# INFLUENCE OF AIR QUALITY PERFORMANCE REQUIREMENTS ON THE DEMAND OF ENERGY

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## ABSTRACT

The aim of this paper is to show the effects of variable ventilation rates on the demand of energy and air quality in dwellings, and how airtightness and wind affect this relation. It is interesting to estimate the relation between the air ventilation rate and airtightness of dwellings which makes the dwelling to be under-pressure in order to avoid infiltrations.

The main aspects discussed in this paper are:

1. Influence of wind direction and airtightness in infiltration and the effects in IAQ.
2. Influence of air quality performance requirements in the demand of energy and IAQ.

## KEYWORDS

IAQ, Equivalent ventilation rate, Airtightness, Infiltration, Ventilation, Air change rate n50

## 1 INTRODUCTION

The International Energy Agency (IEA) [1] states that buildings represent 32% of the total final energy consumption, which means almost 40% of the primary energy consumption. The need for reduction of $CO_2$ emission leads to paying attention to the energy demand in buildings. According to the IEA, ventilation and infiltration are responsible for about 33% of total space conditioning energy usage calculated as average of 13 countries joining the tertiary and residential sectors.

On the other hand the Department of Energy in the University of Seville has estimated this percentage for Spanish residential buildings to be between 40-50%. Thus, there exists a potential energy saving in reducing ventilation and infiltration rates.

This paper carries out simulation studies to determine the influence of ventilation and infiltration rates on energy demand and IAQ, highlighting important parameters such as wind direction and airtightness which affect the results significantly.

## 2 DEFINITIONS

In order to help the reader to properly understand the contents presented in this paper, some definitions are provided:

- Ventilation: Air Infiltration and Ventilation Center [2] defines ventilation as the process by which 'clean' air (normally outdoor air) is intentionally provided to a space and stale air is removed. This may be accomplished by either natural or mechanical means.
- Infiltration: It is the process by which the air goes inevitably into a building through adventitious or unintentional gaps and cracks in the envelope.
- Ventilation and infiltration load: It is the energy required to maintain the building in thermal comfort conditions due to air ventilation and infiltration. The amount of air that enters into the building depends on the following factors:
    - Wind speed and direction which affects over-pressure or under-pressure in the façade.
    - Size, location and permeability of elements in the façade.
    - Stack effect.
    - Air extractors which produce under-pressure.
- Air change rate n50: It is a measure of the global airtightness in buildings using a pressure difference of 50 Pascal. This value can be obtained analytically using the following expression:

$$n_{50} = airtight\_wall\_4Pa(m^3/m^2h) \cdot \frac{A_{wall}(m^2)}{Vol(m^3)} \cdot \left(\frac{50}{4}\right)^{0.67} + airtigh\_window\_100Pa(m^3/m^2h) \cdot \frac{A_{window}(m^2)}{Vol(m^3)} \cdot \left(\frac{50}{100}\right)^{0.67} \quad (1)$$

## 3 VENTILATION MODELS

Among the different ventilation models, this paper focuses on the two well-known models called single zone in pressure/single zone in flows (single-zone model) and multizone in pressure/multizone in flows (multizone model).

### 3.1 Single-zone model

A single-zone model is one in which internal partitions are not considered. Although these types of buildings are not frequent in practice, we can use this simplified model with buildings where the effect of internal partitions has little influence on the movement of air, such as small homes or buildings with large interior spaces. Any building where the effect of loss associated to the air through doors or air movement in zones is considered negligible can also be treated using a single model.

Internal conditions in the single model can be considered homogeneous, so there exists only one volume with one pressure and temperature value assigned to a single node.

To solve the network nodes, we firstly remove the internal pressure from the system equation. Once calculated, it is possible to evaluate the flows throw the building envelope (walls and roof), grilles and windows using the following equation:

$$q_v = C \cdot (\Delta P)^n \quad (2)$$

Figure 1 and equation 3 show an example of single-zone model with three external nodes corresponding to a windward façade, leeward façade and roof.

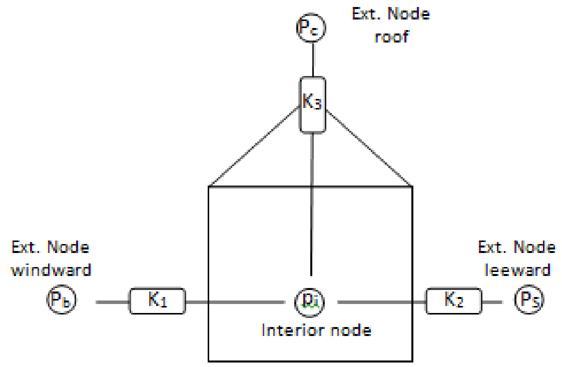


Figure 1: Network nodes in single-zone model

$$tightness\_wall \cdot A_{wall\_w} \cdot \left(\frac{\Delta p_w}{4}\right)^{0.67} + tightness\_window \cdot A_{h\_w} \cdot \left(\frac{\Delta p_w}{100}\right)^{0.67} + C_{grill\_w} \cdot \left(\frac{\Delta p_w}{20}\right)^{0.5} + \\ + tightness\_wall \cdot A_{op\_l} \cdot \left(\frac{\Delta p_l}{4}\right)^{0.67} + tightness\_window \cdot A_{h\_l} \cdot \left(\frac{\Delta p_l}{100}\right)^{0.67} + C_{grill\_l} \cdot \left(\frac{\Delta p_l}{20}\right)^{0.5} + q_{ex} = 0 \quad (3)$$

where,

$\Delta p_w = p_w - p_{\text{int}}$ and $p_w = 0.5 \cdot C_p\big|_w \cdot \rho_0 \cdot v^2$

$\Delta p_l = p_l - p_{\text{int}}$ and $p_l = 0.5 \cdot C_p\big|_l \cdot \rho_0 \cdot v^2$

- $tightness\_wall$ and $tightness\_window$ are the permeability of the walls and windows at 4Pa and 100Pa respectively, in $m^3/hm^2$,
- $C_{grill}$ is the grille coefficient, in $m^3/h$,
- $q_{ex}$ is the air flow extraction, in $m^3/h$,
- $C_p$ is the pressure coefficient,
- $\rho_0$ is the air density, in $kg/m^3$,
- $v$ is the air velocity, $m/s$.

The subscript w means windward and l means leeward. The equation 3 has only one unknown $p_{\text{int}}$, so once calculated, it is possible to know the air flow for each element.

### 3.2 Multizone model

The multizone model is a more complex and accurate model which solves the equilibrium equation for each zone. The equation to calculate the indoor pressure in each room has the same form as equation (3), but one per room is needed. The following equation shows how to calculate the flow between two zones through a grille:

$$q_{i \to j} = C_{ij} \cdot (p_i - p_j)^{0.5} \quad (4)$$

Where:

- $C_{ij}$ is the air flow that goes through the grille when the pressure difference is 1 Pa.
- $P_i$ is the pressure in the ith zone.
- $Q_{i \to j}$ is the air flow between two zones through the grille.

Although there are several tools to calculate the infiltration rate and $CO_2$ distribution such as CONTAM [3] or TRNSYS [4], the Department of Energy in the University of Seville has developed its own tool called VENTItool with the aim of being able to integrate this software as an additional capacity into the official energy performance certificate software.

## 4 RELATION BETWEEN IAQ-VENTILATION RATE-CONSUMPTION

The qualitative relation between IAQ and ventilation rate is predicted in [2, 5] and shown in figure 2. Note that the higher the ventilation rate, the lower the pollutant concentration.

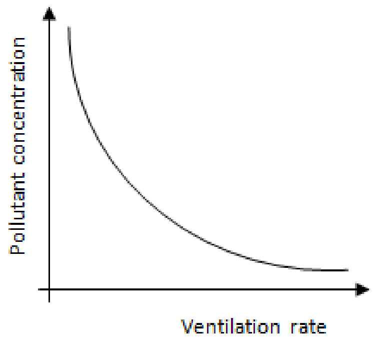


Figure 2: Qualitative relation between IAQ and Ventilation rate

Although this relation seems to be obvious, this curve could have a different behaviour in real buildings where infiltrations can occur. This is what may happen when wind speed rises and n50 has a high value. Figure 3 shows schematically the difference between the ideal situation where the whole building is under pressure and air goes in due to mechanical ventilation (infiltrations are null), and real situation where air goes into the building due to mechanical ventilation and infiltrations, with zones in overpressure where air moves out.

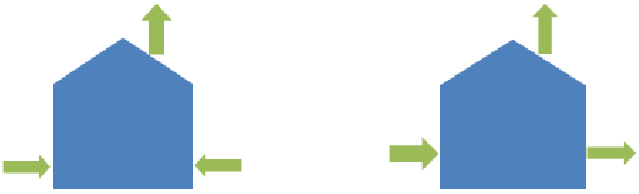

Figure 3: Ideal situation (left) and real situation (right).

The air flow extraction (ventilation flow) which makes the situation ideal can be determined drawing ventilation rate ($ACH_{vent}$) against ventilation plus infiltration rate ($ACH_{vent+inf}$). Figure 4 shows this relation, where ventilation rates higher than 0.72 (vertical blue line) provokes the ideal situation.

The value of ventilation rate in the ideal situation depends on the airtightness, wind speed, wind direction and the model used to calculate air flows. This graph has been calculated using a single zone model considering half façade windward and half façade leeward for simplicity, though we will discuss in subsequent sections the influence of using different wind directions and a multizone model instead of the simplified one.

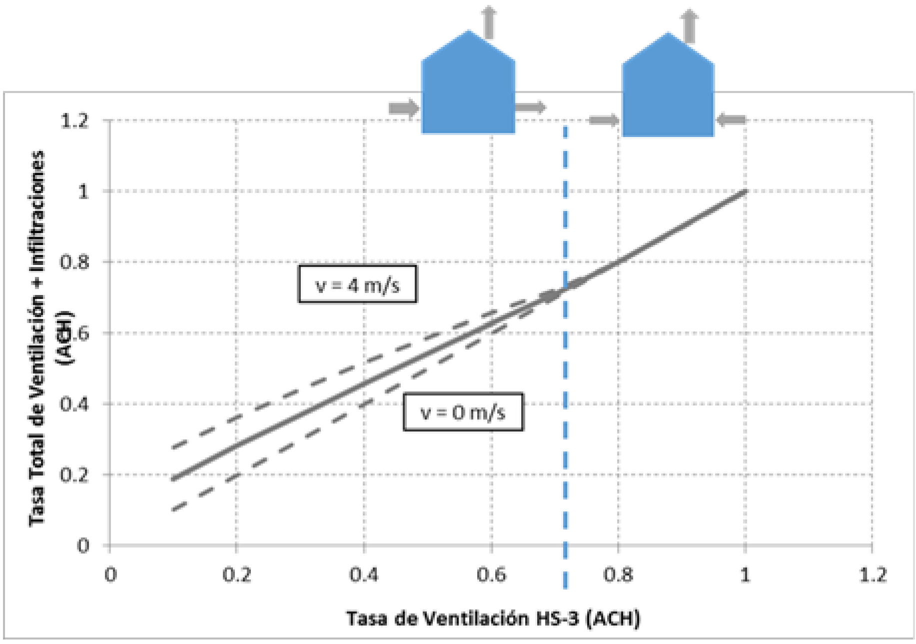


Figure 4: Relation between ventilation + infiltration rate and ventilation rate

Finally the demand of energy rises when ventilation and infiltration rate increases. Ventilation and infiltration loads are directly proportional to the air flow that goes into the building, thus the evolution is linear as shown in figure 5:

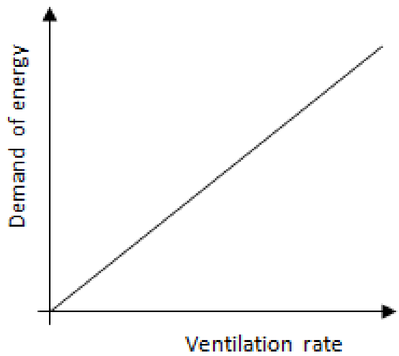


Figure 5: Qualitative relation between demand of energy and ventilation rate

## 5 DEFINITION OF STUDIED BUILDING

The building used to perform the simulations is the same as that presented by the Spanish Regulation in its document called HS-3. This building consists of 3 bedrooms, a living room, a kitchen and a bathroom. All these spaces are connected by a corridor as shown in figure 6:

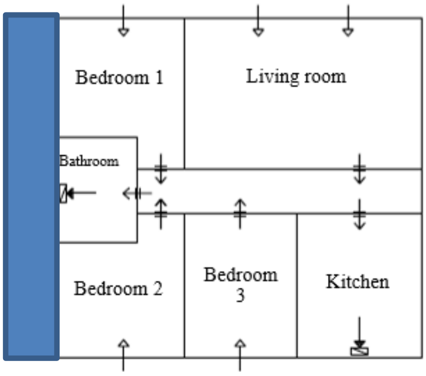


Figure 6: Building used to perform the simulations

The features of the building's construction are indicated in the table below:

Table 1: Features 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 | 1 | 0 | 0 |

An important feature that has not been mentioned above is the airtightness coefficient. This property will be variable in order to perform the study with different values of $n_{50}$, as explained in the following section.

The connections between rooms and corridor have been modelled as a closed door, whose permeability coefficient is 195 $m^3/h$.

Mechanical ventilation will be carried out by extractors located in the kitchen and bathroom. The flow of each extractor will be variable in order to be able to do a parametric analysis, as shown in section 6.

## 5.1 Occupancy schedule

In order to define the pollutant concentration in each room, it is needed to create an occupancy schedule. There is one schedule for each room, distinguishing between working days and holidays, as shown in table 2. Note that the occupation of bedrooms 2 and 3 is the same, while the occupation of the corridor has been neglected.

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

| | | | | | |
|---|---|---|---|---|---|
| 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 |

| | | | | | |
|---|---|---|---|---|---|
| 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 |

## 5.2 Wind direction

In order to know how wind direction affects the results, we have simulated the building with two different wind directions. The first of them (figure 7-left) has a 37% of façade on windward and 63% on leeward. The second one (figure 7-right) has a 63% of façade on windward and 37% on leeward.

The value chosen for wind velocity is 4 m/s. This is the average velocity for buildings located in urban areas in Seville [5]

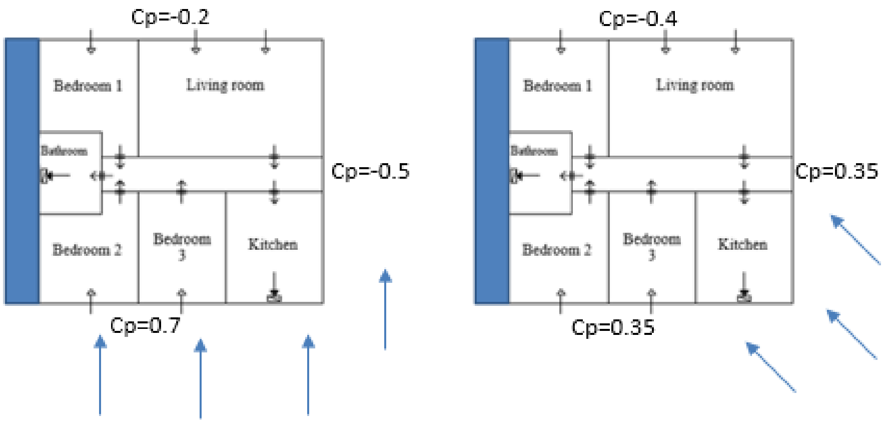


Figure 7: Building with 37% of facade on windward (left) and 63% on windward (right)

The pressure coefficients for each façade are indicated above, and are used to calculate the outdoor pressure as follows:

$$P_{outdoor} = \frac{1}{2}\rho \cdot c_p \cdot v^2$$

Where $\rho$ is the density of air, $c_p$ is the pressure coefficient and $v$ is the velocity.

## 6 RESULTS

This section is divided into three parts. The first one presents the relation between mechanical ventilation and infiltrations, and how this relation varies with airtightness, speed direction and the ventilation model. In the second part the evolution of $CO_2$ concentration when mechanical ventilation rate varies is shown for both ventilation models explained in section 3. Finally it is shown how the mechanical ventilation affects the demand of energy in the studied building.

### 6.1 Relation between mechanical ventilation and infiltrations

The Spanish regulation establishes that it is required to use mechanical ventilation to maintain an acceptable IAQ, but when wind is blowing infiltrations can appear. Avoiding infiltrations is essential to guarantee that in a multizone scenario all rooms have a good air quality.

The next two graphs show the relation between air changes per hour due to mechanical ventilation ($ACH_{vent}$) and air changes per hour due to mechanical ventilation and infiltration ($ACH_{vent+inf}$) for both scenarios presented in section 4.2 using the single-zone model:

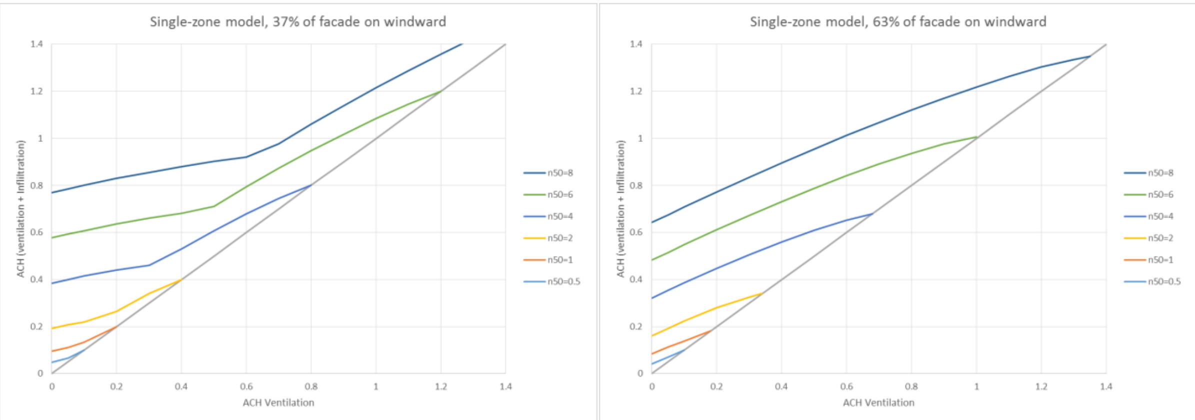


Figure 8: Variation of ACHvent+inf with ACHvent and airtightness using the single-zone model with 37% of façade on windward (left) and 63% of façade on windward (right)

The following observations can be derived from the graphs:

- The higher the air change rate n50, the more infiltrations there are. Thus, the quality of the façade plays an important role in reducing infiltrations.
- The curves presented in figure 8-left change their curvatures for a certain value of $ACH_{vent}$ due to the change in the direction of air flow in a façade. Figure 9 presents what is happening to air flow for an air change rate n50 equal to 6 $h^{-1}$.
- The 45º straight line in grey represents the situation when wind velocity is considered zero, thus the $ACH_{vent}$ is the same as $ACH_{vent+inf}$ (room is under-pressure). Therefore, there exist infiltrations before the curve cuts the straight line. However, after that the behaviour is similar to the 45º straight line, where there are no infiltrations.
- Curves presented in figure 9-right have the same curvature because there is no change in the direction of flow before reaching the 45º straight line. After cutting it the room will be under-pressure and there will be no infiltrations.

- For any n50, the higher the percentage of windward façade, the lower the $ACH_{vent}$ in which there are not infiltrations (the cut with 45° straight line). This behaviour can be guaranteed for a percentage of windward façade between 30%-70%.

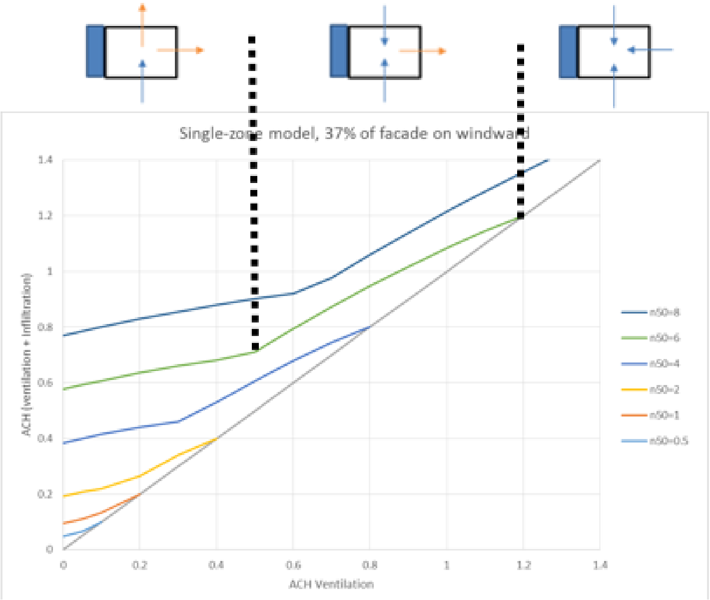


Figure 9: Variation of air flow direction in each facade with ACHvent for n50 equal to 6

The following graphs show the relation between air changes per hour due to mechanical ventilation ($ACH_{vent}$) and air changes per hour due to mechanical ventilation and infiltration ($ACH_{vent+inf}$) using the Multizone model:

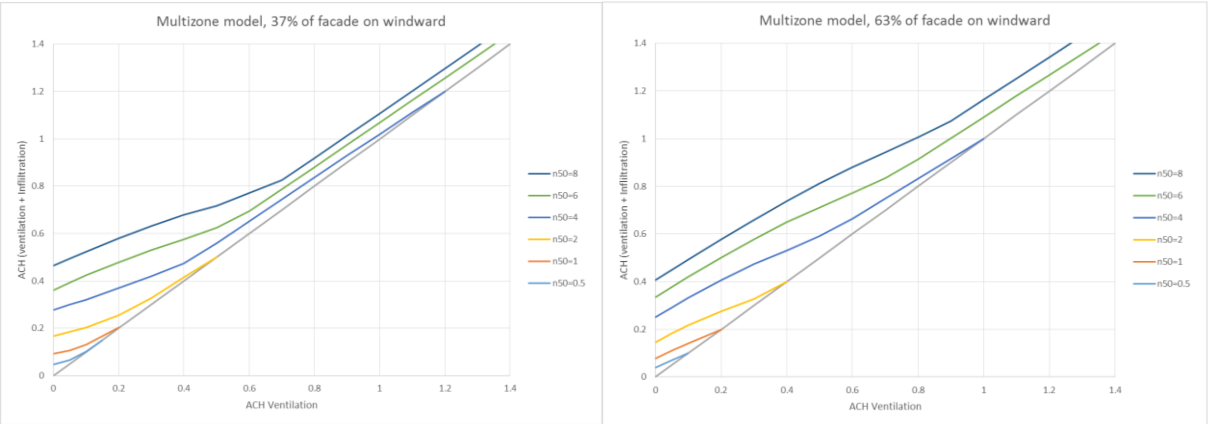


Figure 10: Variation of ACHvent+inf with ACHvent and airtightness using the multizone model with 37% of façade on windward (left) and 63% of façade on windward (right)

The observations derived from the graphs in the multizone scenario are similar to those in the single-zone model, and they are summarized as follows:

- The higher the air change rate n50, the more infiltrations there are.
- The curves presented in figure 10 change their curvatures for certain values of $ACH_{vent}$ due to the change in the direction of air flow in a façade or connection. Figure 11 presents what is happening to air flow for an air change rate n50 equal to 4 $h^{-1}$.

- The 45º straight line in grey represents the situation when wind velocity is considered zero, thus the $ACH_{vent}$ is the same as $ACH_{vent+inf}$ (all rooms are under-pressure). Thus there exist infiltrations before the curve cuts the straight line, however after that the behaviour is similar to the 45º straight line where there are no infiltrations.
- For any n50, the higher the percentage of windward façade, the lower the $ACH_{vent}$ in which there are not infiltrations (the cut with 45º straight line). This behaviour can be guaranteed for a percentage of windward façade between 30%-70%.
- For n50 higher than 5, note how the curve has an asymptotic behavior. This occurs because there is a room with two façades with a different pressure coefficient when the connection door is closed with a low n50 coefficient, so the air flow goes in and out. The following figure shows what is happening in the living room.

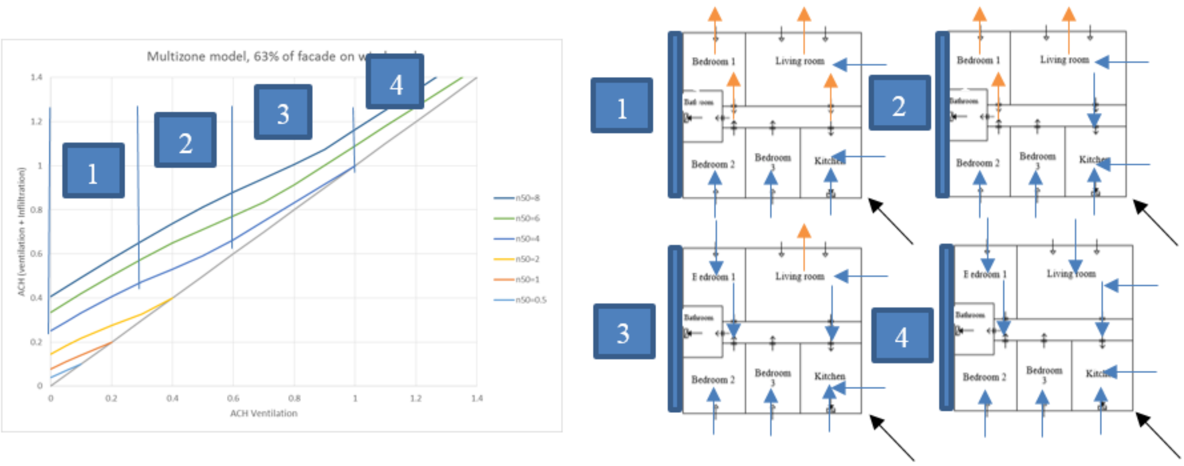


Figure 11: Variation of air flow direction in each facade with ACHvent for n50 equal to 4

As said in the previous section, the single-zone model might differ from the multizone model. Figure 12 illustrates both models superposed for both scenarios presented before:

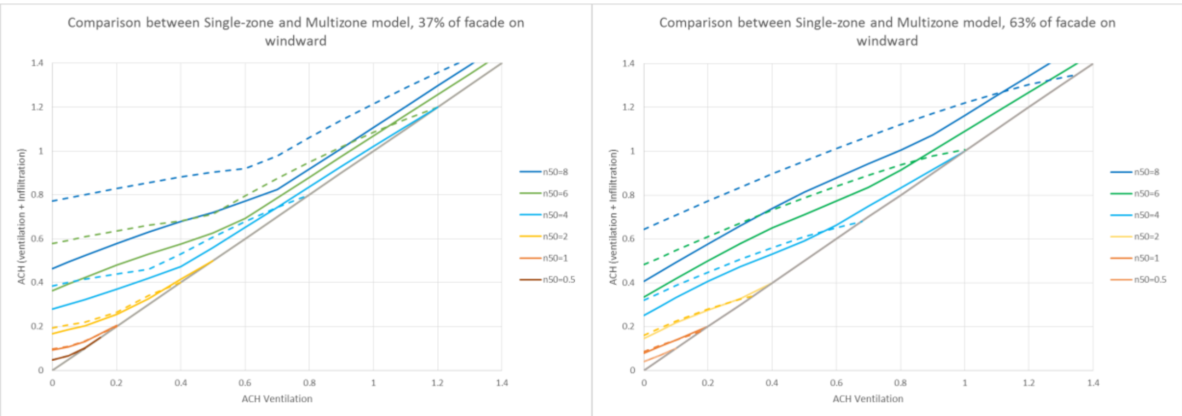


Figure 12: Comparison between single and multizone model for 37% of facade on windward (left) and 63% of façade on windward (right)

For any n50 the curves in single-zone model cuts the 45º straight line (no infiltrations) for an $ACH_{vent}$ value lower than that when using a multizone model. So if we select an n50 using a single zone model in order to avoid infiltrations and guarantee an acceptable IAQ, the single scenario might not be on the safe side.

For a certain value of n50, there is a value of $ACH_{vent}$ where $ACH_{vent+inf}$ coincide for the single and multizone model. So energy-wise, the demand of energy estimated using the single model will be on the safe side for an $ACH_{vent}$ lower than the cut point between both models.

Finally when n50 is sufficiently low (less than 2), both models estimate nearly the same infiltrations. Table 3 shows the maximum error made using single-zone model instead of the multizone one for each n50. This error is reached when mechanical ventilation is zero:

Table 3: Maximum error made using a single model instead of a multizone one for 37% and 63% of façade on windward

| **n50 ($h^{-1}$)** | **Error 37% windward (%)** | **Error 63% windward (%)** |
|---|---|---|
| 0.5 | 0.00 | 0.00 |
| 1 | 4.34 | 3.52 |
| 2 | 15.57 | 11.03 |
| 4 | 38.49 | 27.89 |
| 6 | 59.67 | 44.31 |
| 8 | 66.16 | 58.13 |

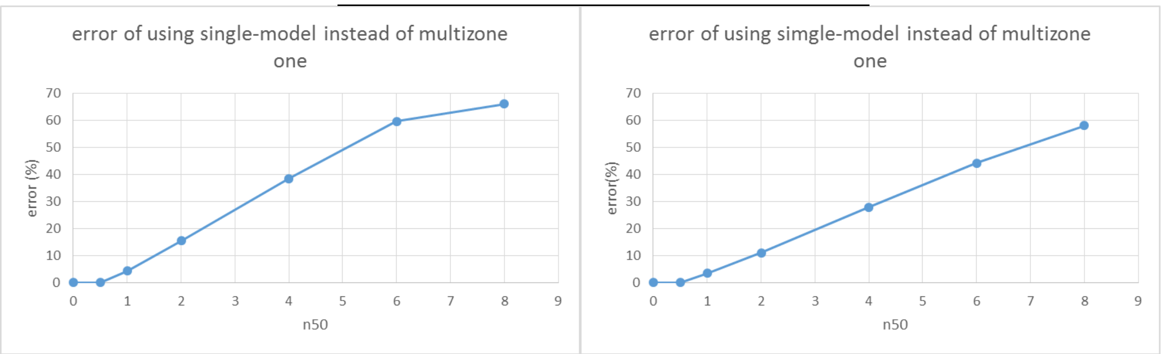


Figure 13: Evolution of maximum error made using a single model instead of a multizone one for 37% (left) and 63% (right) of façade on windward

## 6.2 Relation between mechanical ventilation and IAQ

The aim of this section is to show the problems due to infiltrations to maintain acceptable levels of pollutant in all rooms when using a multizone model. Values of $ACH_{vent}$ near a change of the curvature in curves such as figure 11 might be critical points where the $CO_2$ concentration is high (there might not be air intake in certain room). This is what is known as an asymptotical behaviour of the pollutant when an occupied room is not being ventilated. This asymptotical behaviour cannot be perceived using a single model, as shown in figure 14-blue for n50=4 and 63% of façade on windward. However using a multizone model it is easy to detect which rooms have problems with IAQ, and the value of $ACH_{vent}$ for which this problem arises. Figure 14-red shows the average $CO_2$ concentration using a multizone model for a building with n50=4 and 63% of façade on windward.

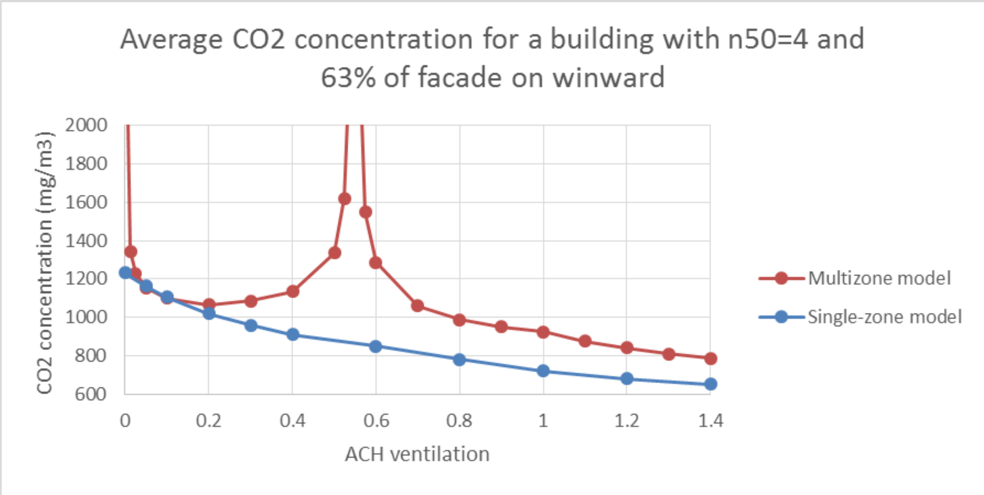


Figure 14: Average CO2 concentration for a building with n50=4 and 63% of facade on windward

The $CO_2$ concentration using a single model is lower than that when using the multizone one due to the higher infiltration estimated by a single model. This $CO_2$ difference between models decreases when $ACH_{vent}$ increases, in particular when infiltrations start being zero.
According to figure 14-red, there are two critical points where the concentration grows rapidly. First of them occurs when there is no mechanical ventilation in the bathroom because there are no connections between the bathroom and outside. Figure 15-left shows the evolution of average and maximum $CO_2$ concentration in the bathroom. The second critical point is reached when $ACH_{vent}$ is nearly 0.55, and this is due to the low air intake in bedroom1 as shown in figure 11 from step 2 to 3. Figure 15-right shows the evolution of average and maximum $CO_2$ concentration in bedroom 1.

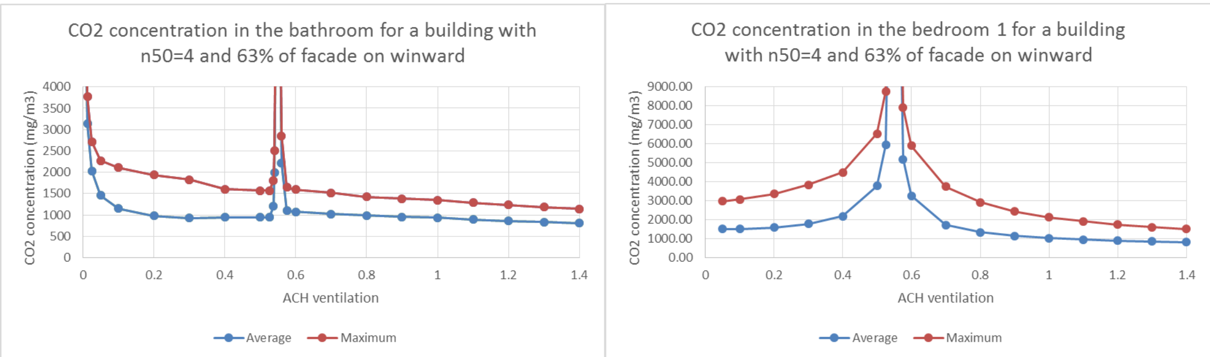


Figure 15: Average (blue) and maximum (red) CO2 concentration in the bathroom (left) and bedroom1 (right) for a building with n50=4 and 63% of façade on windward

For this particular case, there are no problems in IAQ when infiltrations start being nil ($ACH_{vent}$=1), but this point must be considered as critical because there might be scenarios where the $CO_2$ concentration could be high due to low air intake.

### 6.3 Relation between mechanical ventilation and demand of energy

The demand reduction when moving from the single-zone to the multizone model depends on the overall permeability of the building, its geometry and the surface exposed to the wind. The examples developed show that below the cutting point the demand reduction when moving from the single-zone to the multizone model is 37.5 % when n50=8ACH and 30 % when n50=4ACH, both cases without mechanical extraction. As the mechanical ventilation increases,

those values are reduced. For example when there is an extraction of 0.4 ACH, the results become 22 % (n50=8 ACH) and 18 % (n50=4ACH).
As we have seen, the values when n50<=2 ACH are not affected.
Likewise, above the cutting point the calculated demands with the single-zone model may not be conservative enough with respect to those of the multizone model. That cutting point is located on a variable range and thus it is necessary to evaluate it in each individual case. It has been made clear that the mechanical extraction flows implemented in countries of the European Community may be at around that range [6, 7].

# 7 CONCLUSIONS

The main conclusions drawn from the paper are as follows:

- Single-zone and multizone models provide different values for infiltrations. Moreover, the estimated value of $ACH_{vent}$ that avoids infiltrations in the single-zone model is lower than that of the multizone model.
- Wind direction and airtightness affects considerably the infiltrations, so defining these variables accurately is important in order to obtain the real behavior of the dwelling. However, it is quite difficult to find a reliable database with wind direction and velocity and to measure airtightness precisely.
- Having infiltrations in a dwelling leads to an asymptotic behavior of $CO_2$ in zones with leeward façade. Using the multizone model, one can estimate the value of $ACH_{vent}$ that causes this problem and identify the problematic zone. This cannot be predicted using a single-model model.
- n50 lower than two allows us to use the single-zone model without having significant errors. However, this airtightness is quite far from that in real dwellings in Spain.
- When the n50 is higher than 6, the value of $ACH_{vent}$ that avoids infiltrations is increased (much higher than 1.4 ACH).
- Calculating the energy demand based on the resulting flows of the single-zone model is more conservative than doing so through the multizone model. This applies on a general basis when the permeability is high (typically n50>2 ACH) and the extraction flows are below 0.8 ACH. However, those values depend on the geometry of the building and its exposed surface, just as discussed in section 6.1.

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