IMPLEMENTATION OF MULTI-ZONE VENTILATION METHODOLOGY IN THE SPANISH ENERGY PERFORMANCE CERTIFICATION TOOL

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ABSTRACT

The purpose of this paper is to enhance the importance of ventilation regarding energy use and stablishing methods in order to obtain as much data as possible about the behavior patterns of ventilation and infiltration in buildings.

The current Spanish regulation Royal Decree 235/2013 establishes all new-construction, rented or sold buildings must be in possession of the Energy Performance Certificate. There are several examples of dedicated software to calculate it, and the aspiration of this study is to integrate the influence of ventilation in the official Energy Performance Certificate Software developed by the Department of Energy located in the University of Seville. This new feature includes Multi-zone ventilation in pressures and Multi-zone ventilation in air flows. In addition, it allows the user to consider the effect on the demand of energy of the real pressures and air flows given in the different zones compared to the single-zone model for ventilation integrated in the official tool.

The structure of this article is summarized as follows:

1. Introduction.
2. Air flow fundamentals, balance equations, ventilation and infiltration models and CO_2 concentration.
3. Description of the “VENTItool” software to simulate ventilation in dwellings using a multizone model.
4. Validation of results using CONTAM.
5. Results and description of the additional capacity about multi-zone ventilation.
6. Conclusions.

KEYWORDS

Energy performance certificate, multizone ventilation model, ventilation, infiltration, air change rate n50.

1. INTRODUCTION

Ventilation plays a vital role regarding thermal comfort and air quality, meeting the metabolic needs of occupants and diluting and removing pollutants emitted by indoor sources. However, unnecessarily high rates of air change can present an excessive energy burden on a building's heating or cooling needs. It is estimated that ventilation accounts for at least 30% of space conditioning energy demand. For that reason, there is a conflict between a willingness to minimize ventilation rate, reduce energy demand, and maximize ventilation to ensure optimum indoor air quality [1].

The task of anticipating ventilation needs is an intricate one, since they vary depending on the occupant density, climate and pollutant load. It is decisive to understand its purpose and how it interacts with pollutants and energy performance.

For all these reasons, in recent years new ventilation strategies have been applied and developed, with the aim of diminishing the energy demand and making use of the outside air cooling potential in certain conditions.

The current Spanish regulation Royal Decree 235/2013 establishes all new-construction, rented or sold buildings must be in possession of the Energy Performance Certificate. The Ministry of Industry, Energy and Tourism has created a General Register which contains the official documents recognized for the energy performance certification process.

Among these documents an official software developed by the Department of Energy located in the University of Seville can be found, used by thousands of certifiers to perform the Energy Performance Certificate. This Energy Performance Certificate tool allows the user to define a residential or tertiary building with a high precision making use of specific additional capacities.

There are many software tools that are available for ventilation calculations. One example is CONTAM [2], which is a multizone airflow and contaminant transport analysis software for buildings. Another one is COMIS [3], a FORTRAN-based code which models the air flow and contaminant distributions in buildings. However, despite the availability of many calculation options the aspiration of this study was to integrate the influence of ventilation in the official Energy Performance Certificate Software. As a consequence, it was decided to develop our own tool, in order to achieve an optimal coupling.

Thus, one of the four additional capacities found in the new version of the Energy Performance Certificate Software (apart from "Trombe" Wall, Ventilated Façade and Solar Wall) is Multi-zone Ventilation. The aim of this paper is to describe the latter additional capacity about Multi-zone ventilation in pressures and Multi-zone ventilation in air flows. This feature allows the user to consider the effect on the demand of energy of the real pressures and air flows given in the different zones compared to the single-zone model for ventilation integrated in the official tool.

2. METHODOLOGY AND TECHNICAL BASICS

2.1. Air flow fundamentals

A wind flow produces a velocity and pressure field around a building. The free-flow relationship between velocity and pressure in each point of the field can be derived from the Bernoulli equation:

$$P + \frac{1}{2}\rho \cdot v^2 = cte \tag{1}$$

In order to describe the pressure distribution around the building envelope a dimensionless coefficient called "Pressure coefficient" (C_p) is usually used, which corresponds to the ratio between the dynamic pressure over the surface and the dynamic pressure of the undisturbed flow at the reference height. For a point of the surface k (x, y, z), the expression of the pressure coefficient comes from the following equation:

$$C_p\left(z_{ref}\right) = \frac{\left(p_k - p_0(z)\right)}{\frac{1}{2}\rho_0 \cdot v^2(z_{ref})} \tag{2}$$

Consequently, the strategy used to evaluate the C_p is through numerical methods. The C_p values are tabulated depending on different parameters (surroundings of the building, wind direction) and have been obtained through the interpolation of the results in several trials.

2.2. Balance equations

For each considered zone the incoming and outgoing air flows will be accounted. In addition, the difference should be equal to zero. The balance equation for each zone is the following:

$$\sum_{i=No.façade} q_{walls,i} + \sum_{i=No.façade} q_{windows,i} + \sum_{i=No.façade} q_{outgrilles,i} + q_{ingrilles} = 0 \tag{3}$$

Where:

- $\sum_{i=No.façade} q_{walls,i}$ is the sum of air flows through walls due to leakages in m^3/h.
- $\sum_{i=No.façade} q_{windows,i}$ is the sum of air flows through windows due to leakages in m^3/h.
- $\sum_{i=No.façade} q_{outgrilles,i}$ is the sum of air flows through outside grilles in m^3/h.
- $q_{ingrilles}$ is the flow which goes from the corridor through the inside grilles.

2.3. Ventilation and infiltration models

2.3.1. Air flow through gaps

To model all the different effects that can occur an exponential law is commonly used:

$$Q = C_s \cdot f(\rho, v, n) \cdot (\Delta p)^n \tag{4}$$

This exponential law will be different for each type of crack considered, adjusting the parameters experimentally. Finally, the expression remains as follows:

$$Q = C \cdot \Delta p^n \qquad (5)$$

Where "C" and "n" are obtained from experimental results.

2.3.2. Air flow through walls caused by defects

There exists a "wall leakage coefficient" which represents the value of the permeability of walls, which depends on their composition.

Since the pressure difference doesn't necessarily have to be the same as that of the trial, it is recommendable to make use of the following expression:

$$q_{walls} = C_{walls} \cdot S_{walls} \cdot \left(\frac{|\Delta P_{real}|}{\Delta P_{trial}^{walls}}\right)^n \qquad (6)$$

Where:

- q_{walls} is the flow through the walls in m^3/h.
- C_{walls} is the wall leakage coefficient in $m^3/h \cdot m^2$.
- S_{walls} is the walls surface in m^2.
- ΔP_{real} is the pressure difference between the inside and outside of the considered zone in Pa.
- ΔP_{trial}^{walls} is the reference pressures difference used in the trial in Pa.
- n is the leakage exponent.

The UNE-EN 15242:2007 standard [4] recommends an n exponent value of 0.667.

2.3.3. Air flow through windows caused by defects

On the other hand, there is also a "windows leakage coefficient" which indicates their permeability and depends on their quality. The expression used is the subsequent:

$$q_{windows} = C_{windows} \cdot S_{windows} \cdot \left(\frac{|\Delta P_{real}|}{\Delta P_{trial}^{windows}}\right)^n \qquad (7)$$

The UNE-EN 15242:2007 standard [4] also recommends in this case an n exponent value of 0.667.

2.3.4. Air flow through inside and outside grilles

Our study considers the implementation of three different types of grilles whose modeling is going to be outlined.

2.3.4.1. Conventional grilles

The functioning of this type is governed by the following equation:

$$Q = c \cdot \left(\frac{\Delta p}{20}\right)^{0.5} \qquad (8)$$

Where:

- Q is the flow through the grille in m^3/h.
- c is the flow rate in m^3/h when the pressure difference is 20 Pa. Its value determines the size or the cross section of the grille. The bigger the c value, the bigger the grille.
- Δp is the pressure difference between both sides of the grille in Pa.

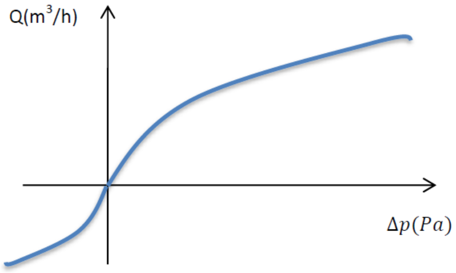


Figure 1: Illustration of the conventional grille's functioning.

2.3.4.2. Self-regulating grilles

This type includes a component which automatically closes when the outside wind velocity increases, reducing the inlet air and obtaining a more uniform air flow.

The equation used is the following, obtained from the SIREN2000 version 8 manual:

$$Q = \begin{cases} c \cdot \left(\frac{\Delta p}{20}\right)^{0.5} & \Delta p < 20 \\ c + b_1 \cdot (\Delta p - 20) & \Delta p \geq 20 \end{cases} \quad (9)$$

Where:

- b_1 is the coefficient which determines the steepness of the line when $\Delta p \geq 20$ Pa, in $m^3/h/Pa$.

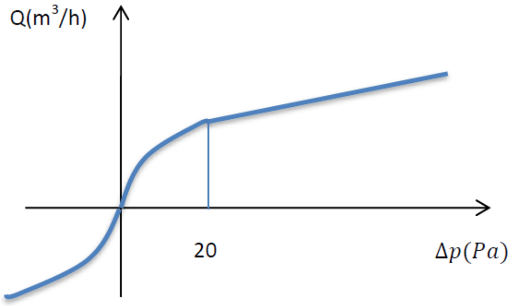


Figure 2: Illustration of the self-regulating grille's functioning.

As is apparent, a linear behavior can be seen when the pressure is over 20 Pa. When smaller, the behavior is similar to that of the conventional grilles.

2.3.4.3. Non-return grilles

They are designed to reduce the air flow going from the inside out.

The equation used is the following, obtained from the SIREN200 version 8 manual:

$$Q = \begin{cases} c \cdot \left(\frac{\Delta p}{20}\right)^{0.5} & 0 < \Delta p < 20 \\ c + b_1 \cdot (\Delta p - 20) & \Delta p \geq 20 \\ -\frac{c}{2} \cdot \left(\frac{\Delta p}{20}\right)^{0.5} & -20 < \Delta p \leq 0 \\ -\frac{c}{2} - b_2 \cdot (\Delta p - 20) & \Delta p \leq -20 \end{cases} \quad (10)$$

Where:

- b_1 is the coefficient which determines the steepness when $\Delta p \geq 20$ Pa in $m^3/h/Pa$.
- b_2 is the coefficient which determines the steepness when $\Delta p \leq -20$ Pa in $m^3/h/Pa$.

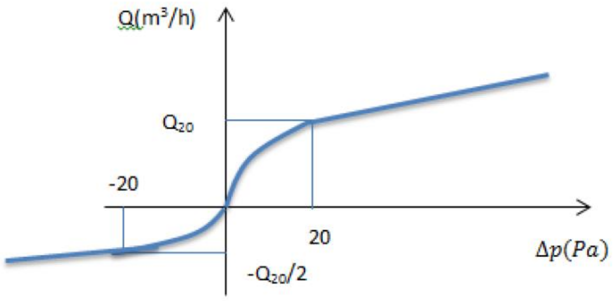


Figure 3: Illustration of the non-return grille's functioning.

As it can be observed, a linear behavior can be seen when the pressure is over 20 Pa. For values between 0 and 20 Pa the behavior is that of the conventional grills. When the pressure difference is negative, the air flow is reduced to a half, and the behavior identical to that of a conventional grille.

2.3.5. Newton-Raphson method

With a view to understanding how our software works, it is necessary to introduce the mathematical fundamentals of the Newton-Raphson method for non-linear equation systems, which is indispensable to solve the equations of the ventilation model.

The recurrence relation of the Newton-Raphson method for non-linear equation systems is:

$$x_{k+1} = x_k - J(x_k)^{-1} f(x_k) \quad (11)$$

Since we are not interested in knowing nor calculating the analytical expression of the Jacobian matrix, this is replaced by its finite difference approximation:

$$\frac{\partial f_j(x)}{\partial x_k} \approx \frac{f(x_k + h_k e_j) - f(x_k)}{h_k} \quad (12)$$

The following diagram shows the used Newton-Raphson algorithm to solve the equation system:

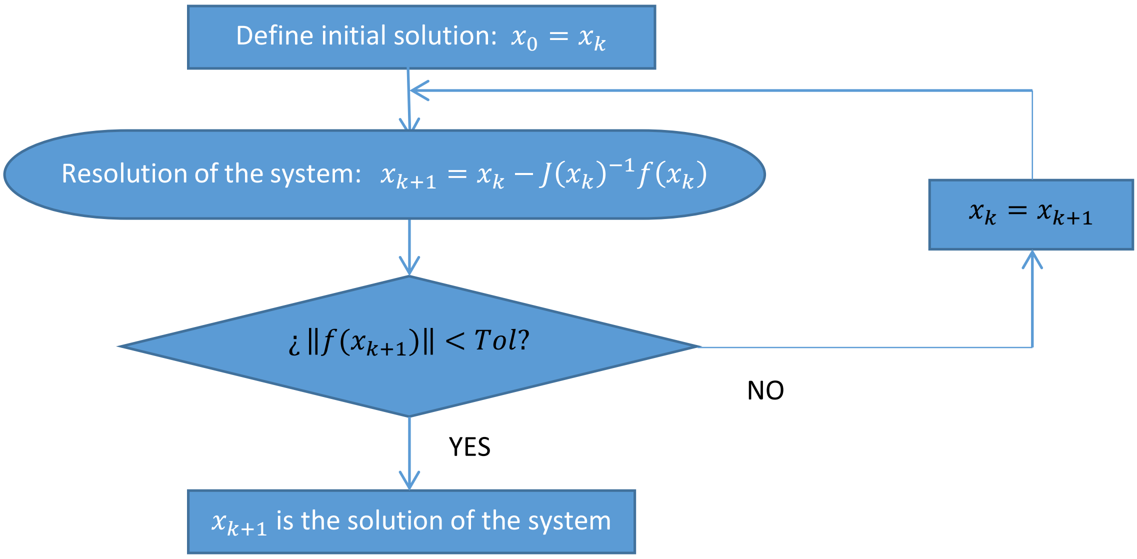


Figure 4: Flowchart of the Newton-Raphson method

2.4. CO_2 concentration

To calculate CO_2 concentration it is necessary to lay out a mass balance in each room. In order to simplify the model the concentration in the zone is supposed to be homogenous.

$$V \cdot \left(C_{int}(t+\Delta t) - C_{int}(t)\right) = \sum_i q_i \cdot C_i(t) \cdot \Delta t + G \cdot \Delta t \tag{13}$$

Where:

- V is the volume of the zone in m^3.
- C is the CO_2 concentration in mg/m^3.
- Δt is the time increment chosen.
- q is the airflow path that goes in or out the zone in m^3/h.
- G is the CO_2 generated by occupants.

3. SOFTWARE TO SIMULATE VENTILATION IN DWELLINGS USING A MULTIZONE MODEL CALLED VENTITOOL

The aim of this section is to introduce the program we designed to calculate CO_2 concentration and air flows for a given dwelling. Figure 5 shows the flux diagram you need to follow the use the program properly.

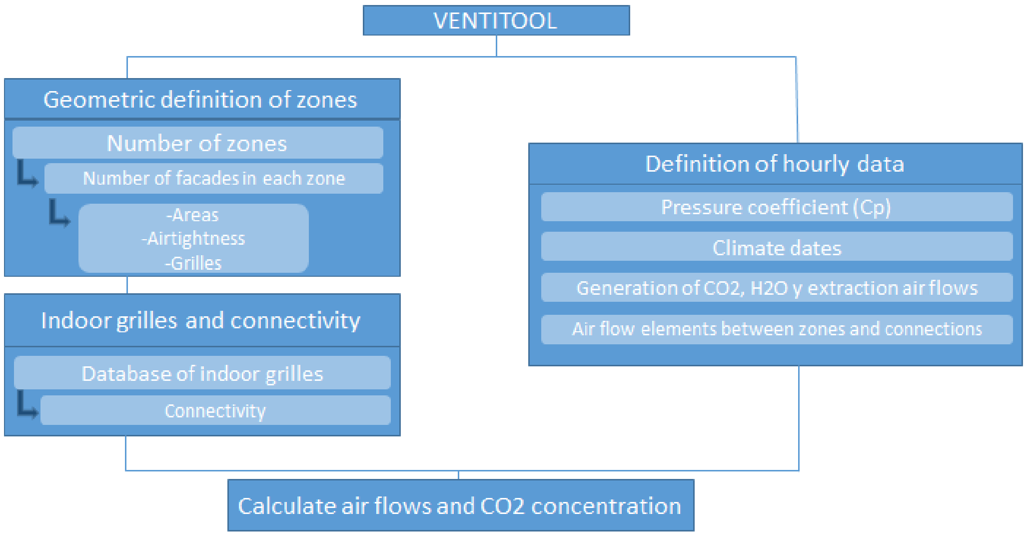


Figure 5: Flux diagram for VENTItool software

There are three steps we must follow before clicking the calculate button:

- Geometric definition of zones: Figure 6-right shows all data needed to define the dwelling, such as number of zones, number of façades in each zone, areas, permeability coefficients for windows and walls and definition of grilles.

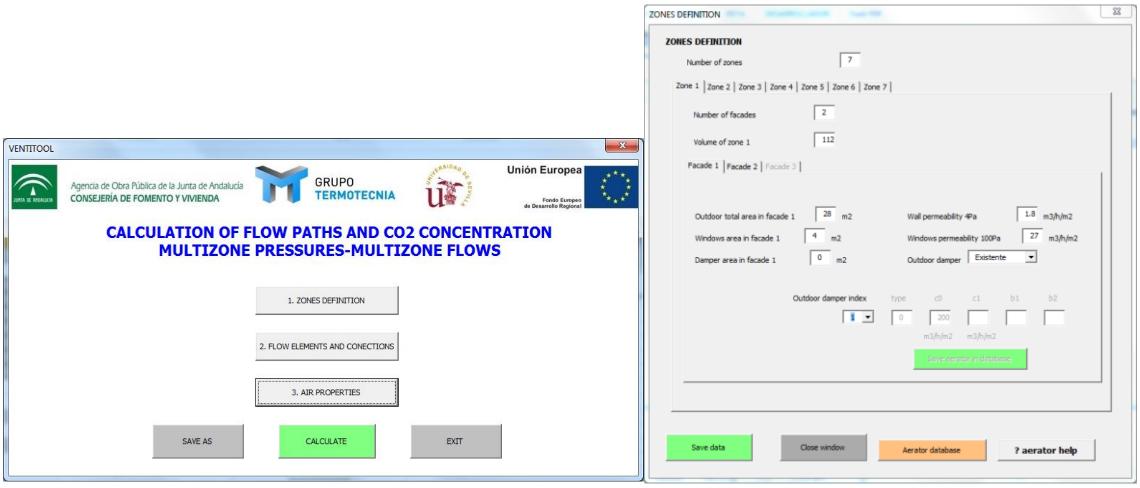


Figure 6: Software Ventitool developed by the Department of Energy in Seville University

- Indoor grilles and connectivity: One must define the kind of connectivity between zones. To do that, firstly you must indicate the type of grilles you will use and what type of grille connects each room. Figure 7-left shows the database of indoor grilles, and figure 7-right shows the connectivity matrix.

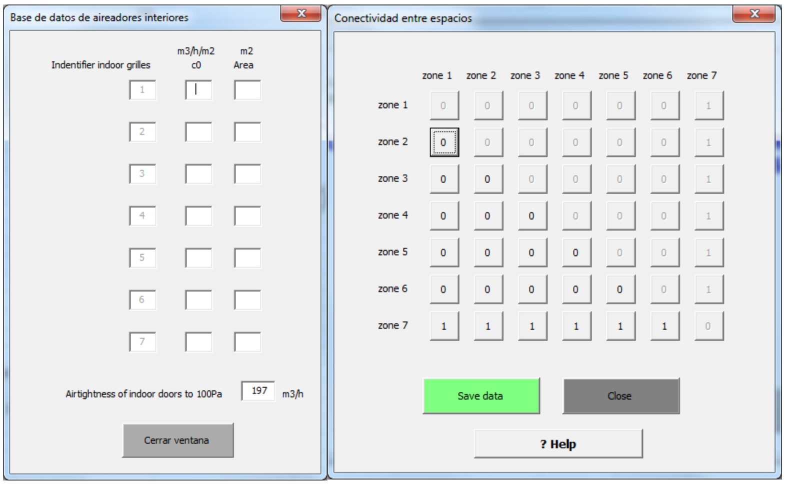
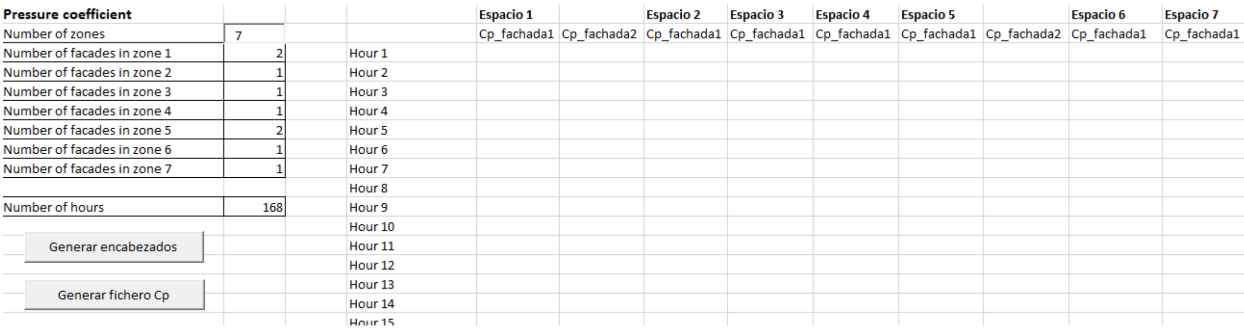


Figure 7: Database of indoor grilles (left) and connectivity matrix

- Definition of hourly data: To be able to do the simulation for a certain number of hours, some coefficients such as pressure coefficient, climate data, generation of CO_2, extraction air flows, air flow element between zones and connections can be defined per hour using text files.



Pressure coefficient	
Number of zones	7
Number of facades in zone 1	2
Number of facades in zone 2	1
Number of facades in zone 3	1
Number of facades in zone 4	1
Number of facades in zone 5	2
Number of facades in zone 6	1
Number of facades in zone 7	1
Number of hours	168
Generar encabezados	
Generar fichero Cp	

	Espacio 1		Espacio 2	Espacio 3	Espacio 4	Espacio 5		Espacio 6	Espacio 7
	Cp_fachada1	Cp_fachada2	Cp_fachada1	Cp_fachada1	Cp_fachada1	Cp_fachada1	Cp_fachada2	Cp_fachada1	Cp_fachada1
Hour 1									
Hour 2									
Hour 3									
Hour 4									
Hour 5									
Hour 6									
Hour 7									
Hour 8									
Hour 9									
Hour 10									
Hour 11									
Hour 12									
Hour 13									
Hour 14									
Hour 15									

Figure 8: Excel sheet that creates the hourly text files

Finally this tool obtains as result airflow paths for each hour and the CO2 concentration evaluated each minute. These results will be shown in subsequent sections.

4. VALIDATION OF RESULTS USING CONTAM

In order to check that our program is providing accurate results, we performed the validation of results with CONTAM. Figure 9 and table 1 show the geometric characteristics of the dwelling:

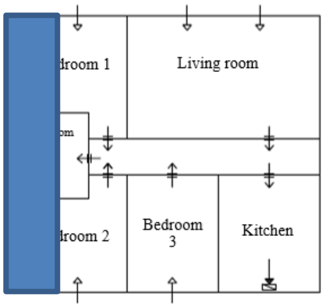


Figure 9: Building used to perform the simulations

The permeability coefficients for windows and walls are supposed to be 27 $m^3/m^2 \cdot h$ and 0 $m^3/m^2 \cdot h$ respectively. The air flow extractions in the kitchen and bathroom are 115 m^3/h and 54 m^3/h respectively.

Table 1: Feature of the building's construction

	Living room	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**	**Kitchen**	**Bathroom**	**Corridor**
Number of facades	2	1	1	1	2	0	0
Volume (m^3)	86.4	43.2	43.2	43.2	43.2	30	34.8
Wall area (m^2)	26.9	9.3	9.3	9.3	20.6	0	0
Window area (m^2)	5.5	1.5	1.5	1.5	0	0	0

Table 2 shows the occupancy schedule used to validate the CO_2 concentration:

Table 2: Occupancy schedule for weekdays (left) and holidays (right)

Time	Livingroom	Bedroom 1	Bedroom 2/3	Kitchen	Bathroom
00:00	0	2	1	0	0
01:00	0	2	1	0	0
02:00	0	2	1	0	0
03:00	0	2	1	0	0
04:00	0	2	1	0	0
05:00	0	2	1	0	0
06:00	0	2	1	0	0
07:00	0	2	1	0	0
08:00	0	0	0	3	1
09:00	0	0	0	0	0
10:00	0	0	0	0	0
11:00	0	0	0	0	0
12:00	0	0	0	0	0
13:00	0	0	0	0	0
14:00	0	0	0	0	0
15:00	0	0	0	0	0
16:00	0	0	0	0	0
17:00	3	0	0	0	0
18:00	3	0	0	0	0
19:00	1	0	1	0	0
20:00	0	0	1	1	1
21:00	3	0	0	0	0
22:00	4	0	0	0	0
23:00	4	0	0	0	0

Time	Livingroom	Bedroom 1	Bedroom 2/3	Kitchen	Bathroom
00:00	0	2	1	1	0
01:00	0	2	1	1	0
02:00	0	2	1	1	0
03:00	0	2	1	1	0
04:00	0	2	1	1	0
05:00	0	2	1	1	0
06:00	0	2	1	1	0
07:00	0	2	1	1	0
08:00	0	0	0	0	3
09:00	4	0	0	0	0
10:00	0	0	0	0	0
11:00	0	0	0	0	0
12:00	4	0	0	0	0
13:00	2	0	0	0	2
14:00	4	0	0	0	0
15:00	4	0	0	0	0
16:00	4	0	0	0	0
17:00	4	0	0	0	0
18:00	4	0	0	0	0
19:00	0	0	0	0	0
20:00	0	0	0	0	0
21:00	1	0	0	0	2
22:00	4	0	0	0	0
23:00	4	0	0	0	0

The difference between intake air flows from the outside calculated with CONTAM and VENTItool are shown in the following table:

Table 3: Difference between intake air flows from the outside calculated with CONTAM and VENTItool

	Intake air flow (m3/h) VENTItool	**Intake air flow (m3/h) CONTAM**	**error**
Living room	85.67	85.69	2.33e-4
Bedroom 1	27.77	27.78	3.59e-4
Bedroom 2	27.77	27.78	3.59e-4
Bedroom 3	27.77	27.78	3.59e-4
Kitchen	0	0	0
Bathroom	0	0	0

The comparison between CO_2 concentration with CONTAM and VENTItool for two scenarios is shown below:

- **Scenario 1:** Figure 10-left shows the wind direction in the scenario 1. Figure 10-right (above) presents the CO2 concentration in the living room using VENTItool, whereas figure 10-right (below) shows the CO2 concentration in the living room using CONTAM.

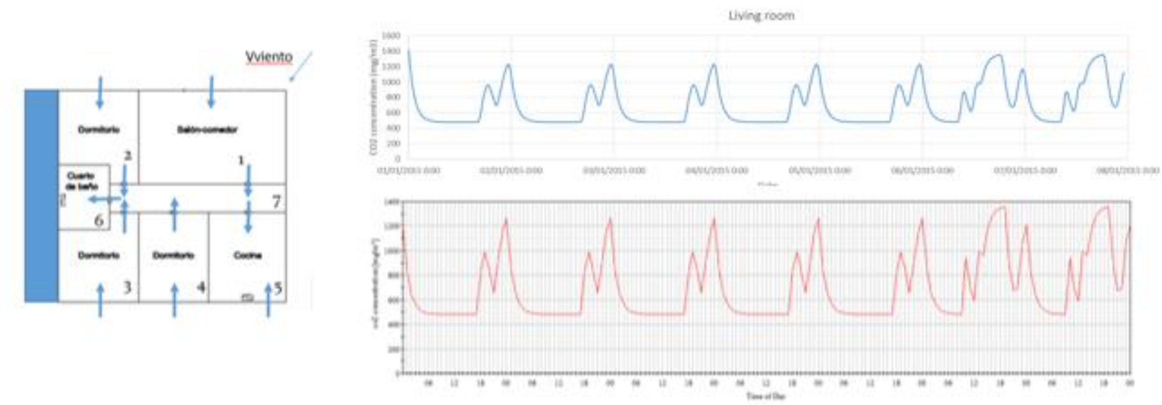


Figure 10: Wind direction in the scenario 1 (left) and CO2 concentration using VENTItool (right-above) and CONTAM (right-below)

Table 4 shows the mean and maximum value in the living room using both programs. The difference is due to the fact that CONTAM presents the hourly values of CO_2 concentration, while VENTItool shows these values each minute.

Table 4: Mean and maximum CO_2 concentration in the living room using CONTAM and VENTItool

CO_2 (mg/m3)	**Mean**	**Maximum**
CONTAM	696.62	1357.49
VENTItool	702.39	1355.31

- **Scenario 2:** Figure 11-left shows the wind direction in the scenario 2. Figure 11-right (above) presents the CO2 concentration in the bedroom1 using VENTItool, whereas Figure 11-right (below) shows the CO2 concentration in the bedroom1 using CONTAM.

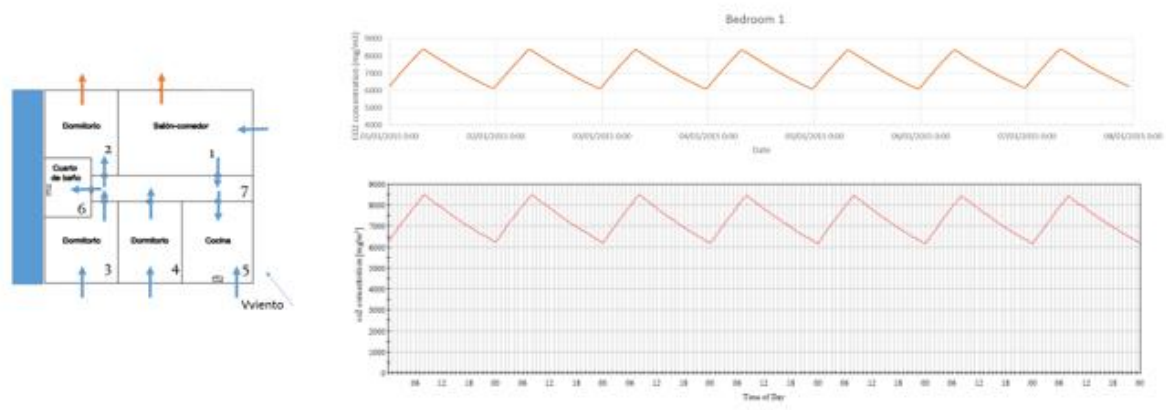


Figure 11: Wind direction in the scenario 2 (left) and CO_2 concentration using VENTItool (right-above) and CONTAM (right-below)

Table 5 shows the mean and maximum value in the living room using both programs.

Table 5: Mean and maximum CO_2 concentration in the bedroom 1 using CONTAM and VENTItool

CO_2 (mg/m3)	**Mean**	**Maximum**
CONTAM	7191.84	8354.32
VENTItool	7204.56	8351.27

According to the comparison between VENTItool and CONTAM, we can conclude that VENTItool provides an accurate solution of air flows and CO2 concentrations.

5. RESULTS

VENTItool is not only used as an additional capacity in the Energy Performance Certificate Software to know the real demand of energy for a multizone scenario, but also to analyse the CO_2 concentration, air flows exchanges between the outside and the zones, and even to calculate infiltrations. This is what will be explained in this section.

a. CO_2 concentration

One of the outputs of the program is the CO_2 concentration. For the scenario represented in figure 12-left, where wind speed is equal to zero and an occupancy schedule as in table 2, VENTItool provides the evolution of CO_2 concentration per minutes and per zone and a table with the maximum and average value per zone:

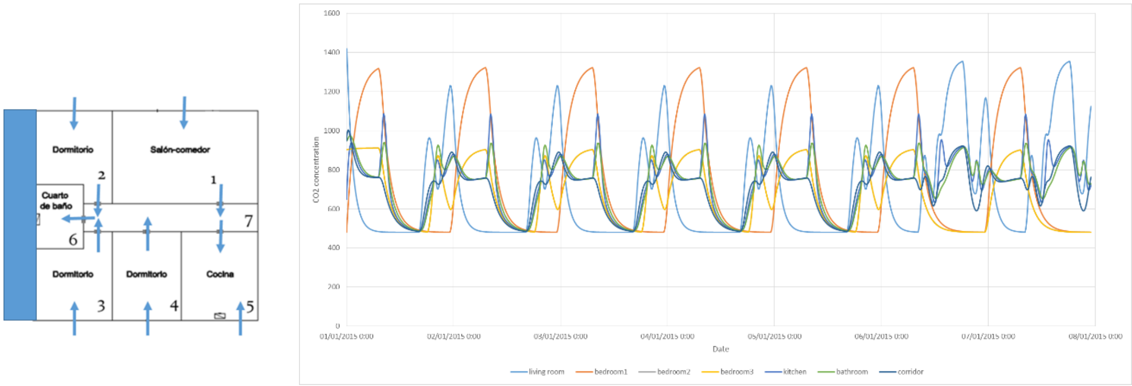


Figure 12: Scenario without wind speed (left) and evolution of CO_2 concentration (right)

Table 6: Mean and maximum CO2 concentration

	Living room	Bedroom1	Bedroom2	Bedroom3	Kitchen	Bathroom	Corridor
CO2 mean	702.39	767.26	669.71	669.71	736.19	733.32	702.75
CO2 maximum	1419.00	1323.21	911.34	911.34	1087.71	974.31	1003.57

As a consequence, it is possible to determine the hour when problems might exist due to a low ventilation rate and high occupancy schedule.

b. Air flows

Another output is the distribution of air flows in each room. For the scenario represented in figure 13-left, where wind speed is equal to 4m/s, VENTItool provides the air flows in any point of time (figure 13-right)

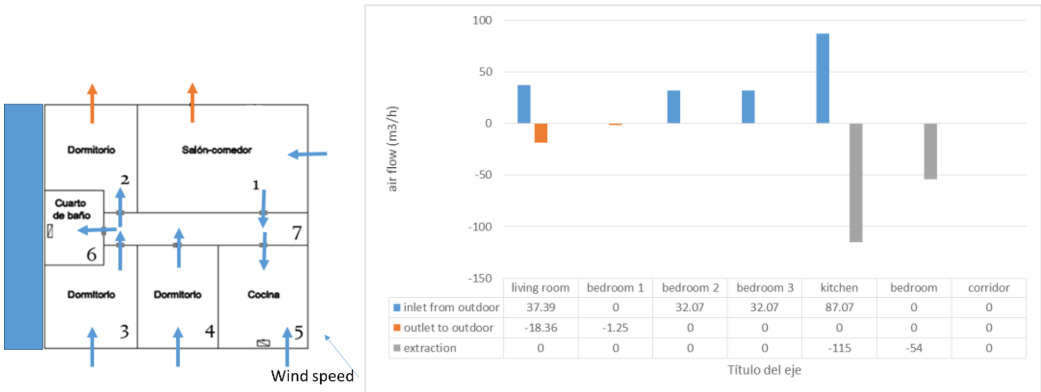


Figure 13: Scenario with wind speed equal to 4m/s (left) and air flows per room (right)

Thus, it is possible to determine at any time which room has problems with air ventilation. In this case note that bedroom 1 has no ventilation flow (a low air flow goes into the room coming from other zones). Figure 14 shows the CO_2 concentration for this scenario, where the concentration in bedroom 1 is too high due to the low air flow.

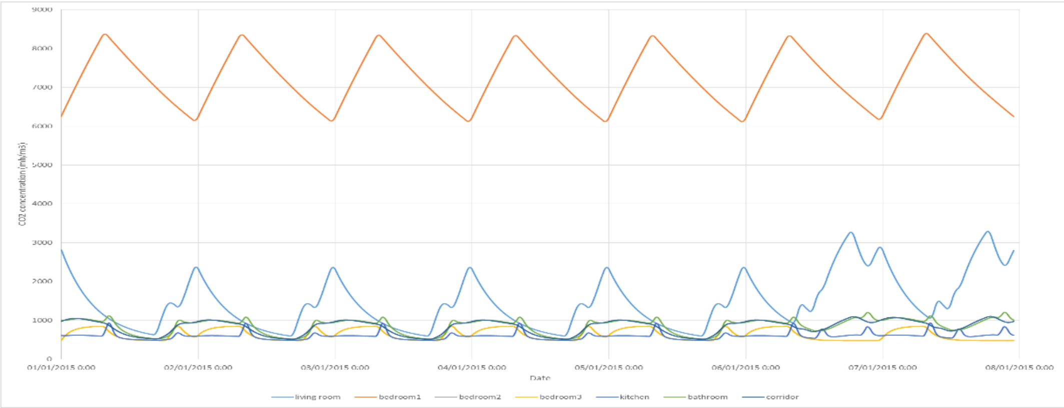


Figure 14: CO2 concentration

c. Relation between mechanical ventilation and infiltrations

VENTItool provides the relation between air change rate due to mechanical ventilation (ACH_{vent}) and the relation between air change rate due to ventilation and infiltration ($ACH_{vent+inf}$). Therefore, it can be determined for any n50 the value of ACH_{vent} required to avoid infiltrations. Figure 15-right shows this kind of graphs for the scenario presented in figure 15-left:

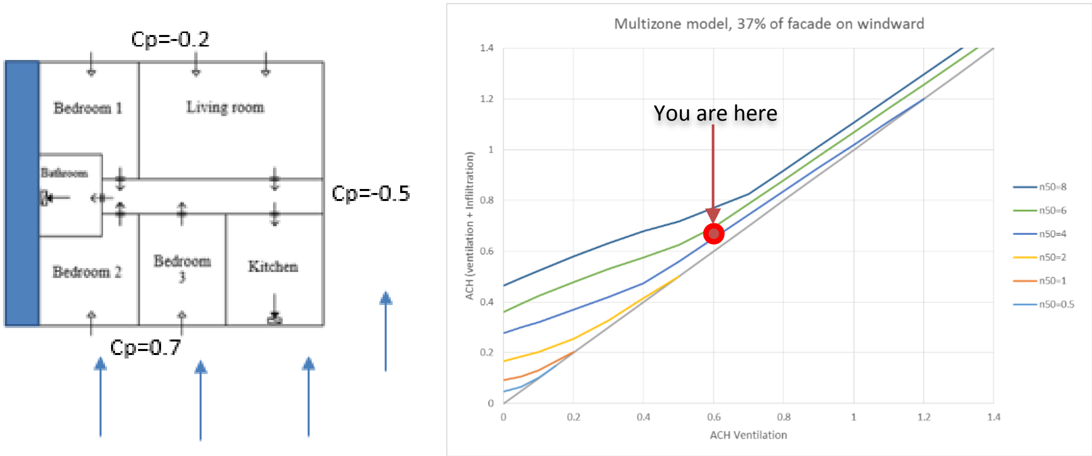


Figure 2: Scenario where 37% of facade is on windward (left) and relation between mechanical ventilation amd infiltration (right)

Note that the program provides the point in which you are working, so you can determine the minimal ACH_{vent} which avoids infiltrations for the airtightness defined by the users.

d. Demand of energy using VENTItool as additional capacity

VENTItool provides the air flows in each room, thus integrating these results into the official Energy Performance Certificate Software we can know the demand of energy for this multizone-scenario.

CONCLUSIONS

In this section the main conclusions are going to be highlighted:

- The Department of Energy at Seville University has developed a software called VENTItool that can estimate the CO_2 concentration for a multizone scenario, thus making it possible to detect for each room if there exists an acceptable IAQ.
- This software can determine the air flow ventilation rate in each room, so it is possible to know if all zones are receiving an acceptable amount of clean air from the exterior.
- VENTItool allows the users to know how many infiltrations there are in the building, and what should be done so as to avoid them.
- Finally, this tool can be integrated as an additional capacity in the Energy Performance Certification Software, therefore it is possible to know the real demand of energy due to ventilation and infiltrations.

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