas. This has been done by considering the same range of variation for any internal doors with the following range of variation: [0.01-0.02], [0.02-0.03], [0.03-0.04], [0.04-0.06], [0.06-0.08], [0.1-0.14]. For the cases considered in this study the external opening area was constant and fixed to 0.031m². Figure 11 present the SRC's computed as for the previous cases for the different simulations as a function of the opening ratios, α, which is the external (Sext) over internal (Sint) opening area. The results concern the kitchen parameters.

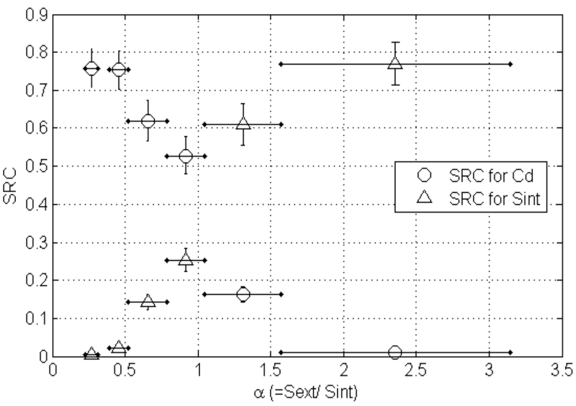


Figure 11. SRC's vs. opening ratio for the discharge coefficient of the external opening in the kitchen (symbol 'o') and the internal kitchen door opening section (symbol 'Δ').

The lowest predictive coefficient Q2 over all the 6 simulations is over 0.98, thus ensuring good linearity for each simulation. The importance index (SRC) for discharge coefficient and the internal opening areas of the internal door are presented. Vertical bars around means values express the standard deviation of each SRC's and horizontal bar represent the range of variation of the opening ratios, α, for each simulation.

Figure 11 clearly show the inverse trend for both parameters depending on the opening ratio. The one representing the greater pressure losses (the smallest opening area) have the greater influence on the considered output. The two parameters are inversing their importance around opening ratios equal to unity.

CONCLUSION

Sensitivity analyses have been performed between discharge coefficient and internal door areas. This study aims to identify which parameter ventilation designers should focus upon in order to achieve target values when the building is built. Several wind incidences were considered with a range of internal door areas. The order of importance identified can be explained by analysing the acting forces (pressure coefficient mainly for wind-driven ventilation).

The widely-held view that uncertainties on the discharge coefficient can be neglected, as they have less influence then the occupant behaviour, might be an error, for certain ranges of opening ratio. Even if these conclusions can sound trivial it has been demonstrated that attention should be paid where pressure losses are the greater.

Considering new energy-efficient buildings with an airtight envelope, airflow passes through controlled (in space) openings. The airflow/pressure laws used to design internal ventilation, and thus the energy consumption is governed, among other parameters, by the uncertainties in the discharge coefficient as well as the occupant behaviour. The relative importance of these two factors depends greatly on the opening ratio.

Thus, a stochastic approach to considering occupant behaviour in the energy consumption of a building is still needed, but research on the discharge coefficient or on corrections that should be applied to the pressure coefficient in order to take into account wind incidences, turbulence, velocity, etc. are also important. Both occupant behaviour and discharge coefficients should be understood to achieve will not guarantee to reach the target of energy efficient building.

ACKNOWLEDGEMENT

The authors would like to thank Fabrice De Oliveira, research engineer at CSTB, Nantes, for his contribution on the use genetic algorithm for sensitivity analyses.

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