TOWARDS BETTER INDOOR AIR QUALITY AND ENERGY EFFICIENCY BY USING AN OPTIMAL MECHANICAL VENTILATION STRATEGY

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Abstract

In cold and temperate climates, the increase of the buildings airtightness favoured a good energy performance but took part to the degradation of the indoor air quality (IAQ). Several methods exists to improve the IAQ and among them, the optimization of the ventilation strategy is one of the most efficient. This paper introduces a methodology combining a mathematical optimization technique and the building energy simulation in order to propose an optimal ventilation strategy monitored on two IAQ criteria while keeping in mind the energy efficiency aspect. In-situ feasibility of the ventilation system has also been taken into account through a smoothness objective of the ventilation profile calculation. Results allowed configuring efficiently the parameters of the ventilation algorithm. Moreover, each of them appeared to be robust according to the different climates.

Introduction

In cold and temperate climates, buildings are more and more insulated and their airtightness increases a lot. However, whereas those aspects are extremely beneficial in terms of energy efficiency, they affect a lot the indoor air quality. Recently, sanitary problems emerge and weaken both the occupant and the building health. Several methods exists to improve the IAQ and among them, the ventilation strategy is probably one of the most efficient. By this way, an efficient mechanical ventilation is unavoidable in recent and retrofitted buildings. This is why the French regulation ordered a required daily average ventilation rate of about 0.3 to 0.5 h^{-1} (CSTB, 2014). This ventilation strategy is quite efficient considering the energy aspect but much less considering the indoor air quality. To overcome this issue, recent ventilation strategies monitored on CO_2 concentration have been implemented and tested (K. Ahmed, 2015), (R. M. S. F. Almeida, 2015), (J. Yang, 2016). Indeed, the CO_2 proves to be the best occupancy indicator. Nevertheless, it is not self-sufficient to provide a good IAQ by the fact that it does not take into account the pollution produced by the building itself as the envelope, the furniture or the activity of the occupants (cooking, cleaning, smoking,..). A solution to improve even more the IAQ consists in monitoring the mechanical ventilation regarding always the CO_2 criterion but also another pollutant more related to the building structure and life. Many different sources of indoor air pollution are known. Among them, we can distinguish the physical, biological and chemical pollutants. For this study, one has focused our interest on chemical pollutants. Given that, to take into account the high quantity of chemical sources in the building, the total volatile organic component (TVOC) appear well adapted, by the fact that they represent a global indicator of the chemical pollutants released by the building envelop, the furniture, the activity of the occupants, etc... In this way, some recent studies showed the necessity to consider in the ventilation strategy both an occupant-related parameter as the CO_2 and a non-occupant-related parameter as the TVOC (C.Y.H. Chao, 2004). Furthermore, the ventilation strategy proposed by the ASHRAE 62.1 specifies a part devoted to the occupants and another one to the building area. In the same manner, the NF EN 15251 european rule requires a ventilation strategy with this kind of repartition.

Therefore, monitored ventilation operates in discharging pollutants from the indoor air. Nevertheless, whereas the regulation of some ventilation systems occurs according to the CO_2 concentration, it remains quite rare to control other IAQ criteria as the TVOC and to regulate simultaneously different IAQ criteria. Nevertheless, some studies have been investigated in the few last years. As an example, Rackes et al. (Adams Rackes, 2014) published a numerical study presenting an optimized ventilation strategy over one day taking into account the TVOC and CO_2 criteria as monitoring parameters without neglecting the energy efficiency aspect. The study concerned an office building in Philadelphia, USA. In the same way, Chao et al. (C.Y.H. Chao, 2004) tested experimentally a ventilation strategy monitored on CO_2 and radon criteria resulting in energy significant savings. Their experiments were carry out in a lecture theatre in China. However, ventilation strategies monitored on IAQ criteria remains unpopular by the fact that it frequently leads to an increase of the energy consumption. In this work, we propose to test numerically and optimize a mechanical ventilation strategy driven by IAQ objectives while taking into account energy considerations. Moreover, this numerical study has been planned to be tested in experimental conditions. That is why we introduced an in-situ deployment objective insuring the smoothness of the ventilation profile. Let us specify that this study is a first preliminary work deserving many improvements, which will be enounced in the perspectives of this paper.

Methodology

The methodology consists in coupling a building energy software (BES) which models the building behaviour (energy performance, thermal comfort and IAQ) with a programming environment, which controls the ventilation strategy.

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Building energy simulation

The EnergyPlus software has been used to model the thermal behavior over a given period of an individual house. This numerical model needs to be able to quantify the indoor air quality through pollutant concentrations. In addition to the thermal behavior, the EnergyPlus software allows precisely to follow the concentration evolution of both the carbon dioxide (CO_2) and an additional pollutant. CO_2 concentrations are estimated from the CO_2 emissions per inhabitants of the house. Concerning the pollutant concentration, several techniques allowing evaluating its evolution are available in the EnergyPlus software. The simpler one assumes a constant emission per thermal zones into the house. Some more detailed and accurate methods are also available. Among them, we distinguish the technique consisting in modeling the pollutant diffusion across the porous layers of the walls. This technique is known to be quite effective but a large drawback resides in the fact that it requires some input data that can be quite difficult to reach. Considering this common lack of data, one chose to use the simplest method that just requires the pollutant constant emission inside each zone of the building**.**

About the mechanical ventilation, EnergyPlus provides several simple strategies based on IAQ objectives that are quite efficient when it deals with only one criterion (CO_2 or pollutant). The Figure 1 and Figure 2 present respectively the TVOC and CO_2 concentrations in an individual house resulting from a ventilation strategy monitored exclusively on respectively CO_2 and TVOC. The dotted lines represent the setpoints. The necessity to consider several IAQ objectives with at least the CO_2 and the TVOC appears clearly on these graphs.

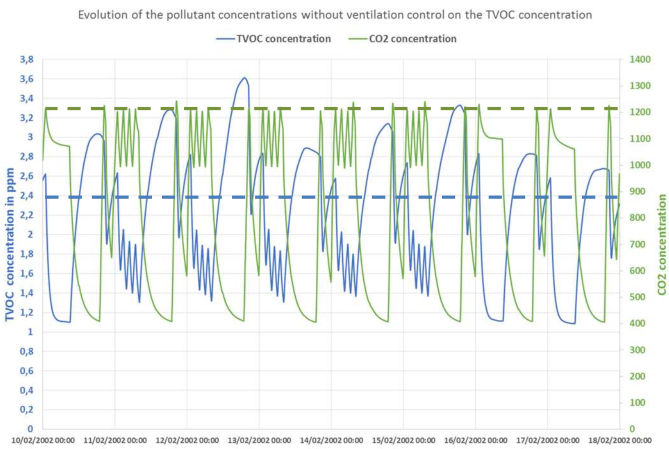

Figure 1 : Evolution of the pollutant concentrations with a ventilation control only based on CO_2 concentration (the TVOC concentration in blue with a setpoint of 2.4 ppm and the CO2 concentration in green with a setpoint of 1200 ppm)

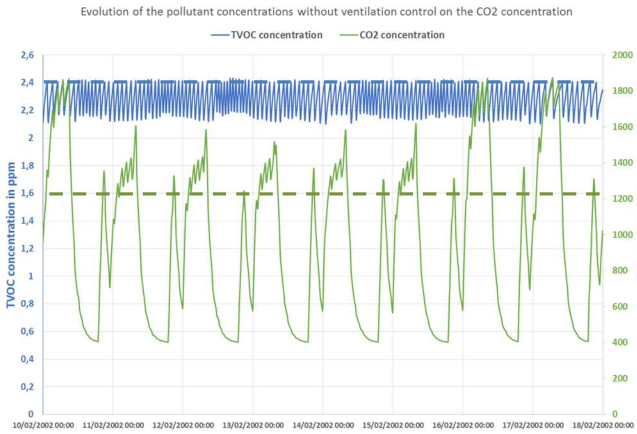

Figure 2 : Evolution of the pollutant concentrations with a ventilation control only based on TVOC concentration (the TVOC concentration in blue with a setpoint of 2.4 ppm and the CO2 concentration in green with a setpoint of 1200 ppm)

Therefore, one proposed to test an in-house strategy taken into account both CO_2 and a pollutant criteria. That is why, this strategy has been implemented as an external algorithm evaluating at each time step the value of the ventilation rate based on the CO_2 and a pollutant concentrations at the previous time step. It has been written in the MATLAB environment. For that, MATLAB and EnergyPlus has been be coupled at each time step. The MATLAB program must be able to evaluate and to return the ventilation rate of the EnergyPlus calculation. Likewise, EnergyPlus must be able to provide the CO_2 and pollutant concentrations to the MATLAB algorithm and to recover the required inputs (ventilation rates). To do that, a communication open-source platform developed by the DOE (Department of Energy) and called BCVTB (Building Control Virtual Test Bed) has been used (cf. Figure 3).

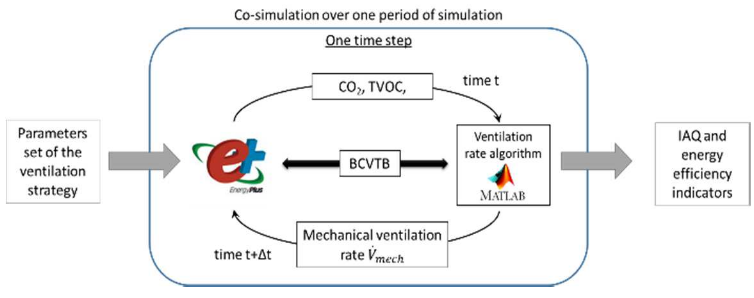

Figure 3: Scheme of the co-simulation

The studied building is a 100-m² energy efficient house on one floor containing height zones. In order to maintain a reasonable computation time, the simulation took place on the short period of the month of February corresponding to a simulation period of 28 days with a time step of 5 min. Several French climates have been tested:

- Bordeaux in the South-West of France.
- Paris in the North of France.
- Strasbourg in the North-East of France.
- Nantes in the North-West of France.

- Nice in the South-East of France.

One has focused more specifically on one bedroom of about 10 m² containing a south oriented window, well-insulated exterior walls on the South and the West façade and partitions on East and North walls. One assumed an occupation of one person in the bedroom and no occupation in other zones. The emission rate of CO_2 per person was fixed to 20 l/h. The occupancy planning in the bedroom is given in Figure 4 in GMT time (for France, +1 in winter and in summer +2 from the UTC time). The room is modelled as a closed system without air transfer from or to other zones or the outdoor environment except by infiltration raising to about 0.1 h^{-1}.

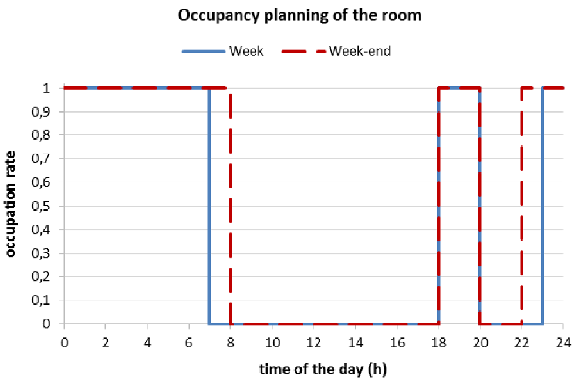

Figure 4: Occupation rate along the day in the room

Considering the pollutant emission, the EnergyPlus software is limited to only one pollutant. Thus, we modelled the variation of the TVOC by assuming an emission rate corresponding to the French A+ category (Journal officiel de la République française du 13 Mai 2011). It suggests a maximal emission for a floor or a ceiling at 1250 µg/m²/h and for a vertical wall at 500 µg/m²/h (Journal officiel de la République française du 13 Mai 2011). Contrary to the CO_2 emission linked to the occupation, this emission rate has been set in all zones of the house.

Our objective was both to optimize the IAQ and the energy efficiency. Thus, the heating consumption are also calculated. The heating system considered in the simulation is an electric convective heater. The schedule of the heating setpoint is given in Figure 5.

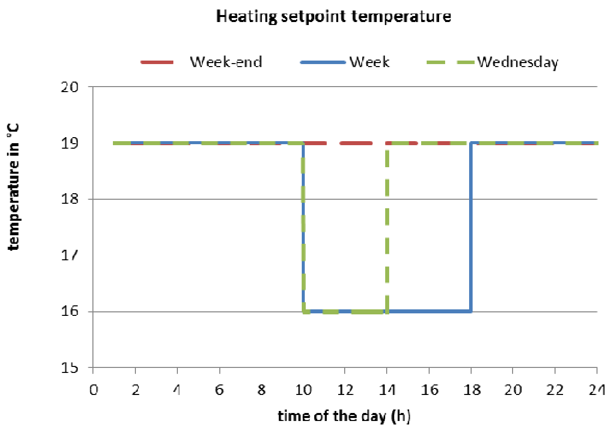

Figure 5: Planning of the heating setpoint temperature

Fans modelled in the simulation assume variable flows and are really efficient.

Concerning the thresholds, the CO_2 and TVOC concentration setpoints were respectively fixed to 1200 ppm and 3 mg/m³ (Schriver-Mazzuoli, 2009), (Legris, 2007), (Molhave, 1991). The chosen threshold for the TVOC is the highest bound of the usually prescribed values (from 0.3 to 3 mg/m³) but this numerical work was constrained by the feasibility of the experimental phase. Moreover, EnergyPlus expressed the pollutant concentration in ppm. Given that the TVOC concentration has been converted in ppm. This conversion is function of the molar mass and the molar volume:

$$C(ppm) = C(mg/m^3)\frac{V_M}{M}$$

where V_M is the molar volume (L.mol^{-1}) and M the molar mass (g.mol^{-1}). TVOC contains many different molecules. The concentration is expressed in formaldehyde basis which corresponds to $V_M = 24.05\ L/mol$ at 20°C, 1 atm, and $M = 30\ g/mol$. Thus, the TVOC setpoint raises to 2.4 ppm.

MATLAB algorithm

The control command has been implemented in the MATLAB numerical environment. The objective of the monitoring algorithm is to estimate at each time step the value of the ventilation rate in h^{-1}. To do that, some variables have been introduced:

- **C_CO₂(t-Δt)** : the CO_2 concentration at the previous time step in ppm
- **C_TVOC(t-Δt)**: the TVOC concentration at the previous time step in ppm
- **C_CO₂max**: the CO_2 concentration setpoint in ppm
- **C_TVOCmax**: the TVOC concentration setpoint in ppm
- **Ventilation_rate(t)**: the resulting ventilation rate at the time step in h^{-1}
- **rate_TVOC_CO2**: initial ventilation_rate in h^{-1} imposed when both CO_2 and TVOC concentrations exceed their setpoints
- **rate_TVOC**: initial ventilation_rate in h^{-1} imposed when only TVOC concentration exceeds its setpoint

- **rate_CO2**: initial ventilation_rate in ACH imposed when CO_2 concentration exceeds its setpoint
- **rate_neither** : initial ventilation rate in h^{-1} imposed when both CO_2 and TVOC concentrations respect their setpoints (not necessary equal to zero)
- **rate_inc** : constant increment of ventilation rate in h^{-1}
- **tempo_max** : maximal inactive time in min

More precisely, the monitoring algorithm encloses a ventilation strategy consisting in the application of the given rates (those described above) for each different invalid IAQ conditions:

- $C\_CO_2(t\text{-}\Delta t) > C\_CO_2max$ and $C\_TVOC(t\text{-}\Delta t) > C\_TVOCmax$
- $C\_CO_2(t\text{-}\Delta t) < C\_CO_2max$ and $C\_TVOC(t\text{-}\Delta t) > C\_TVOCmax$
- $C\_CO_2(t\text{-}\Delta t) > C\_CO_2max$ and $C\_TVOC(t\text{-}\Delta t) < C\_TVOCmax$

Moreover, the algorithm offers the opportunity to increase gradually this ventilation rate until a maximal value as long as the invalid situation remains unchanged or evaluates even worst. Furthermore, a temporisation has been considered as a parameter of the ventilation strategy in order to maintain the same ventilation rate during a specific time.

Therefore, the ventilation rate is calculated at each time step and is then returned to the EnergyPlus software. As we mentioned before, the concentration setpoints *C_CO₂max* and *C_TVOCmax* have been fixed to respectively 1200 ppm and 3 mg/m^3 (that is 2,4 ppm in a formaldehyde basis) in agreement with the health values. Concentrations *C_CO2* and *C_TVOC* are supplied by the EnergyPlus software at each time step.

The unknown parameters *tempo_max*, *rate_TVOC_CO₂*, *rate_TVOC*, *rate_CO₂*, *rate_neither* and *rate_inc* will be evaluated with an adapted optimization technique.

In order to adapt the algorithm to a real occupied environment, one has proposed to add a hysteresis. The goal is to avoid the sudden and frequent variations that could degrade the mechanical ventilation system in a real building. Thus, we will try to smooth the ventilation profile as far as possible. The Figure 6 schematizes this hysteresis. The abscissa corresponds to the time. Indeed, one consider reference rates for all different configurations of concentrations profiles. But instead of moving the ventilation rate each time the value of the schedule is reached, the rate is modified only when the concentration goes up C_{up} and goes down C_{down}, C_{up} being higher than C_{down}.

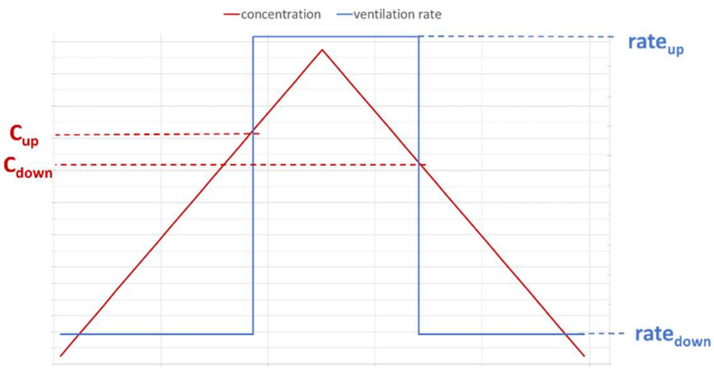

Figure 6: Evolution of the ventilation rate considering the pollutant concentration

C_{up} and C_{down} are two variables of the ventilation algorithm that will be estimated for each pollutant with the optimization technique. Thus, four parameters dedicated to the hysteresis characteristics will be estimated with $C_{TVOC,up}$, $C_{TVOC,down}$, $C_{CO2,up}$ and $C_{CO2,down}$. To do that efficiently, a criterion of smoothness will be added to the IAQ and energy efficiency aspects in the optimization problem.

Finally, ten parameters will be identified from a well-chosen optimization technique with the aim to find the best solution considering three different objectives: the indoor air quality, the energy efficiency and the smoothness of the ventilation profile. All of them will be evaluated in order to respect as much as possible the three following criteria with the IAQ, the energy efficiency and the smoothness objectives. To do that, we employed the optimization technique called Particle Swarm Optimization (PSO). In the following section, we propose to explain it briefly and to introduce the objective function used to resolve the optimization problem

Optimization technique: Particle Swarm Optimization (PSO)

The objective of our study is to propose an optimized ventilation strategy improving the indoor air quality (IAQ), the energy efficiency (EE) and the smoothness of the ventilation profile. In order to do that, we employed an optimization technique based on a mathematical approach. The objective of such a technique is to find as fast as possible the set of unknown parameters allowing reaching one or several criteria. A simple way would be to randomly draw and test several parameters sets but it would require a large amount of explorations to be sure to have the best solutions. More the number of parameters sets to test, more the increase of the computation time. Indeed, each set of parameters must be tested numerically that can lead to a huge computation time. In order to avoid this effect, the optimization technique employed in this study allows reducing drastically the amount of explored parameters sets that leads to a minimal resort to the numerical model.

Principle of the PSO

The PSO algorithm is a meta-heuristic optimization algorithm. This technique has been developed by Eberhart and Kennedy (Eberhart, 1995). It is inspired by the social behavior of birds' displacement. Indeed, their collective displacements can be quite complex, whereas the individual displacements are generally really basics. The algorithm uses this principle by using both the individual and collective information to generate optimized displacements that will define the new positions of each birds. Concretely, a bird corresponds to parameter set. Generally, one speaks about "particle".

An initial particles basis constituted from *N* parameters sets is generated. Each particle are constituted of *D* parameters that is a vector of D-dimension. For our application, one particle consists in one set of the 6 unknown parameters given above. Thus, the dimension of the particle is D=6. Then, each particles with its objective functions are send to the PSO algorithm. New positions are generated from the following rules:

- $v_{i,j}^{t+1} = w.v_{i,j}^{t} + c_1.r_{1_{i,j}}^{t}\left(p_{best_{i,j}}^{t} - x_{i,j}^{t}\right) + c_2.r_{2_{i,j}}^{t}\left(g_{best_j}^{t} - x_{i,j}^{t}\right)$
- $x_{i,j}^{t+1} = x_{i,j}^{t} + v_{i,j}^{t+1}$

i varies from 1 to *N* and defines which particle is considered, *j* varies from 1 to *D* and is the dimension of the particles and *t* varies from 1 to *iter* and is the iteration number. $v_{i,j}^{t+1}$ is improperly called the velocity and it characterizes the spatial displacement of each particle. $x_{i,j}^{t+1}$ is the new position of the particle. $c_1.r_{1_{i,j}}^{t}\left(p_{best_{i,j}}^{t} - x_{i,j}^{t}\right)$ characterizes the cognitive displacement of the particle and $c_2.r_{2_{i,j}}^{t}\left(g_{best_j}^{t} - x_{i,j}^{t}\right)$ the social displacement. c_1 and c_2 are constants parameters and $r_{1_{i,j}}^{t}$ and $r_{2_{i,j}}^{t}$ are two random numbers varying between 0 and 1. *w* is an inertial parameter allowing to control the influence of the displacement direction. $p_{best_{i,j}}^{t}$ and $g_{best_j}^{t}$ are calculated with the following formulation :

- $p_{best_i}^{t+1} = \begin{cases} p_{best_i}^{t} & \text{if } f(x_i(t+1)) \geq p_{best_i}^{t} \\ x_i(t+1) & \text{otherwise} \end{cases}$
- $g_{best_j}^{t} = \arg min_{p_{best_i}^{t+1}} f\left(p_{best_i}^{t+1}\right), \ \ 1 \leq \mathrm{i} \leq N$

f being the objective function. New positions are recalculated *iter* times for each particles. Thus, without any convergence criterion, the total exploration number will be *iter* x *N*.

Advantages and drawbacks of the PSO

The PSO technique has the great advantage to be really easy to implement and most of the time, it is really efficient to converge towards the best solution.

However, the PSO algorithm has some disadvantages, notably concerning the large number of constant parameters to define: c_1 the cognitive constant, c_2 the social constant, *w* the inertial parameter, *N* the number of particles and *iter* the number of iterations. Moreover, the PSO algorithm can converge on a local optimum instead of a global one. Some techniques exists to avoid this problem.

Parameters of the PSO

For our study, one has considered a number N of particles of 20 and a number of iteration of 25. This selection allowed reaching the convergence of the model.

Multi-objective optimization problem: definition of the objective function

The definition of the objective function plays a crucial role in the optimization problem. In our application, a particularity appears given the multi-objective issue with the IAQ, the energy efficiency and the smoothness of the ventilation profile. The multi-objective optimization can be quite complicated by the fact that it is rarely possible to satisfy all the criteria. Thus, a multi-objective optimization problem cannot guarantee the uniqueness of the solution. However, it will give as results a set of solutions, each of them allowing reaching as well as possible the different criteria. Several methods considering multi-objective optimization exists and among them, two techniques are particularly employed in the building field (Vasileios Machairas, 2014), (Evins, 2013), (Anh-Tuan Nguyen, 2014): first, there is the Pareto optimality or Pareto non-dominance consisting to keep the only feasible solutions able to improve one objective without deteriorating at least another one. The second method consists in formulating the multi-objective problem as a mono-objective one. All the objective functions are then gathered in one unique objective defined as a weighted sum function of all these different objectives. Furthermore, in this last case, the definition of the objective function is even more determinant for the optimization problem. For our study, one has chosen to employ the Pareto non-dominance method. Thus, the method results in a set of solutions presented as a solutions frontier defined by all the explored points that minimize at least one criterion compared with another explored point. This frontier is commonly called the "Pareto front".

First, we will define an objective function for each criterion, energy efficiency (EE), indoor air quality (IAQ) and the smoothness of the ventilation profile.

EE objective function

The objective function allowing quantifying the energy efficiency is given by the following equation. It deals with the estimation of the consumption on the simulation period (in our case, one month). It is expressed in kWh.

$$fitnessEE = \frac{\sum_t Power_t}{1000} \cdot \frac{\Delta t}{60}$$

where $Power_t$ is the power at each time step, $A_{building}$ the building area and Δt the simulation time step. Then, the objective function of the energy efficiency criterion corresponds to the heating needs along the simulation period and is expressed in kWh/m²/year. Consciously, we do not take into account the fan contribution in the calculation of the EE function regarding the large efficiency of the selected fans.

IAQ objective function

The objective function allowing quantifying the IAQ is enounced as follows. This criterion is quite more complicated to implement compared with the energy efficiency indicator by the fact that it deals with a temporal field. This parameter does not have physical meaning and can exceed 100% but it can be interpreted as smaller the objective function, better the indoor air quality. This indicator has been extracted from (Adams Rackes, 2014).

$$fitnessIAQ = \sum_{i=1}^{2}\sum_{j=1}^{2}\omega_j.\left(\frac{max(metric_{ij}, setpoint_i) - setpoint_i}{setpoint_i}\right)^{N_{power}} * 100$$

$$\begin{cases} metric_{11} = \max(C_{TVOC}) \\ metric_{12} = \text{mean}(C_{TVOC}) \\ metric_{21} = \max(C_{CO2}) \\ metric_{22} = \text{mean}(C_{CO2}) \end{cases}$$

where the index *i* indicates which pollutant among TVOC and CO_2 is considered. The $metric_{ij}$ is either the maximum or the arithmetic mean of the CO_2 and TVOC concentration. ω_j is a weight given to each of these metrics *j* (0.25 for the maximum and 0.75 for the mean). $setpoint_i$ is the concentration setpoint (C_CO2max for the CO_2 and C_TVOCmax for the TVOC). And N_{power} is a power number that allows to increase non linearly the importance of IAQ criterion in the optimization problem when the resulting concentration is too high compared with the setpoint and to decrease drastically this impact when this difference is less important. For our purpose, we assumed a value of N_{power} of 2 in order to remain focused precisely on the IAQ criterion. Finally, the factor 100 is added in order to express this dimensionless objective function in percent.

Smoothness objective function

As it has been mentioned above, it would be better to have ventilation profile with only few sudden and frequent variations to prevent the fan erosion. Thus, one has proposed to add this aspect as an objective of the optimization technique. The smoothness indicator has been defined from the Fourier transform. Indeed, it allows translating with high frequency the non-smooth behavior of the ventilation profile. More precisely, the smoothness indicator has been calculated with the integral of the Fourier spectrum. Larger the indicator, smaller is the smoothness and inversely.

Summary of the methodology

The Figure 7 summarizes the employed methodology. Note that the energy efficiency consideration is not taken into account as a ventilation controller. However, the MATLAB algorithm encloses the ventilation strategy, whose efficacy according to the IAQ, the energy efficiency and the smoothness aspects depends on unknown input parameters.

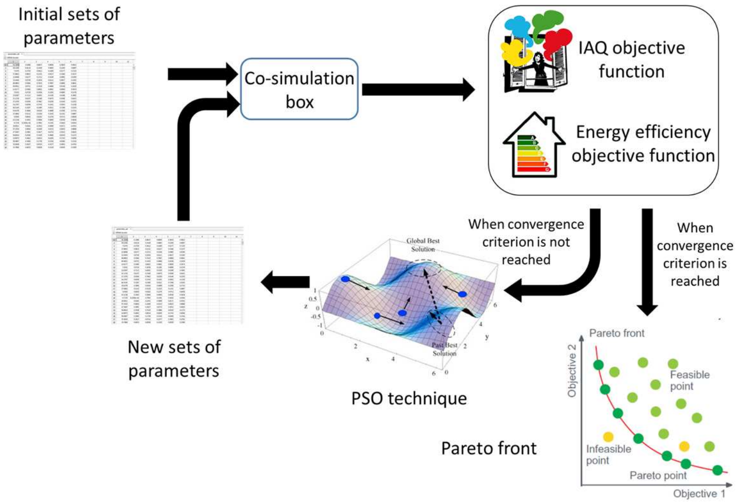

Figure 7: Optimization method (C. Gollub, 2009)

In total, there are 10 parameters of the ventilation algorithm to estimate: *tempo_max*, *rate_TVOC_CO₂*, *rate_TVOC*, *rate_CO₂*, *rate_neither*, *rate_inc*, $C_{TVOC,up}$, $C_{TVOC,down}$, $C_{CO2,up}$ and $C_{CO2,down}$. Each of them varies over a range of values given here:

- tempo_max : [5; 60] min
- rate_TVOC_CO_2 : [0.1; 1] h^{-1}
- rate_TVOC : [0.1; 1] h^{-1}
- rate_CO_2 : [0.1; 1] h^{-1}
- rate_neither : [0.1; 1] h^{-1}
- rate_inc : [0.1; 0.3] h^{-1}
- $C_{TVOC,up}$: [1.8; 2.2] ppm
- $C_{TVOC,down}$: [2.2; 2.6] ppm
- $C_{CO2,up}$: [800; 1100] ppm
- $C_{CO2,down}$: [1100; 1400] ppm

The limitation to 1 h^{-1} for the ventilation rate is simply due to the fact that an experimental phase would follow this theoretical study and the expected fan is limited to 1 h^{-1}.

Results and discussion

Two levels of results will be summed up in the following. A first level will consist to treat specifically the Bordeaux climate. This study will consist to estimate the ten parameters. To do that, one proposes to visualize and study different sets of solutions resulting from the optimization phase and to deduce the best compromise relative to the three criteria. The second level will consist to apply the resulting estimated parameters to other climates and to check the robustness of both the ventilation algorithm and the estimated parameters.

How to determine the best solution among several optimized non-dominated solutions?

As we mentioned before, the multi-objective optimization does not allow giving a single unique solution. More specifically, in our study, the three objectives are contradictory. Indeed, a good energy efficiency is associated with a small ventilation rate, which leads to a bad IAQ. The inverse situation is obviously also true. Moreover, the smoothness criterion should spoil even more the energy efficiency when the IAQ is successfully reached. Inversely, when the EE aspect is well respected, the IAQ criterion should be degraded because of the smoothness condition. Therefore, an important step is then to be able to identify the best solution considering the objectives of the user and its physical expertise. One proposed in this paragraph to present few solutions belonging to the Pareto front and to see their impact on the three different criteria. For this study, the Bordeaux climate has been used. The optimization algorithm gave 20 Pareto non-dominated solutions. Six of them are summed up in the following table. The Table 1 gathers the values of each objectives for those six solutions.

Table 1: Objectives for the six studied Pareto non-dominated solutions

N° of the solution	Energy efficiency indicator (kWh)	Indoor air quality indicator (%)	Smoothness indicator
1	761	0	7
2	224	4714	2.0
3	355	69	6.2
4	418	6	11.0
5	413	0.7	31.0
6	407	0.04	109.2

Remember that the energy efficiency indicator is the monthly heating consumption, and the indoor air quality and the smoothness indicators are both non-dimensional values without specific physical meanings. In a general way, smaller the indicators, better the solution. Thus, obviously, it appears that none of these solutions is able to minimize all the objectives in a same solution. The choice of the "best" solution will then be a compromise considering the expectations of the user. First, it is interesting to see the temporal evolution of the ventilation profile and the occurrence of the TVOC and CO_2 concentrations considering certain of these solutions. One proposed to present three extreme cases and the best compromise between the three aspects:

- the solution n°1 for which the energy efficiency is remarkably bad.
- the solution n°2 for which the IAQ is remarkably bad.
- the solution n°6 for which the smoothness is remarkably bad.
- the solution n°5 which appears as the best compromise between the three different objectives.

The following part will consist to explain the choice of the solution n°5 as the best compromise regarding the indoor air quality, the energy efficiency and the smoothness of the ventilation profile.

As we mentioned above, best energy efficient solutions are generally correlated with worst IAQ and inversely. Moreover, these kinds of extreme solutions result in a good smoothness indicator given the fact that the ventilation profile is almost constant. The Figure 8 shows the ventilation profile for the solutions 1, 2 and 5 during one week of the February month. One observes clearly the fact that a bad IAQ and a bad EE (solution n°2 and n°1 respectively) lead to an almost constant ventilation rate. More precisely, a solution exclusively focused on a good EE resulting on a bad IAQ as the solution n°2 (in yellow on the Figure 8) causes a small ventilation rate. Inversely, a solution exclusively focused on a good IAQ resulting on a bad EE as the solution n°1 (in blue on the Figure 8) conducts to a large ventilation rate.

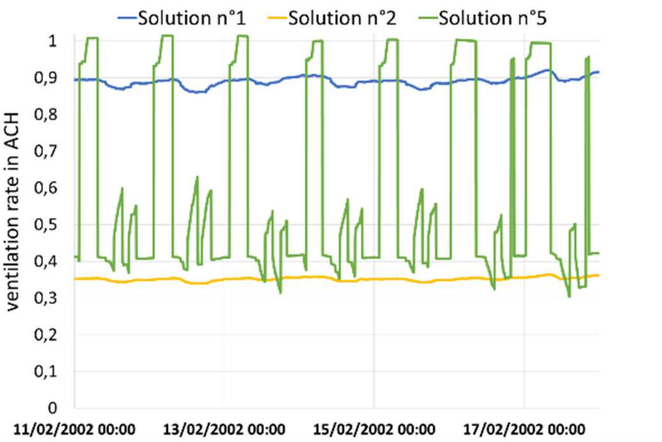

Figure 8: Ventilation flow profile for the solution n°1, the solution n°2 and the solution n°5 during one week of the February month

The profile of the solution n°5 is clearly less smooth as the two others. However, compared with the solution n°1, it appears clearly as a better solution considering the energy efficiency aspect. Indeed, the solution n°1 presents an energy efficiency indicator raising to 761 kWh whereas the solution n°5 boasts an energy consumption of 413 kWh. Concerning the IAQ aspect, a compromise is absolutely needed to combine the EE expectation. That is why the objective obtained with the solution n°1 is not realistic for a multi-criteria optimization. However, it is possible to reach a reasonable degree of indoor air quality while maintaining a good energy efficiency. In this way, one can see the large improvement in IAQ obtained with the solution n°5 compared with the solution n°2. Indeed, the Figure 9 and Figure 10 presents the histograms and the cumulative probability function (CPF) of the pollutants frequency along the February month for the solution n°5.

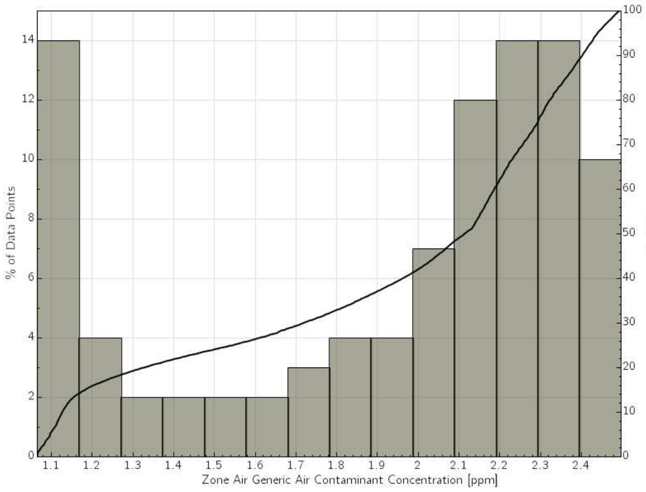

Figure 9 : Histogram and cumulative probability function for the solution n°5 of the TVOC concentration over the February month

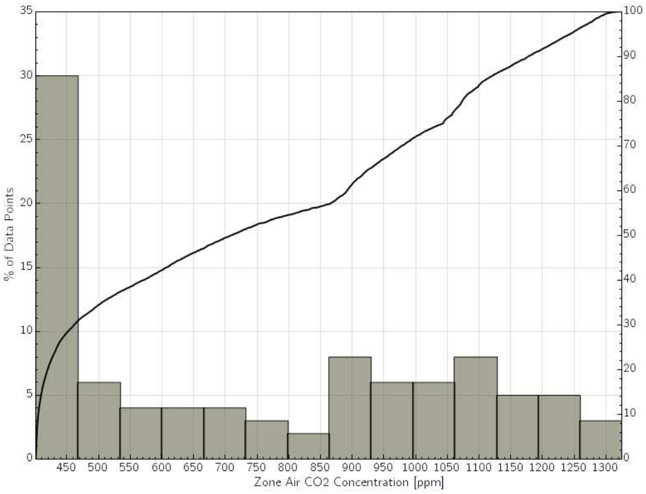

Figure 10 : Histogram and cumulative probability function for the solution n°5 of the CO_2 concentration over the February month

Likewise, the Figure 11 and Figure 12 present the histogram and the cumulative probability function of the pollutants concentration during the month of February for the solution n°2. One observes clearly a higher frequency of concentrations values above the thresholds defined previously (1200 ppm for the CO_2 and 2.4 ppm for the TVOC) for the solution n°2.

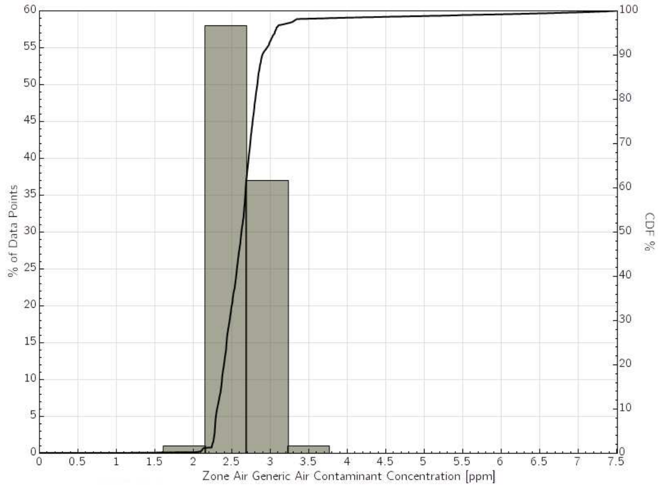

Figure 11: Histogram and cumulative probability function for the solution n°2 of the TVOC concentration over the February month

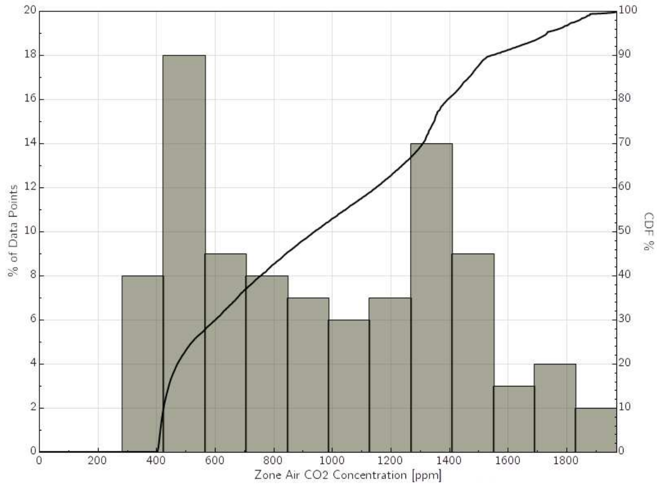

Figure 12: Histogram and cumulative probability function for the solution n°2 of the CO_2 concentration over the February month

Thus, the solution n°5 allows improving the indoor air quality while maintaining a good energy efficiency. Let us look at this solution considering the last criteria of smoothness. As we mentioned above, a solution presenting a totally smooth ventilation profile is not conceivable given the two other IAQ and EE objectives. However, the optimization technique suggests that a compromise is possible. The Figure 13 presents the ventilation profile for the solution n°19 during the same period as the Figure 8. This solution presents quite similar results as the solution n°5 considering the IAQ and the EE aspects. However, as it was expected, it shows a bad smoothness of the profile given the large amount of ventilation peaks. This profile can be compared with the solution n°5 represented in green on the Figure 8. Despite some unavoidable peaks of ventilation, they are really less abundant. Moreover, an almost constant ventilation rate is maintained for a more reasonable period. By this way, it could limited a lot the erosion of the ventilation system.

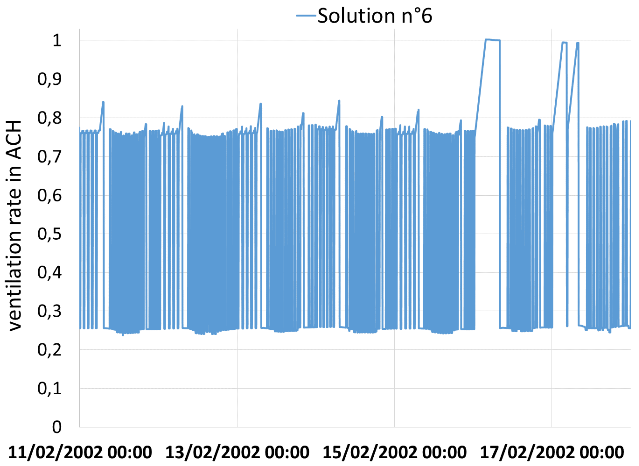

Figure 13 : Ventilation flow profile for the solution n°6 during one week of the February month

Finally, considering the three objectives of indoor air quality, energy efficiency and smoothness of the ventilation profile, the best compromise seems to be the solution n°5. The estimated parameters are equal to:

- tempo_max = 60 min
- rate_TVOC_CO$_2$ = 0.58 h^{-1}
- rate_TVOC = 0.45 h^{-1}
- rate_CO$_2$ = 0.89 h^{-1}
- rate_neither = 0.39 h^{-1}
- rate_inc = 0.005 h^{-1}
- $C_{TVOC,up}$ = 2.15 ppm
- $C_{TVOC,down}$ = 2.48 ppm
- $C_{CO2,up}$ = 800 ppm
- $C_{CO2,down}$ = 1297 ppm

To conclude this part, we propose to compare the solution n°5 with results obtained for the French constant regulatory ventilation rates of 0.3 and 0.5 h^{-1} . The Table 2 presents this comparison. Compared with the two regulatory strategies, one observes shorter IAQ indicator for the solution n°5. This aspect is even more remarkable for the 0.3 h^{-1} ventilation rate. Considering the smoothness indicator, we registered a smaller indicator given that the ventilation rate is always equal to 0.3 or 0.5 h^{-1}. Last, considering the energy efficiency considerations, our optimal ventilation strategy presents a better performance compared with the 0.5 h^{-1} ventilation rate. However, the regulatory strategy of 0.3 h^{-1} shows a quite smaller monthly consumption, but considering the huge gain on the indoor air quality, the compromise is largely acceptable. Thus, these results show the great efficiency of our ventilation strategy compared with the traditional one.

Table 2: Comparison between the optimized solution n°5 and the regulatory strategies at the constant ventilation rate of 0.3 and 0.5 h^{-1}

Case study	Energy efficiency indicator (kWh)	Indoor air quality indicator (%)	Smoothness indicator
Solution n°5	413	0.7	31.0
Regulatory solution at 0.5 ACH	507	2.6	4.0
Regulatory solution at 0.3 ACH	364	52.7	2.4

In the following, the above estimated parameters will be applied to other climates. From this study, we will see the robustness of the ventilation algorithm and the estimated parameters.

The robustness of our optimal ventilation strategy considering the climate change

This part consists in showing the robustness of our optimal ventilation strategy. In order to have a reference value for each indicator, the French constant regulatory ventilation rates of 0.5 and 0.3 h^{-1} has been also tested on other climates. The Table 3 and Table 4 gather the respective results.

Table 3: Indicator values for the French regulatory flow rate of 0.5 ACH for each studied climate

Localization	Energy efficiency indicator (kWh)	Indoor air quality indicator (%)	Smoothness indicator
Bordeaux	507	2.6	4.0
Paris	701	2.0	4.0
Strasbourg	908	1.7	4.0
Nantes	529	3.1	4.0
Nice	171	2.9	4.0

Table 4: Indicator values for the French regulatory flow rate of 0.3 h^{-1} for each studied climate

Localization	Energy efficiency indicator (kWh)	Indoor air quality indicator (%)	Smoothness indicator
Bordeaux	364	52.7	2.4
Paris	533	27.1	2.4
Strasbourg	710	20.3	2.4
Nantes	383	37.5	2.4
Nice	86	42.0	2.4

We can again see the constant value of the smoothness indicator considering all the climates. Then, the optimal solution n°5 has been applied to the four other climates. Results are summed up in the Table 5.

Table 5: Indicator values for each studied climate considering the parameters obtained with the solution n°5 in the Bordeaux climate

Localization	Energy efficiency indicator (kWh)	Indoor air quality indicator (%)	Smoothness indicator
Bordeaux	413	0.7	31.0
Paris	585	0.6	31.1
Strasbourg	759	0.6	32.8

Nantes	429	0.7	30.8
Nice	118	0.6	28.1

The results show a good robustness of our ventilation strategy considering all the indicators. Indeed, the IAQ and smoothness criteria are quite similar considering each localization and the monthly energy consumption is varying obviously function of the climate but remains always smaller than the 0.5 h^{-1} ventilation rate. Moreover, the loss in energy efficiency registered compared with the regulatory ventilation of 0.3 h^{-1} is always compensated by the huge gain on the indoor air quality. Finally, we can conclude that the combined IAQ and EE compromise is always more effective with our optimal ventilation strategy than the regulatory strategies. These considerations reinforce even more the robustness of our optimal ventilation strategy.

Conclusions and perspectives

In this paper, a methodology determining an optimized ventilation strategy has been introduced in order to improve the indoor air quality while maintaining a good energy efficiency. Moreover, a component of in-situ feasibility has also been taken into account. Therefore, the study was focusing on three different objectives. First, the indoor air quality took part through both the CO2 concentration for the occupant-related pollution and the TVOC concentration for the non-occupant-related pollution. Second, the heating consumption allowed evaluating the energy efficiency. Third, the smoothness of the ventilation profile was chosen to represent the in-situ feasibility. By using an efficient and adapted optimization technique, an optimal and robust ventilation strategy has been deduced. Its robustness has been tested successfully on several French climates.

As we mentioned above, this study presents first preliminary results that would deserve many improvements. Thus, many perspectives follow this work:

- To test other building configurations (geometries, usages) in order to check the robustness of the methodology.
- To improve the ventilation algorithm by introducing as an example a PID.
- To improve the pollutant modelling by testing and evaluating the different methods available in the EnergyPlus software.
- To improve the definition of the indicators to improve the optimization phase and to simplify the interpretation of the results.
- To add some other pollutants as the physical or biological pollutants and also the humidity.
- To understand the impact of the input parameters of the building energy simulation on the ventilation strategy (sensitivity analysis)

Finally, this numerical work has been associated with first experimental tests. Employed IAQ sensors to measure CO_2 and TVOC concentration are the Nanosense E4000. Many improvements need to be done but first results were really convincing and motivate the following of the study.

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References

Adams Rackes, Michael S. Waring. "Using multiobjective optimizations to discover dynamic building ventilation strategies that can improve indoor air quality and reduce energy use." *Energy and Buildings* 75 (2014): 272–280.

Anh-Tuan Nguyen, Sigrid Reiter, Philippe Rigo. "A review on simulation-based optimization methods applied to building performance analysis." *Applied Energy* 113 (2014): 1043–1058.

C.Y.H. Chao, J.S. Hu. "Development of a dual-mode demand control ventilation strategy for indoor air quality control and energy saving." *Building and Environment* 39 (2004): 385-397.

CSTB. *Avis Technique 14/13-1911: Systèmes de ventilation mécanique hygroréglable ATLANTIC.* 2014.

Eberhart, James Kennedy and Russell C. "Particle Swarm Optimization." *Proceedings of the 1995 IEEE International Conference on Neural Networks*, 1995: 1942–1948.

"Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria." no. ISO 7730:2005. ISO, 2005.

Evins, Ralph. "A review of computational optimisation methods applied to sustainable building design." *Renewable and Sustainable Energy Reviews* 22 (2013): 230-245.

"Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics." no. NF EN 15251. 2007.

J. Yang, B. Zhou, M. Jin, J. Wang, F. Xiong. "A novel complex air supply model for indoor air quality control via the occupant micro-environment demand ventilation." *Chaos, Solitons and Fractals* 89 (2016): 474-484.

Journal officiel de la République française du 13 Mai 2011, texte 15. *Arrêté du 19 Avril 2011*. 2011.

K. Ahmed, J. Kurnitski, Piia Sormunen. "Deman controlled ventilation indoor climate and energy performance in a high performance building with air flow rate controlled chilled beams." *Energy and Buildings* 109 (2015): 115-126.

Legris, Michel. *Les valeurs de référence de confort et indicateurs de la qualité de l'air.* Vol. 30. Objectif prévention, 2007.

Molhave, Lars. "Volatile organic compounds, Indoor Air Quality and Health." *Indoor Air* 4 (1991): 357-376.

R. M. S. F. Almeida, V. P. de Freitas. "IEQ assessment of classrooms with an optimized demand controlled ventilation system." *Energy Procedia* 78 (2015): 3132-3137.

Schriver-Mazzuoli, L. "La pollution de l'air intérieur-Sources-Effets sanitaires-Ventilation." (Dunod) 2009.

Vasileios Machairas, ArisTsangrassoulis, KleoAxarli. "Algorithms for optimization of building design : A review." *Renewable and Sustainable Energy Reviews* 31 (2014): 101-112.