

Optimization of indoor air quality through controlled cross ventilation in the retrofitting of residential buildings

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ABSTRACT

As an alternative to adopting active architectural systems (mechanical systems) and taking advantage of the resources provided by nature, natural ventilation contributes interesting solutions to control the thermal balance and the air quality, and it is applicable in a variety of climate zones. Natural ventilation also solves some of the more common problems of mechanical systems, such as the noise factor and installation and maintenance costs. However, it is not sensible to pretend that natural ventilation on its own can satisfy all of the air quality needs of a dwelling. Its greatest limitation is that its effects are random, variable, and difficult to control and regulate because the airflow varies as a function of the environmental conditions at any given time. The result is that the minimum required airflow rate for an acceptable level of air quality occasionally cannot be obtained.

To solve these lacks, it is possible to take advantage of the characteristics of hybrid ventilation (since these installations combine natural and mechanic ventilation systems) and demand-based regulation (in accordance with a specific concentration of contaminants or human presence).

The application of this design option to new construction is widely disseminated. However, its integration in retrofitting residential neighbourhoods, particularly those built in the second half of the twentieth century, is especially important and represents an added complication. This complication requires implementing a methodology to analyse its different components and design alternate construction solutions.

The methodology is then applied to the case study of CITYFiED European project (RepliCable and InnoVaTive Future Efficient Districts and cities), in the case of Torrelago district, in the municipality of Laguna de Duero, surrounding the metropolitan area of Valladolid. The retrofitting actions involve 31 residential buildings in use nowadays and counting 1,488 dwellings.

Based on characterizing the temperature and wind factors that influence natural ventilation processes, the available flow rates for the case being studied are estimated. For this case, there are procedures based on complex numerical simulations using CFD software in combination with experimental tests.

Combined with experimental data (in situ measurements and pressurization tests to determine the air tightness of the enclosures), the values obtained in this way allow the quantification of the air renewal cycles in the different dwellings and the estimation of their ability to provide quality air to their users.

Those results must be subject to a critical review and to the development of new design alternatives, which may be incorporated in retrofitting works so as to guarantee at all times the indoor air quality by means of the most efficient option as regards energy.

KEYWORDS

Ventilation, building retrofitting, IAQ, ventilation efficiency, pressurization test

1 INTRODUCTION

Buildings are among the main consumers of energy in Europe, and it is commonly stated that, in 2013, the residential sector represented approximately 26.8% of all of the primary energy consumption in the EU (Eurostat, 2015). Therefore, to achieve the strategic 20-20-20 objectives, building retrofitting became a priority that has experienced a significant boom in recent years, with measures designed to improve the energy and comfort conditions in dwellings built under other, less-stringent guidelines.

The need to effectively ventilate affects both energy consumption and the indoor air quality. It seems reasonable that the design of ventilation should take advantage of the motion of natural air, acting in turn to address the larger problem of natural ventilation, which is its randomness resulting from its dependence on climate factors. It is possible to take advantage of these natural processes through support systems, something known as hybrid ventilation, and demand-based regulation, in accordance with a specific concentration of contaminants or human presence.

The application of this type of installation is widely accepted in the design of new buildings. However, when incorporating them into retrofitting occupied buildings, significant complications arise, including adequately quantifying the existing flow rate and prioritizing systems that minimize the disturbances resulting from their installation.

This study involves the analysis of and design proposal for a ventilation installation applied to a case study of the CITYFIED European project (RepliCable and InnovaTive Future Efficient Districts and cities (CITYFIED, 2015), which includes the comprehensive renovation of three large urban districts in Laguna de Duero-Valladolid (Spain), Soma (Turkey) and Lund (Sweden). The intervention in Laguna de Duero consists of retrofitting the Torrelago Urban Development (Figure 1), which is made up of 31 buildings with a total of 1,488 dwellings built between 1977 and 1981.



Figure 1: Aerial view of the Torrelago Development and the area being simulated

2 PRESSURE GRADIENT IN ENCLOSURES

The pressure gradient is the result of the combined effect of two simultaneous processes: natural convection (due to density differences in the air, a product of different temperatures on different sides of the enclosure) and forced convection (of natural origin resulting from the wind, or artificial origin, from mechanical ventilators).

In the Torrelago buildings, natural convection (or stack effect) becomes particularly important due to the height of the space where it is produced, that is, through the integrated vertical cores

in the building (elevators, stairwells, shafts, etc.). The calculation of natural convection has been widely studied and compared (Etheridge, 1996; Meiss, 2015).

Wind action, however, is one of the most complex physical phenomena to simulate. The high number of variables that contribute to its effect makes it impossible to consider all of the parameters that affect the behaviour of wind in the urban environment. Of particular importance is the need to provide the best possible approximation of the fluid dynamic characteristics of the air and the geometric and roughness characteristics of the environment (Feijó, 2009) because the flow may enter the turbulent regime with the existence of obstacles or because of the air viscosity, fluid velocity and medium characteristics (Amorim, 2013; Blocken, 2007; Kim, 2004; Richards, 1993).

Computational Fluid Dynamics, or CFD, is a numerical-method based computational simulation that can be applied to fluid dynamics studies. This technique takes into account the physical processes that develop in a fluid domain bounded by different surfaces, and it can approximate the wind behaviour in predictive models that are simulated using Ansys Fluent R15.0© software. This study adopts the Reynolds-averaged Navier-Stokes model (RANS-Realizable-Enhanced Wall Treatment (EWT)) as the most appropriate model for simulating time-averaged static processes to obtain the fluid behaviour in urban environments under turbulent flow regimes (Hertwig, 2012; Moonen, 2011). The required validation was performed through stabilized solutions in an infinite time period with data obtained from a wind tunnel in static conditions (Leitl, 2000; CEDVAL, 2002), validating the velocity variables and turbulence profiles (k-e) and their behaviour in an isolated building and in the urban model (Padilla, 2015). The precision obtained in both models was considered acceptable for obtaining results applicable to the real case (Table 1).

Table 1: Precision of the validation model results

Variable	Isolated Building	Urban Model
Velocity	± 1.05%	± 3.68%
X Velocity	± 1.14%	± 2.01%
Y Velocity	± 12.30%	± 12.46%
Z Velocity	± 4.57%	± 4.23%

The study of the location was focused on the predominant wind velocities from the WSW and NE directions, during winter and summer and for the annual mean (IDEA, 2015), affecting both the isolated block (Figure 2) and the complete urban model (Figure 3) (Meiss, 2015). The CFD simulation provides a large quantity of data for the flow model: velocity distributions, static and dynamic pressures, particle trajectories, age of the air, and other parameters.

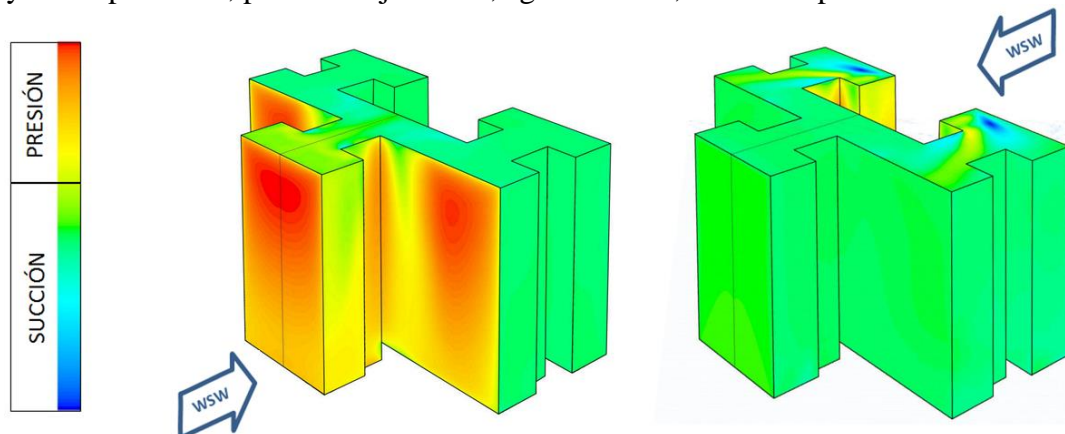


Figure 2: Wind effects on the building

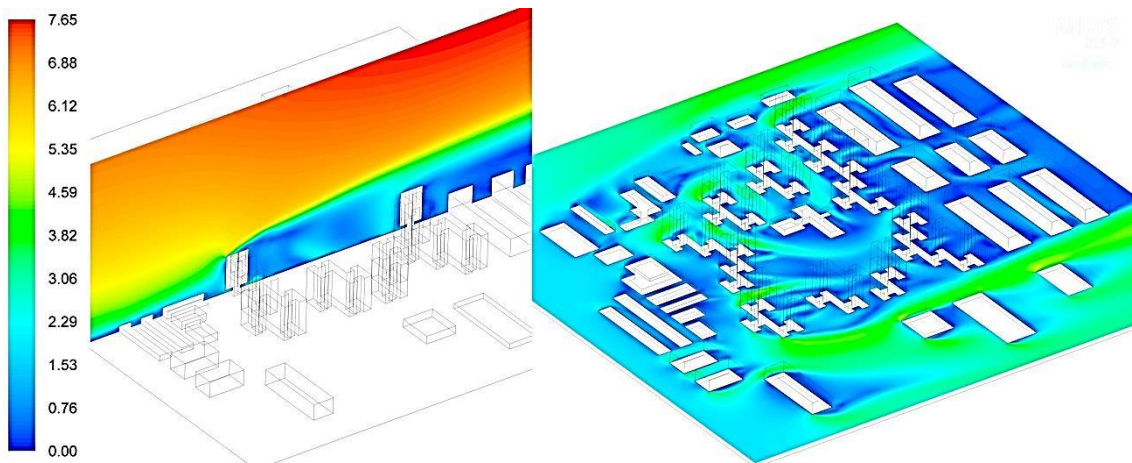


Figure 3: Wind velocity distribution from the WSW at district level (floor plan and cross-section)

The superposition of pressures, a product of thermal and wind action, allows calculating the effects of wind on the surface of each of the dwelling enclosures: the resultant pressures represent different cases throughout the year, with alternating seasonal pressures and suction on the high and low floors.

3 AVAILABLE FLOW RATE OF NATURAL VENTILATION

The owners of the different dwellings in the urban district altered the apartments original design in different ways: replacing the original framing, changing the shutters, renovating the bathrooms and kitchens, blocking shared vertical ventilation shafts, etc. Thus, this study has sought a dwelling (Block 25, Apartment 9C) that in principle would serve as a reference because it retains the construction characteristics of the original project. The process to be developed seeks to quantify its available natural ventilation flow rate.

Pressure tests in dwellings can determine the permeability of the enclosure, distinguishing the values for blind spots and holes based on the method in the European Norm EN13829. The characteristics of these dwellings lead us to assume that infiltrations calculated this way occur mostly through the outer envelope (Meiss, 2015).

Based on these data, it is possible to quantify the natural ventilation flow rate of the dwelling (Table 2) through a process that jointly analyses the different enclosures exposed to different pressure gradients. The procedure is based on the European Norm EN13465 calculation methods for obtaining airflow rates in dwellings, which follows classical theoretical guidelines for natural ventilation. The systems of equations thus formulated are solved iteratively using the Engineering Equation Solver (EES) calculation software, obtaining air flow rates by solving for the unknown pressure inside the dwelling (considered a single volume).

Table 2: Summary of natural ventilation flow rates

Dwelling	according to EN 13829						Presence of natural intake in the shunt
	n ₅₀ rate	n exp.	Permeabilidad al aire de las carpinterías a 100 Pa (m ³ /h·m ²)				
Block 25 Apartment 9C	6.2	0.64	48.6				Yes
	according to EN 13465						Requirement in the DB-HS3 (1/h)
	Estimated Volumetric Flow (m ³ /h)			ACH Natural Ventilation (1/h)			
	Winter	Summer	Annual	Winter	Summer	Annual	
	164.20	97.18	140.85	0.75	0.44	0.65	≥ 0.74

The results indicate that the air renewal rate (ACH), a product of natural ventilation, is not sufficient for the annual mean or during the summer. During the winter, the rate reaches the

minimal values; however, this result is due to the low quality of the original framed openings (i.e., an aluminium sliding window with single-pane glass), which implies that its replacement would result in lower ventilation flow rates.

4 REQUIRED VENTILATION FLOW RATE

The Spanish Technical Building Code (CTE) includes the requirement HS3 “Indoor Air Quality”, which was added after the buildings in this study were built. Such a requirement, being performance-based, expresses that “buildings shall have means to ventilate their indoor spaces adequately, eliminating contaminants that may be produced commonly during normal use of the buildings, so that there is a sufficient flow rate of exterior air that guarantees the extraction and expulsion of contaminated air.”

The Basic Document that addresses this provision (DB-HS3) quantifies that requirement using reference flow rates by activities based on the number of people or the room surface area for different cases.

4.1 Fundamentals

Even if the global flow rates predicted for each dwelling are fulfilled, it is easy to see that there may be areas inside of a dwelling that exhibit an excess or deficit of ventilation given their specific spatial configurations.

It is important to understand that reference flow rates are identified using the pattern of perfectly mixed flow, that is, with an efficiency $\varepsilon^a=50\%$. This fact, in combination with the performance-based nature of the CTE, adequately justifies modifying the flow rates as a function of the ventilation efficiency in each case.

The problem is illustrated in the simulation of an operating ventilation system (Figure 4): the air penetrates the gap beneath a door and leaves the space through a similar adjacent opening. It can be observed that large areas of stagnant, un-renovated air are created, indicating that only a small proportion of the provided air is dispersed throughout the space. This result qualitatively shows that the design of this system is not efficient when “providing air to those areas of the dwelling that require it,” even though it fulfils the minimum flow rate specified by the CTE.

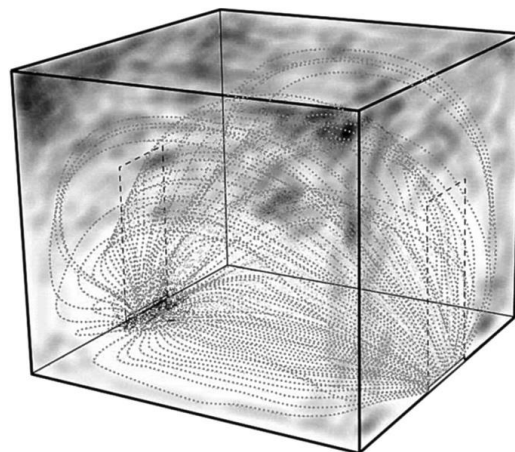


Figure 4: Stagnation of air with low efficiency ε^a

To establish the air flow pattern inside of the dwelling, the physical locations of the inlet, pass and exhaust openings have significant effects on the air change efficiency of a room, ε^a (Awbi, 2000; Gao, 2011). This concept is defined as the ratio between the minimum possible time it takes to replace the air, or turn-over time τ_t , and the corresponding mean time, or average time

of exchange of air $\bar{\tau}_{exc}$, which is equal to twice the room average age-of-the-air (Sandberg, 1981):

$$\varepsilon^a = \frac{\tau_t}{\bar{\tau}_{exc}} \cdot 100 \quad (\%) \quad (1)$$

In experimental tests, the efficiency ε^a is calculated by dividing the local mean age-of-the-air at the exhaust point τ_e by twice the room average age-of-the-air $\langle \bar{\tau} \rangle$ (because we use the optimum model, the so-called “piston flow,” as a reference (Sandberg, 1983)):

$$\varepsilon^a = \frac{\tau_e}{2 \cdot \langle \bar{\tau} \rangle} \cdot 100 \quad (2)$$

When the situation arises in which the contaminant source is not located and one wishes to simultaneously ensure adequate air quality in the entire volume of the room, the efficiency ε^a enables a generic analysis of the rooms and their ventilation systems, so this coefficient is applied in this study (Mundt, 2004).

4.2 Basis for the experimental and numerical procedure

Having a test chamber in the Ventilation Laboratory of the Architecture School of Valladolid (Figure 5) has allowed us to carry out a comprehensive experimental study of air flow, at a 1:1 scale, of the different room configurations, which can be compared with those that make up the dwelling being studied.



Figure 5: Ventilation Laboratory of the Architecture E.T.S. of Valladolid

Boundary conditions were established for this phase of the study:

- Opened doors or windows is not considered, nor is any other action that produces a non-static regime (with the purpose of analysing the efficiency while fulfilling the minimum ventilation conditions);
- The regime is isothermal, with no differences in temperature between the inlet air and the air contained in the room (given that previous studies show that the global efficiency result obtained is not altered (Meiss, 2013)). The remaining surfaces that make up the volume are considered smooth and isothermal walls.

In measurements carried out at control points arranged according to the European Norm EN13141, a tracer gas (SF_6) is used to characterize the flow of air from the time it enters until it leaves each room. The tests were conducted according to the method of falling concentration,

obtaining results with mean deviations with respect to the experimental mean of $\pm 2\%$. These values validate the numerical CFD model that reproduces the air flow in different rooms in the dwelling.

4.3 Application to the dwelling being studied (B25 – Apartment 9C)

The reference dwelling is made up of four bedrooms, a living room, a kitchen and two bathrooms, all of which have openings on their façades, except for one of the interior bathrooms (Figure 6). It is expected that exterior air flows through suction from the least contaminated rooms (the bedrooms and living room) to the more contaminated rooms (the kitchen and bathrooms).

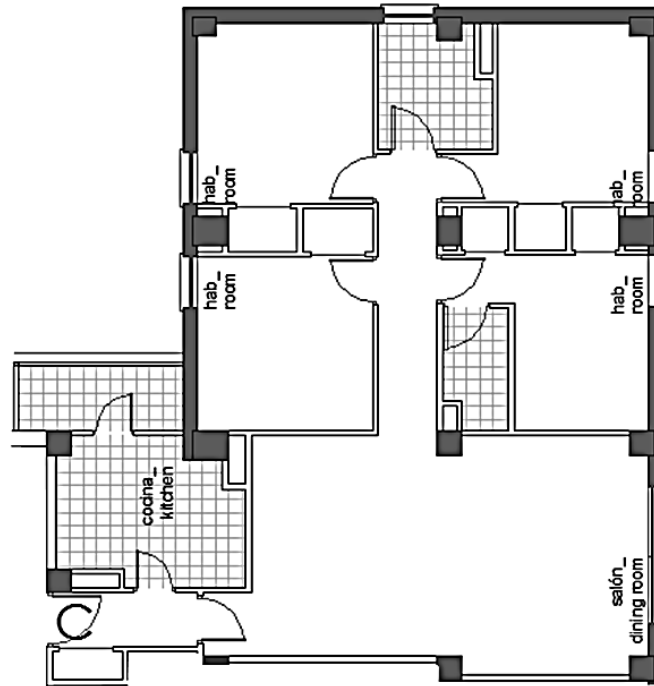


Figure 6: Reference dwelling

Calculating the efficiency allows exceeding the simple quantitative minimum value specified by DB-HS3 to qualitatively control the air change in the entire habitable space (with the possibility of being able to reduce or increase the flow rate recommended by the norm (Meiss, 2011)). If such an analysis is performed in the design phase of the building, it is possible to locate the openings to achieve the most efficient airflow. In the case of a retrofit, the CFD simulation is limited to calculating the efficiency according to the current locations of the openings.

Through the use of a collection of CFD simulations (1152 in total, encompassing practically all of the cases related to the rooms in dwellings) in our own laboratory with the support of the Spanish research project “Optimization of air inlet openings for the CTE-HS3” (Meiss, 2009), we were able to directly calculate the air change efficiency ϵ^a values for each habitable room (Figure 7). This calculation makes it possible to obtain the average age-of-the-air in the dwelling and compare it to the one deduced using HS3 (that is, an average age-of-the-air based on ventilation through a mixed air flow distribution pattern at a specific concentration of contaminants).

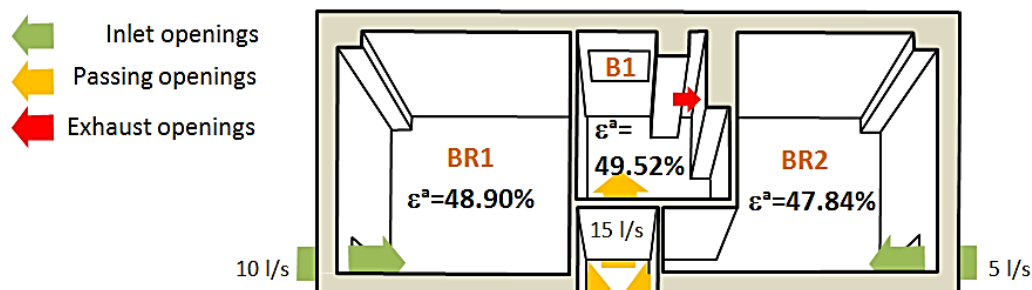


Figure 7: Study of the ventilation airflow

Table 3: Ventilation needs as a function of ventilation efficiency

Room	DB-HS3 Flow rate (l/s)	Vol (m ³)	τ_e room (s)	$\langle \bar{\tau} \rangle$ $\varepsilon^a=50\%$ (s)	$\varepsilon^a=\text{real}$ (%)	$\langle \bar{\tau} \rangle$ $\varepsilon^a=\text{real}$ (s)	Equivalent Flow rate (l/s)
Bedroom BR1	10	22.1	2210	2210	48.90	2260	10.2
Bedroom BR2	5	20.73	4145	4145	47.84	4332	5.2
Bath B1	15	9.20	615	615	49.52	621	15.4
Bedroom BR3	5	8.56	4280	4280	48.90	4376	5.1
Bedroom BR4	10	7.62	1905	1905	47.84	1991	10.4
Bath B2	15	2.13	355	355	46.19	384	15.5
Living room L	14.2	26.25	3697	3697	48.55	3807	14.2
Kitchen K	14.2	7.08	997	997	50.05	996	14.2

With efficiency ε^a values below to 50%, that in spite of complying with the norm-based ventilation flow rate, we are not able to adequately ventilate the space, and the resulting air quality is not good enough (that is, it does not fulfil the basic indoor air quality requirement). The only solution is to slightly increase the circulating ventilation flow rate up to a different equivalent flow rate because the arrangement of ventilation openings is not the most appropriate (Table 3).

5 CONCLUSIONS: CONTROLLED VENTILATION PROPOSAL

Applying the methodology allows correctly characterizing the availability of natural ventilation and the specific needs of the dwelling to be retrofitted. Results have shown that it is impossible to rely solely on natural contributions because the required continuity of air renovation cannot be guaranteed. The result is that controlled ventilation systems are required.

DB-HS3 already predicted this situation in its so-called “hybrid ventilation,” but its novel implementation in 2006 was directed to a more generic dwelling, with a very rigid formulation in terms of the flow rates and material aspects of the installation. Clearly the case of retrofits, as would be relevant to our study, was not specifically considered.

As a conclusion to the experiences discussed in this paper, the objective of which was to solve the problems that have been detected when applying HS3, we propose an optimization of ventilation based on the following general principles:

- The air quality should be quantified and prescribed as a function of the use of the space.
- Natural ventilation should be prioritized over any mechanical procedure, which would be reserved for times with an absence of passive resources.
- The expected ventilation flow rates should be variable and should adjust to the needs of the activity that takes place at each moment.
- The system should control and ensure the minimum quality levels that were previously prescribed, taking into account the permeability of the dwelling.
- Damp rooms in the dwelling (kitchens and bathrooms) should be ventilated through suction with respect to the other rooms during the times in which they become contaminated.
- Fossil energy consumption should be minimized given the adverse impact of ventilation on comfort conditions.
- The ventilation system should allow the free contributions of heat and cold from the outdoor air to achieve comfortable conditions.
- To implement the system in retrofits, even in occupied buildings, its installation should be simple and independent from other dwellings.
- The system should be able to be managed individually for each dwelling, making the user aware of the advantages of installation through directly controlling its operation.

With these premises, a specific system we refer to as “controlled cross ventilation” (CCV) is proposed based on a hybrid behaviour resulting from its two operation regimes:

- A passive regime using crossed natural ventilation, with the aid of mixed inlet and exhaust openings; in other words, the openings can act as inlet or exhaust points depending on wind pressures. These openings could be in the form of aerators or use micro-ventilation procedures based on the exterior framing. The bathrooms and kitchens would also contribute to the movement of air through their extraction openings, which at those times would act as mixed depending on the specific pressure differential.
- An active regime using forced ventilation generated by mechanical extractions located in damp spaces. In this case, the mixed openings distributed throughout the remaining rooms, such as living and bedrooms, would act as entry openings.

The so-called active regime would be activated only when its contribution is necessary to ensure the ventilation quality. The quality would be controlled by detectors or sensors of various phenomena that indicate a lack of quality. Specifically in living rooms and bedrooms, a good air quality indicator would be the CO₂ concentration because in those locations, contamination comes from the metabolic activity of the occupants.

In kitchens, there would be a greater number of symptoms that could indicate the presence of contaminants. In addition to carbon dioxide, increased relative humidity or the presence of combustible gases could also be indicators in a gas range. However, the ventilation system should also be activated by other signals that may be accompanied by contaminant emissions, such as turning on the electric range or oven, and even the detection of people, either directly or through turning on lights.

In bathrooms and laundry rooms, the most representative contaminant likely to be detected is relative humidity. Olfactory contamination would be detected indirectly by the presence of people who are directly detected, or as a result of turning on lights.

However, mechanical extraction could be accomplished through a single multi-zone aspirator for a series of damp rooms in the dwelling or through several individual aspirators in each bathroom or kitchen. Intermediate solutions could also be formulated, which would depend on the dwelling configuration and the limitations of the building.

The extracted air would leave directly towards the exterior of facades, except when the contaminated air is emitted into interior courtyards, in which case it would be necessary to install an extraction duct leading to the roof. If this duct were shared, there would have to be a gate in each mechanical aspirator with automatic opening during expulsion periods.

In addition, to recover the substantial energy lost to the ventilation flow rates, it would be beneficial to have a heat recovery system. This system could operate using a closed circuit with a fluid that facilitates an energy balance in the air that goes through the exterior openings of the dwelling.

Finally, in extreme cases of excessive exterior pollution, appropriate filters could be used in inlet or mixed-use openings. Their characteristics would depend on a map of the air quality in the city where the dwelling is located.

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