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Performance based approaches in Standards and Regulations for smart ventilation in residential buildings: a summary review

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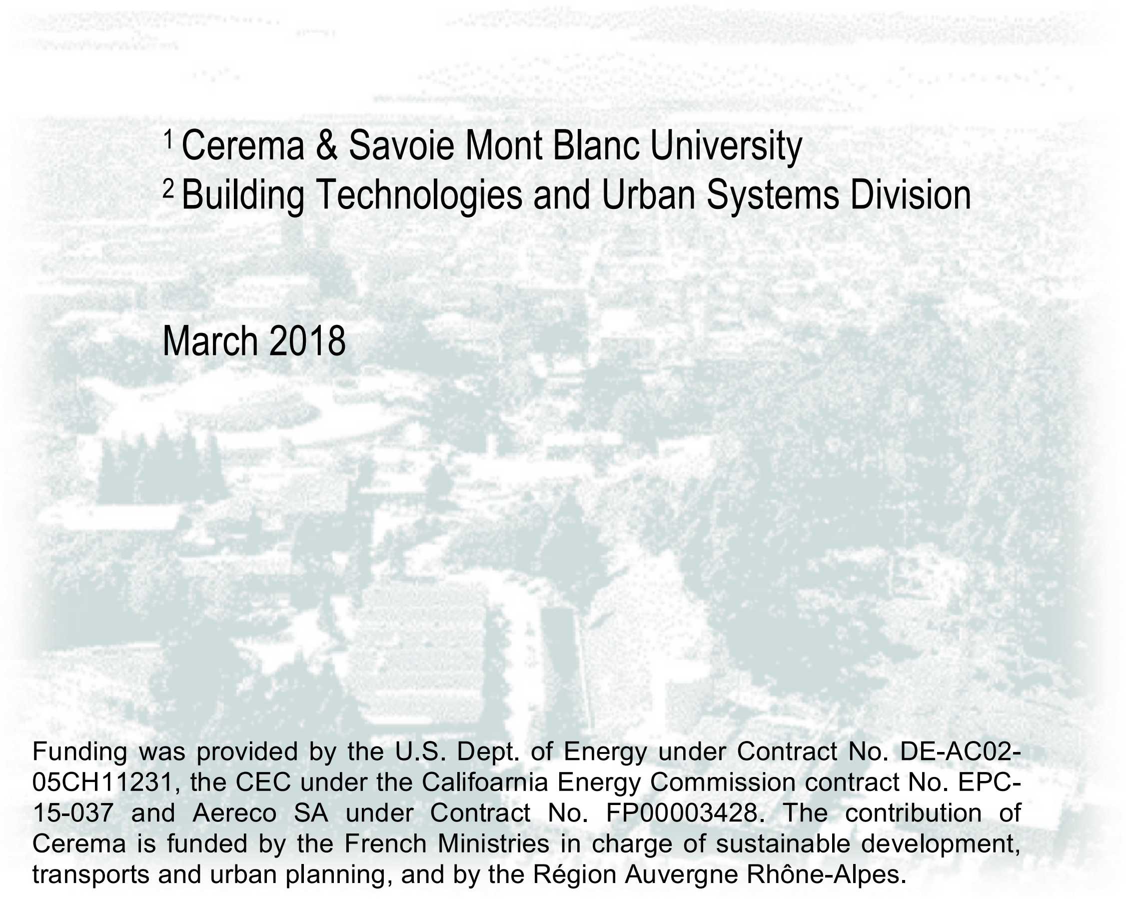

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Abstract

As ventilation systems become more sophisticated (or "smart") standards and regulations are changing to accommodate their use. A key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. This paper discusses the favorable contexts that exist in many countries, with regulations and standards proposing "performance-based approaches" that both enable and reward smart ventilation. The paper gives an overview of such approaches from five countries. The common thread in all these methods is the use of metrics for the exposure to an indoor generated parameter (usually CO2), and condensation risk. As the result, demand-control ventilation strategies (DCV) are widely and easily available on the market, with more than 20-30 systems available in some countries.

Keywords: Ventilation, indoor air quality (IAQ), energy performance (EP), residential buildings, DCV

Introduction

Energy-efficient homes have low envelope losses making ventilation and natural infiltration an increasing fraction of the overall energy use. Therefore, more effort is required on the treatment of air flows to reduce energy impacts is of increasing importance. For high performance homes, envelope airtightness treatment becomes crucial (Erhorn et al., 2008) and should be combined with efficient ventilation technologies.

Indoor air quality (IAQ) is another major area of concern in buildings which is influenced by ventilation. Indoor air quality is a major factor affecting public health because people spend most of the time in residential buildings (Klepeis et al., 2001), especially in their bedrooms (Zeghnoun et al., 2010), and 60-90% of their life in indoor environments (homes, offices, schools, etc.) (Klepeis et al., 2001; "Communiqué de presse - Indoor air pollution: new EU research reveals higher risks than previously thought," 2003; Brasche and Bischof, 2005; Zeghnoun et al., 2010; Jantunen et al., 2011). (Logue et al., 2011) estimated that the current damage to public health from all sources attributable to IAQ, excluding second-hand smoke (SHS) and radon, was in the range of 4,000–11,000 µDALYs (disability-adjusted life years) per person per year. By way of comparison, this means the damage attributable to indoor air is somewhere between the health effects of road traffic accidents (4,000 µDALYs/p/yr) and heart disease from all causes (11,000 µDALYs/p/yr). According to the World Health Organization (WHO, 2014), 99,000 deaths in Europe and 81,000 in the Americas were attributable to household (indoor) air pollution in 2012. Health gains in Europe (EU-26) attributed to effective implementation of the energy performance building directive, which includes indoor air quality issues, have been estimated at more than 300,000 DALYs per year.

Today we ventilate our buildings to provide a healthy and comfortable indoor environment, with attention to health, moisture and odor issues. Indoor pollutant sources include outside air, occupants and their activities, and the furnishings and materials installed in buildings.

As the list of identified indoor pollutants is long and may still increase, it has been impossible to create definitive IAQ metrics for standards and regulations governing residential buildings (Borsboom et al., 2016). Consequently, IAQ performance-based approaches for ventilation at the design stage of a building are rarely used. Instead, prescribed ventilation rates have been used, assuming that at the same time they would control human bio-effluents, including odors, they would control also any other contaminant as well (Matson and Sherman, 2004). As a result, standards and regulations, such as ASHRAE 62.2-2016 and others in Europe (Dimitroulopoulou, 2012), often prescribe ventilation strategies requiring three constraints on airflow rates:

1. A constant airflow based on a rough estimation of the emissions of the buildings, for instance one that considers size of the home, the number and type of occupants, or combinations thereof;
2. Minimum airflows (for instance during unoccupied periods);
3. Sometimes also provisions for short-term forced airflows to dilute and remove a source pollutant generated by activities as cooking, showering, house cleaning, etc.

In order to conciliate energy saving and indoor air quality issues, interest in a new generation of smart ventilation systems has been growing. Thanks to "performance-based approaches", such systems must often be compared either to constant-airflow systems ("equivalence approaches") or to IAQ metrics thresholds.

This paper provides a review of performance-based approaches used in five countries for the assessment of smart ventilation strategies. We can identify two types of approaches. The United States and Canadian (CAN/CSA-F326-M91 (R2014) - Residential Mechanical Ventilation Systems) standards specify ventilation systems on a building-by-building basis and allow a range of system designs - so long as they meet minimum requirements for airflow sound, etc. Other countries certify ventilation system designs that can then be applied to any building.

The present paper is a part of the project called "Smart Ventilation Advanced for Californian Homes" further developed in (Guyot et al., 2017b). This report includes a literature review on the suitability of common environmental variables (pollutants of concern, humidity, odours, CO_2, occupancy) for smart ventilation applications, the availability and reliability of sensors, the description of available control strategies. Next, a meta-analysis of 38 studies on smart ventilation used in residential buildings, develops the energy and indoor air quality performances, data on the occupant behaviour and on the suitability of a multizone approach for ventilation.

Smart ventilation and demand-controlled ventilation (DCV) definitions

The key smart ventilation concept is to use controls to ventilate more at times it provides either an energy or IAQ advantage (or both) and less when it provides a disadvantage. The fundamental goal of this concept is to reduce ventilation energy use and cost while maintaining the same IAQ level (or improving IAQ) compared to a continuously operating system.

The concept of "Demand-controlled ventilation (DCV)" is a specific subset of smart ventilation. Such strategies have been widely used in scientific literature and in materials associated with available technologies over 30 years. Different definitions of DCV are available. According to the IEA Annex 18, DCV denotes continuously and automatically adjusting the ventilation rate in response to the indoor pollutant load (Mansson et al., 1997). (Limb M.J, 1992, p. 36) defines a DCV strategy as "*a ventilation strategy where the airflow rate is governed by a chosen pollutant concentration level. This level is measured by air quality sensors located within the room or zone. When the pollutant concentration level rises above a preset level, the sensors activate the ventilation system. As the occupants leave the room the pollutant concentration levels are reduced and ventilation is also reduced*".

A recent meta-analysis of 38 studies of various smart ventilation systems with control based on either CO_2, humidity, combined CO_2 and TVOC, occupancy, or outdoor temperature shows that ventilation energy savings up to 60% can be obtained without compromising IAQ- even sometimes improving it (Guyot et al., 2017a). However, the meta-analysis did include some less-than favourable results, with energy over-consumption of 26% in some cases.

The concept of "smart ventilation" more recently developed in the LBNL is another subset of smart ventilation. It was developed in order to control fans to minimize energy use (Sherman and Walker, 2011; Walker et al., 2011; Turner and Walker, 2012; Walker et al., 2014). This smart ventilation concept uses the equivalent ventilation principle (Sherman and Walker, 2011; Sherman et al., 2012) further developed in the paper, to allow for modulation of ventilation airflows in response to several factors, including outdoor conditions, utility peak loads, occupancy, and operation of other air systems. One incarnation of smart ventilation developed by LBNL is the "RIVEC" system that controls a ventilation fan based on real-time calculation of dose and exposure relative to a continuously operating fan. Figure 1 is an illustrative example showing operation of a RIVEC controlled fan that combines forced fan off times with response to operation of other fans.

Ventilation energy savings were estimated to be at least 40% by studying diverse climates (16 California climate zones), various home geometries and values for envelope airtightness to give a good representation of the majority of the Californian housing stock. This reflects absolute energy savings between 500 and 7,000 kWh/year per household with a peak power reduction up to 2 kW in a typical house (Turner and Walker, 2012).

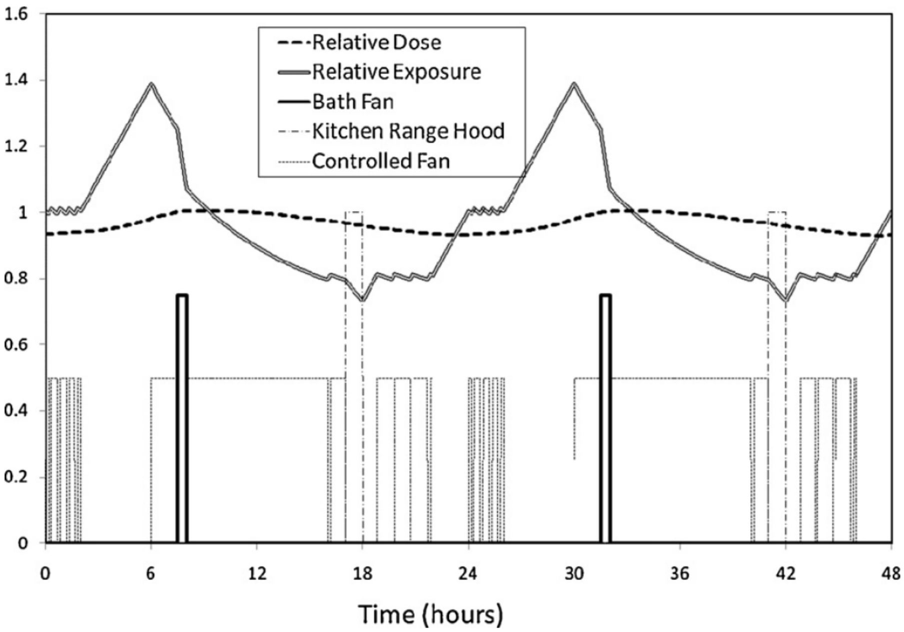


Figure 1 : Simulated controlled whole-house ventilation fan (continuous exhaust) with RIVEC and other household fan operation during the winter, source : (Sherman and Walker, 2011)

Overview on standards and regulations for residential buildings integrating smart ventilation

A number of ventilation standards and national regulations have progressively integrated an allowance for smart ventilation strategies and/or DCV systems in residential buildings. Simultaneously, energy performance regulations include the opportunity to claim credit in energy calculations for savings from such systems. In 2004 in the United States a federal technology alert concluded that the HVAC systems in buildings should use DCV to tailor the amount of ventilation air to the occupancy level, for energy and IAQ reasons (Federal Technology Alert, 2004). Some years later, an update to the ventilation standard ASHRAE 62.2 (ANSI/ASHRAE, 2013) allowed the use of smart ventilation technologies. However, in the US, building energy codes and rating system do not explicitly include the effects of smart ventilation controls. In Europe, several countries enable the use of DCV systems in ventilation codes, including Belgium, France, Spain, Poland, Switzerland, Denmark, Sweden, the Netherlands, Germany (Savin and Laverge, 2011; Kunkel et al., 2015; Borsboom, 2015).

Smart ventilation and/or DCV systems must generally prove their IAQ performance through a performance-based approach, in order to comply with the ventilation regulation and get a credit in the energy-performance regulatory calculation.

Pushed by the international movement toward nearly-zero energy buildings, smart ventilation system success is not about to end. In Europe, two recently published directives n°1253/2014 regarding the eco-design requirements for ventilation units and n°1254/2014 regarding the energy labelling of residential ventilation units (European Parliament and the Council, 2014) are moving toward a generalization of low-pressure systems, DCV systems and balanced heat recovery systems by 2018. According this second directive, for central- and local-

DCV systems, it will be possible to use a correction factor of 0.85 and 0.65, respectively, in the energy consumption calculation performed specifically for this labelling.

Given these opportunities, DCV strategies have been used at massive scale, notably in France and in Belgium, for more than 30 years. As of August 1st 2016, between 20 and 40 DCV systems have received an agreement in France, Belgium, and the Netherlands. Most of them are CO_2 or humidity-based strategies.

IAQ performance-based approaches for smart ventilation used in residential buildings

IAQ performance-based approaches could be used in many ways. Each country uses different indicators, calculated with different methodologies and compared to different thresholds. The common thread in all of these methods is the use at a minimum, of the exposure to a pollutant generated indoors (very often the CO_2) and condensation risk. A minimum airflow rate for unoccupied periods is also often required.

In the United States, the equivalence principles in ventilation and indoor air quality described in (Sherman, 2004; Sherman et al., 2012) have been partially integrated in the current version of the ventilation standard ASHRAE 62.2 2016. Some state building regulations, such as the Title 24 energy-performance regulation in California, require compliance with this standard. This standard gives a method to calculate the minimum constant airflows for residential buildings. It also allows the use of variable volume mechanical ventilation, which could be: 1) ventilation averaged over short periods, 2) scheduled ventilation or 3) ventilation continuously controlled in real time. In the first strategy, total airflow rate equivalence is required over any three-hour period. This allows for switching off the ventilation system during short periods if high airflow rates can be performed later. In any of the three cases, the equivalent ventilation principle is required: the annual exposure must be not higher than that produced by constant airflow systems. The calculations use single zone modelling, with a constant pollutant emission rate, and a time-step no longer than one hour. At each time step i, the relative exposure R_i is calculated from Equation 1 and Equation 2, and shall not exceed a value of 5 in order to avoid peak exposure. The annual average relative exposure must be less than one. The manufacturer, specifier or designer is supposed to certify that the calculation meets the requirements.

$$R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_i \Delta t / V_{space}} < 5 \quad if\ Q_i \neq 0$$

Equation 1

$$R_i = R_{i-1} + \frac{Q_{tot} \Delta t}{V_{space}} < 5 \qquad if\ Q_i = 0$$

Equation 2

$$R_0 = 1$$

Equation 3

Where Q_{tot} is the minimum constant ventilation rate calculated according to section 4.1 of the ASHRAE 62.2, Q_i is the real-time airflow in the variable mechanical ventilation system at time step i, Δt is the time-step used in the calculation, V_{space} is the volume of the space.

In France, manufacturers must follow a compliance procedure for DCV to ensure adequate ventilation. Once a system receives certification of compliance via this procedure, called "Avis technique", it can be used in new dwellings according to its specifications. The agreement is a document of at least 30-60 pages which specifies how the system must be designed, how all the components of the system, including the inlets, outlets and ducts, must be installed, and precisely how the system must be commissioned and maintained. For each type and size of dwelling, the agreement gives the references of inlets and outlets and the input data for energy calculation. The procedure (CCFAT, 2015) describes the common scenario used to evaluate the DCV systems using the multizone software MATHIS (Demouge et al., 2011). Each room of the dwelling is modeled as single zone, with a time-step of 15 min. This procedure is based on the evaluation of humidity-based DCV systems having a widespread use for more than 30 years and thus must be adapted for other types of DCV systems. Typical input data given in the procedure include:

- External data: calculation period (October 1st-May 20th), outdoor CO_2 concentration, meteorological data and wind effects parameters. Only the heating season is considered because it is assumed that window opening is influencing the $_{CO2}$ concentrations for the rest of the year. This approach is also used in the Belgian and Netherlands regulations;
- The dwellings: geometry of the 24 representative dwellings, airtightness of the dwellings and its distribution on the different facades);
- The occupancy scenario: metabolic emission rates of CO_2 and humidity, number of occupants, occupancy schedules, activity levels, and associated moisture emission rates;
- The ventilation components: trickle ventilators positioning, aeraulic characteristics of hygrovariable air inlets and outlets, effects of external and internal temperatures being taken into account as well, schedules for toilets exhausts, schedules for high-speed kitchen exhausts.

Firstly, the cumulative CO_2 exposure indicator E_{2000} (Equation 4) must be calculated and must be under 400,000 ppm.h in each room. This threshold is supposed to represent the mean cumulative exposure under a constant ventilation strategy, although the exact source of this number is not readily available in the literature.

$$E_{2000} = \sum_{t=0}^{T} C_{CO_2>2000}(t) * t < 400\,000\, ppm.h$$

Equation 4

Where $C_{CO_2>2000}(t)$ is the absolute concentration in the room at t time-step, if it is higher than 2000 ppm.

Second, the number of hours when relative humidity is higher than 75%, $T_{RH>75\%}$, must be calculated. This value is representative of the condensation risk (Equation 5).

$$T_{RH>75\%} = \sum_{t=0}^{T} t < 600\ h\ in\ kitchen, 1000\ h\ in\ bathrooms, 100\ h\ in\ other\ rooms$$

Equation 5

Once both IAQ requirements are fulfilled, an “energy calculation” can be performed. This gives the conventional input data, the mean equivalent exhausted airflow ($m^3.h^{-1}$) and the total air inlet mean area (m^2), to be used in the energy performance (EP) calculation of each designed new dwelling. The EP calculation is a single zone modelling calculation. The detailed performance-based approach is performed once for each new DCV system, in order to be later taken into account in each dwelling EP-calculation as average values. The ventilation system may not be switched off during unoccupied periods, the trickle ventilators cannot be closed, and the total minimum airflow is set between 10 and 35 $m^3.h^{-1}$ according to the number of rooms in the building. The agreement is obtained for a 3-years period, after which it is recalculated in order to take into account possible updates in regulations, agreement procedure, and available knowledge and technologies.

In Spain, the procedure is very close to the French one and shares the performance-based approach. Because of current regulations are expressed as constant ventilation flows, DCV systems must pass through a compliance procedure. Once a system receives agreement certificated of compliance, called "Documento de Idoneidad Técnica" (DIT), it can be used in new dwellings according to its specifications. The DIT is a document of about 30 pages that specifies how the system must be designed, how components of the system such as inlets, outlets and ducts, must be installed, and precisely how the system must be commissioned and maintained. For each type of dwelling and climate, the DIT gives the product number of air inlets and outlets, and the input data for energy calculations in the form of an equivalent reduction of constant ventilation flow rates specified in the current regulations. The DIT is adopted for a 5-year period and subject to yearly reviews. The compliance assessment involves reference scenarios: each room of the dwelling is modelled as single-zone with the multizone software CONTAM (Walton and Emmerich, 1994), with a time-step of 40 seconds. Standardized input data are given which include:

- External data: calculation period (all year), outdoor CO_2 concentration, meteorological data;
- The dwellings: geometry of the 14 standard dwellings, air infiltration is not considered;
- The occupancy scenario: metabolic emission rates of CO_2 and humidity, number of occupants, occupancy schedules, a schedule of their activities and associated moisture emission rates;
- The ventilation components: trickle ventilators positioning, aeraulic characteristics of hygrovariable air inlets and outlets, schedules for toilets exhaust.

As a result, if the following IAQ indicators can be achieved, the annually averaged ventilation airflow can be implemented in the EP-calculation:

- Annual averaged CO_2 concentration must be lower than 900 ppm,
- Annual cumulative CO_2 exposure over 1600 ppm E_{1600} (see Equation 4) must be lower than 500,000 ppm.h in each room.

Future changes to the building code are being reviewed (Linares et al., 2014; Garcia and Linares, 2015; Linares et al., 2015). The changes aim to implement a performance-based approach with respect to IAQ requirements at the design stage of each new building. The proposed IAQ requirements are the same ones that are used in the current procedure for DCV. They would also be calculated using a multizone code like CONTAM, with prescribed input data concerning human CO_2 generation, proposed occupancy schedules, and occupancy rate selected according to the national population and 2011 housing census. The minimum airflow during unoccupied periods will be set to 1.5 $l.s^{-1}$ in each room.

In Belgium, the procedure for residential buildings was similar to the French and the Spanish ones until 2015. In order to get a credit in energy calculation, each new system had to pass through an IAQ equivalence procedure before receiving an agreement called "ATG-E", delivered by a national organization (UBATC), then consolidated through a Ministerial Order in each region. The equivalence procedure was described in (ATG and BCCA, 2012) and was also based on a multizone modelling, with CONTAM (Walton and Emmerich, 1994) using a time-step of five minutes. The standardized input data were both deterministic (geometry of the typical house, air leakage, moisture buffering parameters, indoor temperature, exterior climate file, calculation period from October to April) and stochastic (building orientation, wind shielding and terrain roughness, occupancy scenario and contaminant generation). Contaminants considered were CO_2, relative humidity and a tracer gas emitted in toilet and in bathrooms each time these rooms are occupied, for five minutes. 100 datasets were used per level of envelope air leakage (v_{50}=0.6; 3; 6; 9 and 12 $m^3.h^{-1}.m^{-2}$). The reviewed system was then compared to the three reference systems defined in the regulation (A=natural, C=exhaust, D=balanced). The IAQ performance was evaluated through three indicators: the per-person cumulative CO_2 exposure indicator E'_{950} (Equation 6), the time per month critical thermal bridges were exposed to relative humidity over 80% from December 1st to March 1st, the exposure to the tracer gas.

$$E'_{950} = \sum_{t=0}^{T} \left(C_{CO_2>950}(t) - 950\right) * t$$

Equation 6

Where $C_{CO_2>950}(t)$ is the absolute concentration at which an occupant is exposed at t time-step, if it is higher than 950 ppm.

Once the IAQ indicators have been calculated they must be equal or better than the worst IAQ performing reference system. Then, the energy savings coefficient f_{reduc} is calculated from Equation 7, based on the heating season integrated ventilation heat loss E (MWh/year), excluding infiltration heat losses which are treated separately in the EP-calculation method. E_X is calculated for the studied smart system X. E_{ref} is the energy use of a system that has the same CO_2 exposure indicator as the system being rated and is determined as shown in Figure 2.

$$f_{reduc} = \frac{E_X}{E_{ref}}$$

Equation 7

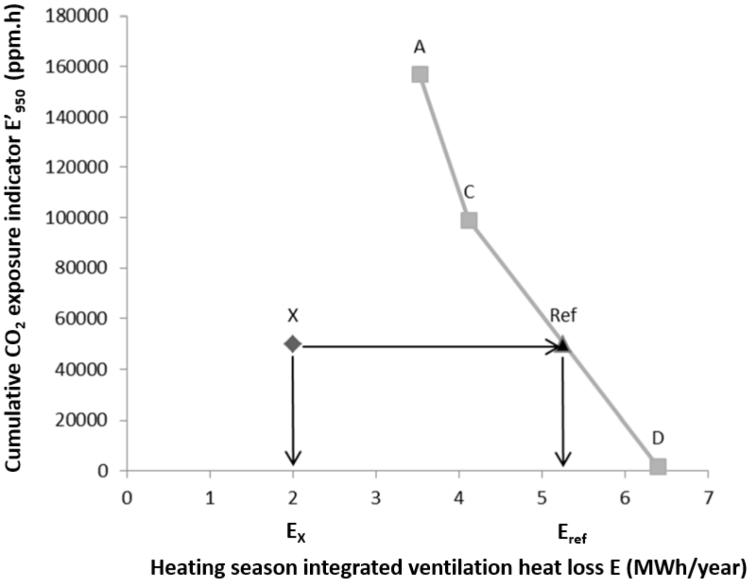


Figure 2 : Energy saving coefficient calculation for a DCV system X (ATG and BCCA, 2012)

In 2014, the Belgian regions considered DCV systems mature enough to be directly integrated in the EP-calculation method. A study (Caillou et al., 2014b) evaluated the 35 ATG-E approved systems. They improved the initial method by taking into account its limitations, such as the fact that the three reference systems defined in the regulation are not equivalent, which is illustrated on Figure 2. Authors added generation of a VOC pollutant emitted proportionally to the surface area of each room to the evaluation method and calculation of the cumulative exposure to this pollutant. Authors proposed classifying DCV systems according to the sensing type: type of sensor, type of spaces, local or centralized and the regulation type: exhaust only, supply only, balanced and local vs. centralized. For each class of DCV systems, they proposed standard values for the energy saving coefficient f_{reduc}. As a result, as of January 1st 2016, only the energy saving coefficient f_{reduc} given in the tables (

Table 1) of an Ministerial Order (Moniteur Belge, 2015) can be used directly in the EP-calculation. This Order requires sensors to conform to the stipulations on accuracy and a minimum airflow over 10% of the minimum constant airflow for each room. Intermittent ventilation is allowed if the 15-minute average airflows is equal to this 10% requirement.

Table 1: Energy saving coefficient f_{reduc} for all types of DCV systems (natural, exhaust-only, supply-only, balanced) used in residential buildings with a regulation of air inlets based on needs in dry spaces and/or with a regulation of air outlets based on needs in humid rooms (another table is available for exhaust-only systems with a regulation of air outlets based on needs in dry spaces)

Type of detection in dry spaces	**Type of regulation of air inlets in dry spaces**	**Local detection in humid spaces with regulation of air outlet Local regulation**	**Local detection in humid spaces with regulation of air outlet No local regulation**	**Other or no detection in humid spaces**
CO_2-local : at least a sensor in each dry space	Local	0.35	0.38	0.42
	2 zones (night/day) or more	0.41	0.45	0.49
	Central	0.51	0.56	0.61
CO_2- partially local : at least a sensor in each bedroom	Central	0.60	0.65	0.70
CO_2- partially local : at least a sensor in the main bedroom + at least a sensor in the living room	2 zones (night/day) or more	0.43	0.48	0.53
	Central	0.75	0.81	0.87
CO_2-central : at least a sensor in the exhaust duct(s)	Central	0.81	0.87	0.93
Occupancy-local : at least a sensor in each dry space	Local	0.54	0.60	0.64
	2 zones (night/day) or more	0.63	0.67	0.72
	Central	0.76	0.82	0.88
Occupancy-partially local : at least a sensor in each bedroom	Central	0.87	0.93	1.00
Occupancy-partially local : at least a sensor in the main bedroom + at least a sensor in the living room	2 zones (night/day) or more	0.66	0.72	0.78
	Central	0.87	0.93	1.00
Other or no detection in dry spaces	No, local, per zone, or central	0.90	0.95	1.00

In the Netherlands, for DCV systems used in residential buildings, it is possible to use correction factors on the ventilation airflow in the EP-calculation, based on the standard NEN 8088 (NEN, 2011). The standard provides standard energy reduction factors for quite a few DCV systems, ranging from 0.52 to 0.95. A complementary equivalence approach can be performed (VLA, 2013), using COMIS simulation software, in a semi-probabilistic approach (7 dwelling types, different occupant types, different airtightness levels, different wind exposure). The IAQ metric employed is the cumulative CO_2 exposure index requirement per person, LKI_{1200}, calculated for the considered heating period September 29th-April 25th with Equation 8. For a new product type, manufacturers should submit their report to one of three predefined research institutes or consulting companies for review. At the end of the process, an agreement is published on the Dutch Association of Air Handling Equipment Manufacturers (VLA) website, and shortly thereafter a declaration of equivalence is published in the database of the Bureau of Control and Registration (Borsboom, 2015). A minimum air flow is prescribed according to the number and the type of occupants.

$$LKI_{1200} = \sum_{t=0}^{T} \left(\frac{C_{CO_2 > 1200}(t) - 1200}{1000} \right) * t < 30{,}000\, ppm.h$$

Equation 8

Where $C_{CO_2 > 1200}(t)$ is the absolute concentration at which an occupant is exposed at t time-step, if it is higher than 1200 ppm, or 800 ppm above the outdoor concentration.

Country	**Person in charge**	**Ventilation Equivalence method**	**Calculated IAQ indicators**	**Credit in EP-calculation**	**Minimum airflow**
USA (ASHRAE 62.2 2016)	The manufacturer, specifier or designer	Single zone modelling, $\Delta t<1h$, constant pollutant emission rate	No specifically defined pollutant Yearly average relative exposure $R<1$ At each time-step $R_i<5$	No	Can be null if the total airflow rate equivalence is required over any 3-hour periods
France	The manufacturer for each (humidity) DCV system	Multizone modelling with MATHIS, $\Delta t = 15$ min, Conventional entry data	Per room, over the heating period: 1/CO_2 cumulative exposure indicator $E_{2000} <$ 400,000 ppm.h 2/Number of hours $T_{RH>75\%}$ <600 h in kitchen, 1000 h in bathrooms, 100 h in other rooms	Reduced average equivalent exhausted airflow ($m^3.h^{-1}$)	10-35 $m^3.h^{-1}$ according to the number of rooms in the building Switch off not allowed
Spain (<2017)	The manufacturer for each DCV system	Multizone modelling with CONTAM, $\Delta t = 40$ s, Conventional entry data	Per room, over the year: 1/ Yearly average CO_2 concentration < 900 ppm 2/ Yearly cumulative CO_2 exposure over 1600 ppm E_{1600} < 500,000 ppm.h	Reduced yearly average ventilation airflow	
Spain (future)	The designer of the building, of the base of information given by the manufacturer	A performance-based approach for all ventilation systems, using a software and conventional data at the design stage of each building	Per room, over the year: 1/ Yearly average CO_2 concentration < 900 ppm 2/ Yearly cumulative CO_2 exposure over 1600 ppm E_{1600} < 500,000 ppm.h	Reduced yearly average ventilation airflow	1.5 $l.s^{-1}$ in each room during unoccupied periods
Belgium (< 2015)	The manufacturer for each DCV system	Multizone modelling with CONTAM, $\Delta t = 5$ min, conventional entry data both deterministic and stochastic	Per room, over the heating period: 1/CO_2 cumulative exposure indicator E'_{950} 2/Monthly average RH> 80% on critic thermal bridges from December 1st to March 1st 3/Exposure to a tracer gas emitted in toilets and in bathrooms	An energy saving coefficient f_{reduc} is extrapolated	

			They must be at least equal that the worst performing reference system.		
Belgium (since 2015)	The person involved in EP-calculation and manufacturer for each DCV system	No-more existing. An advanced equivalence method has been performed by (Caillou et al., 2014) on all the 35 systems having an agreement.	No-more existing.	Published conventional energy saving coefficients used directly	10% of the minimum constant airflow for each room. An intermittent ventilation is allowed if the average on 15 minutes enables to comply with this 10%.
The Netherlands	The person involved in EP-calculation (standard approach) OR the manufacturer for each DCV system (equivalence approach)	For equivalence procedure : multizone code COMIS, in a semi-probalistic approach	Per person, over the heating period : Cumulative CO_2 exposure over 1200 ppm: $LKI_{1200} < 30,000$ ppm.h	Either, correction factors given in the standard for quite a few DCV systems OR Correction factors from the equivalence procedure	A function of the number of type of occupants

Table 2 : Overview of equivalence principles for smart ventilation and/or DCV in some residential building regulations

To our knowledge, only one study (Sherman et al., 2012) proposes consideration of an "IAQ equivalence" based on health-related metrics. The authors propose a method taking advantage of available data in previous work (Logue et al., 2011b, 2011a) and using the disability-adjusted life years (DALYs) metric. Based on disease incidence models, (Logue et al., 2011b) calculated the DALYs lost as a result of long-term exposure to indoor pollutants in residences and published values of the DALYs lost per incidence of disease. In this calculation, they used the unit damage estimate (UDE) value for each pollutant of interest. The "IAQ equivalence" also proposes use of these UDE_i values in order to set a DALY limit value (Equation 10) and then proposes checking that the combination of contaminant concentrations according to Equation 9 stays below this limit. (Sherman et al., 2012) evaluated this limit as 8,200 µDALY per person per year for the pollutants in Table 3. It can be seen that $PM_{2.5}$ dominates this list. If radon, ozone, and $PM_{2.5}$ can be handled through prescriptive measures, the DALY limit decreases to 90 µALY/p/year. This approach is obviously limited, since it assumes that indoor contaminants of concern are clearly identified and prioritized. This equivalent methodology also needs to include acute exposure issues. Nevertheless, it could be integrated into evaluation methods for innovative smart ventilation systems, and even directly into the control of such systems with real-time sensors.

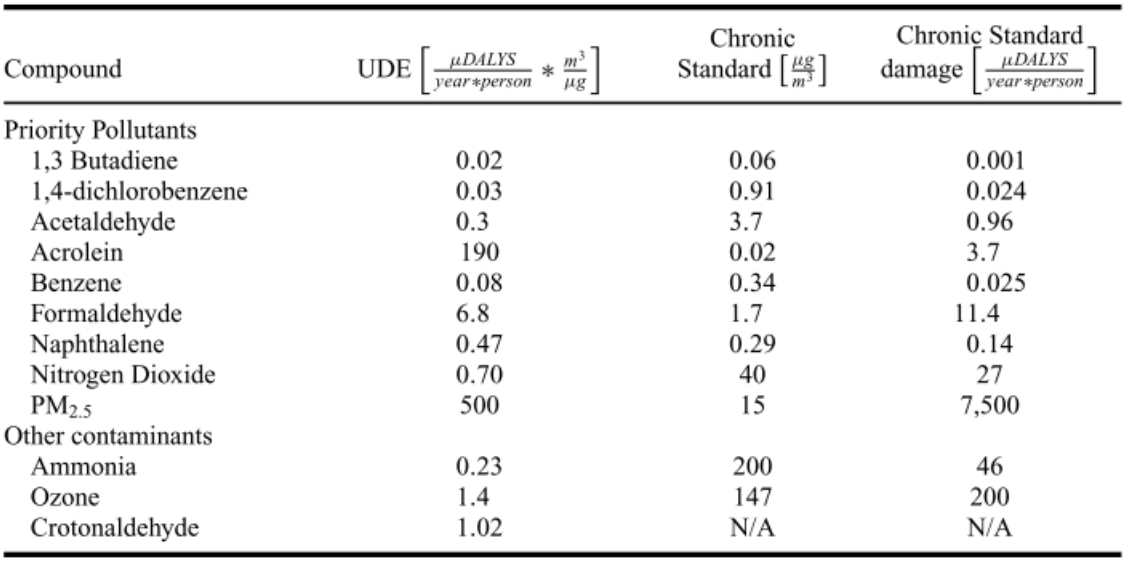
$$DALY = \sum_i \ Concentration_i * UDE_i$$

Equation 9

$$DALY_{limit} = \sum_i \ Standard_i * UDE_i$$

Equation 10

Table 3: Indoor air contaminants – UDE_i and $Standard_i$ values in order to implement the IAQ equivalence principle according to Equation 9 and Equation 10 , source : (Sherman et al., 2012)



Compound	UDE $\left[\frac{\mu DALYS}{year*person} * \frac{m^3}{\mu g}\right]$	Chronic Standard $\left[\frac{\mu g}{m^3}\right]$	Chronic Standard damage $\left[\frac{\mu DALYS}{year*person}\right]$
Priority Pollutants			
1,3 Butadiene	0.02	0.06	0.001
1,4-dichlorobenzene	0.03	0.91	0.024
Acetaldehyde	0.3	3.7	0.96
Acrolein	190	0.02	3.7
Benzene	0.08	0.34	0.025
Formaldehyde	6.8	1.7	11.4
Naphthalene	0.47	0.29	0.14
Nitrogen Dioxide	0.70	40	27
$PM_{2.5}$	500	15	7,500
Other contaminants			
Ammonia	0.23	200	46
Ozone	1.4	147	200
Crotonaldehyde	1.02	N/A	N/A

State of the art of the pollutant sensors used for smart residential ventilation

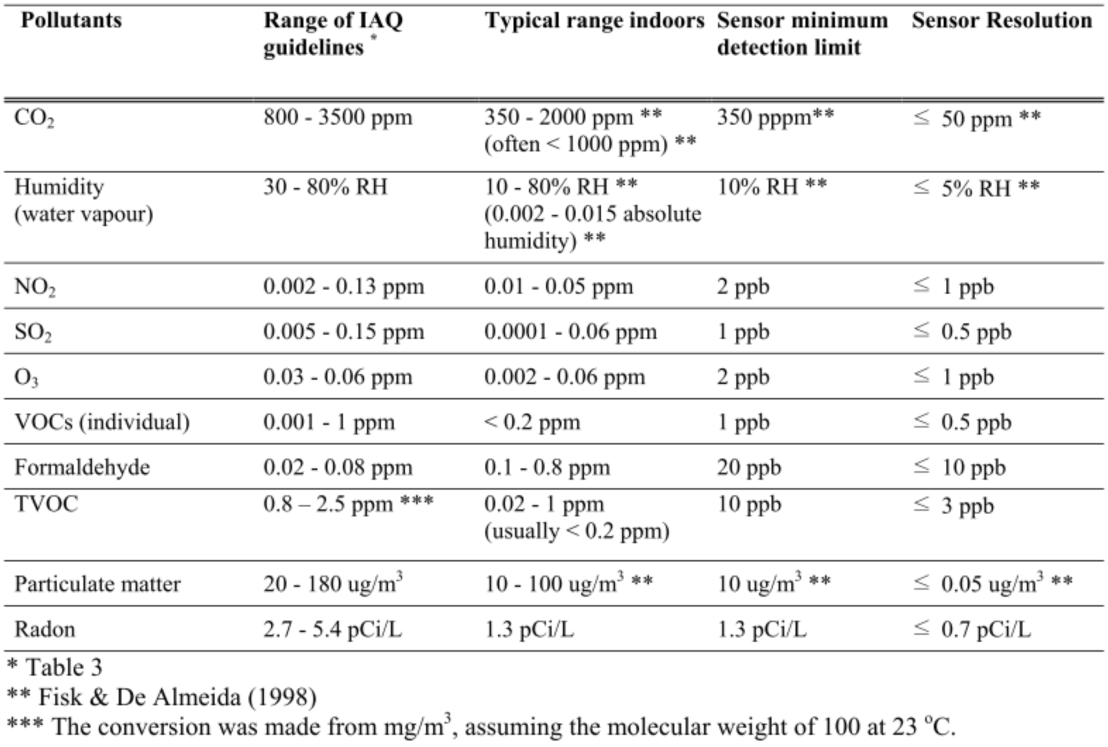
In smart ventilation strategies, sensors need to have a real-time output signal to allow the system to react and adjust the airflow. Selection of sensors for DCV applications should consider three criteria: Performance (whether the performance range can cover the typical IAQ range or guideline thresholds, whether resolution can meet the suggested level, and if the calibration frequency is not more than once a year), Cost and IAQ (the pollutant must be relevant and faced to an effective risk). The word “sensor” can refer to a single direct sensor or several components (filters, amplifiers, modulators of other signals). Many factors can affect sensor performance and should be considered in the choice of a sensor for smart ventilation applications, along with other factors such as size, extent of signal conditioning, reliability, robustness, maintainability, and cost (Bishop 2002).

An extensive Canadian review of the state of the art included sensors for CO_2, humidity, VOCs, formaldehyde, NO_2, SO_2, ozone, particulate matter and radon (Won and Yang, 2005) was updated in 2011 for formaldehyde sensors (Won and Schleibinger, 2011). Suggested performance and specifications of available sensors are summarized in

Table 4 and

Table 5, authors recommending that: 1) sensor minimum detection thresholds should be equal to the lower concentrations expected inside buildings, 2) sensor resolution and maximum drift between calibrations should be less than 10% of a typical indoor concentration, and 3) 30 minutes is a typical ventilation time constant and acceptable sensors should reflect this.

Table 4: Suggested performance levels of sensors for DCV (Won and Yang 2005)



Pollutants	Range of IAQ guidelines *	Typical range indoors	Sensor minimum detection limit	Sensor Resolution
CO_2	800 - 3500 ppm	350 - 2000 ppm ** (often < 1000 ppm) **	350 pppm**	≤ 50 ppm **
Humidity (water vapour)	30 - 80% RH	10 - 80% RH ** (0.002 - 0.015 absolute humidity) **	10% RH **	≤ 5% RH **
NO_2	0.002 - 0.13 ppm	0.01 - 0.05 ppm	2 ppb	≤ 1 ppb
SO_2	0.005 - 0.15 ppm	0.0001 - 0.06 ppm	1 ppb	≤ 0.5 ppb
O_3	0.03 - 0.06 ppm	0.002 - 0.06 ppm	2 ppb	≤ 1 ppb
VOCs (individual)	0.001 - 1 ppm	< 0.2 ppm	1 ppb	≤ 0.5 ppb
Formaldehyde	0.02 - 0.08 ppm	0.1 - 0.8 ppm	20 ppb	≤ 10 ppb
TVOC	0.8 – 2.5 ppm ***	0.02 - 1 ppm (usually < 0.2 ppm)	10 ppb	≤ 3 ppb
Particulate matter	20 - 180 ug/m^3	10 - 100 ug/m^3 **	10 ug/m^3 **	≤ 0.05 ug/m^3 **
Radon	2.7 - 5.4 pCi/L	1.3 pCi/L	1.3 pCi/L	≤ 0.7 pCi/L

* Table 3

** Fisk & De Almeida (1998)

*** The conversion was made from mg/m^3, assuming the molecular weight of 100 at 23 °C.

Table 5: General specifications of commercial sensors (Won and Yang 2005)

Pollutants	Detection Range	Detection Limit	Accuarcy	Resolution	Price (CAD$)	Calibration	Method
CO_2	0-5,000 ppm		±50 ppm or ±5%	1 ppm	~ $500	Not required, but calibration every 5 years is recommended	Non-dispersive infrared (NDIR)
Humidity (RH)	0-90% RH		±2-3% RH	0.1%	< $500	Not required, or once every 2 years	Thin film capacitive sensor
Humidity (dew point)	-20 to 50°C		±2°C		$700	Not required, or once every 1 or 2 years	Calculated from RH measurements w/ thin film sensor
NO_2	0-20 ppm		±2-5%	0.1 ppm	$500 - > $1,000	Not required, or once every 6 months or 1 year	Elecrochemical
	0-0.05/0.2 ppm	50 ppt			>= $10,000		Chemiluscence
SO_2	0-20 ppm		±2-5%		$1,000-$2,000	"	Elecrochemical
O_3	0-1 ppm		±2-5%		$1,000-$2,000	Once every 6 months or 1 year	Elecrochemical
	0-0.17 ppm			1 ppb	$1,000-$2,000		Metal oxides
TVOC	0.02-20 ppm		±25%		$5,000 (w/ T & RH)	Not required or every 6 months or 3 years	PID
Formaldehyde	0-2/10 ppm		±5%	0.01 ppm	$2,000 - $4,000	Not required, every 1 year	Elecrochemical
A set of VOCs	low ppb - low ppm	low ppb			$20,000 - $35,000		An array of QCM, QMB, MOS, &/or SAW
Particle	0.3 - 25 µm	37-74 ppb*			$4,000-4,500 (hand-held) > $10,000 (portable)		Light scattering
	0.3 - 5 µm	5-55 ppb*			$2,000-4,000		
Radon	0-1,000 pCi/L			1 pCi/L	$150 - $4,000	Once every 6 months or 1 year	Various

* The number concentration in Table 17 was converted to the mass concentration, assuming all particles have a size of 1 µm and a density of 1 g/cm^3

CO_2 sensor technologies are not new; DCV strategies have existed for more than 30 years. Available technologies are mostly non-dispersive infrared sensors, but also include photoacoustic CO_2 sensors. Fisk (2010) studied the accuracy of 208 single-location CO_2 sensors in 34 commercial buildings. Even if the average errors were small (i.e., 26 ppm and 9 ppm, respectively, at 760 and 1,010 ppm), they found occasional respective absolute of errors of 118 at 760 ppm (16%) and 138 at 1,010 ppm (14%). Authors showed that there were also statistically significant differences between different technologies and manufacturers, and that sensor age was not statistically significant. These observations were confirmed by (Shrestha and Maxwell 2009), which reported numerous errors greater than 75 ppm; cases of errors greater than 200 ppm were not uncommon.

Unlike other pollutant sensors, CO_2 sensors can be considered quite easy to calibrate, since gas mixtures with necessary CO_2 concentrations can be accurately and readily manufactured using pure CO_2.

In the Belgian regulation for DCV strategies, a CO_2-based DCV system must include CO_2 sensors with a maximum uncertainty of 40 ppm + 5% of the target value, in the 300 ppm—1,200 ppm range (Moniteur Belge 2015). The non-residential requirements of California's Title 24 regulations state that "*the CO_2 sensors must be factory certified to have an accuracy of no less than 75 ppm over a five-year period without recalibration in the field*."

Costs were evaluated in 2011 (Mortensen 2011) and found to be approximately 3000 DKK$ (~$450 US, ~400 EUR).

Humidity sensors are not new either, as such DCV strategies have been used at large scale, notably in France, for more than 30 years. Won and Yang's review (2005) refers to a previous study (Roveti 2001) that reviews the wide variety of sensors available on the market. In France, for more than 30 years, the market has largely been dominated by humidity-based DCV systems with mechanically variable inlet and outlet cross-sections (Savin, et al. 2014). Advanced materials are used, such as polyamidic fibre, which varies in length with the relative humidity. Polyamidic fibres are not classical sensors, but they could be described as "sensor-actuators"—worthwhile in a whole house ventilation strategy, but not interesting just as sensors. The proper operation of this type of inlet/outlet has been demonstrated in laboratories and the field by the project Performance (Air, H. 2010; Bernard 2009), through measurements over two complete heating seasons in 31 new occupied apartments. Depending on the manufacturer, lifetimes could be up to 30 years, including a warranty of approximately 10 years, without need for recalibration. These products are used not only in France but also in other European countries such as Spain, Poland, and Germany.

Belgian regulations for DCV strategies state that a relative humidity DCV system must include relative humidity sensors, each with a maximum uncertainty of 5% of the target value, in the 10%—90% RH range (Moniteur Belge 2015).

In their market survey, Won and Yang (2005) found that humidity sensors were usually combined with temperature sensors. The average measurement range was found to be between 0% and 90% with an accuracy of +-2%—3%. A majority were thin film capacitive sensors, with a cost below that of CO_2 sensors ($500 CAD, ~$400 US, ~350 EUR). The humidity sensor-actuators described above are not reported in this market survey and are very low-cost (<20 EUR) with a long warranty.

VOC sensing in demand-controlled ventilation is relatively new because, until recently, VOCs could not be measured separately; multi-gas sensors were used instead. Won and Schleibinger (2011) noted cross-sensitivity as a major issue for VOC sensors. Datasheets published by manufacturers allow quantification of this cross-sensitivity issue. (Won and Schleibinger 2011) concluded that no commercial VOC sensor was yet precise and specific enough for ventilation applications. Kumar, et al. (2016) reviewed compact, light-weight, inexpensive sensors up to $500 USD, with some under $100 USD measuring carbon monoxide, benzene, and VOCs. Advanced technologies have been reviewed (Kumar, et al. 2016), including a miniaturized gas chromatography system for monitoring single volatile compounds in indoor air (Zampolli, et al. 2005). In Belgium, those wishing to employ a VOC sensor in bathrooms in a DCV system must prove that there is a correlation between the measured signal and human occupancy (Moniteur Belge 2015). Before beginning to study implementation of such a sensor on a large scale, Caillou, et al. (2014b) consulted several international experts in the field. In 2014, VOC-sensing technology was considered mature enough to be integrated into DCV technologies. A commonly cited problem is the difficulty associated with directly controlling and calibrating such a sensor, as opposed to a CO_2 sensor, for instance.

Other types of sensors such as formaldehyde, particle, NO_2, microelectronic mechanical sensors, nanosensors, multiple-parameter sensors, electronic nose, ozone, sulfur dioxide, and radon were described in Won and Yang's market survey (2005) and are not reported here because of their very limited use in residential applications.

Others topics are subjects of interest for smart ventilation performance and are developed in (Guyot et al., 2017b): occupancy sensors, data transmission, type of control (centralized or per-zone), the number and location of sensors, and control strategy algorithms.

Conclusions

This paper summarizes the strategies used in Europe and the US for development of smart ventilation strategies, such as demand-control ventilation strategies. The paper gives an overview of the regulations and standards proposing "performance-based approaches" in five countries to promote the use of smart ventilation strategies. The common thread in all of these methods is the use, at a minimum, of the exposure to a pollutant generated indoors (very often the CO_2) and condensation risk. As a result, more than 20 compliant DCV systems are available in countries such as Belgium, France and the Netherlands.

From this summary we found that there are areas of commonality between some countries:

- the use of cumulative CO_2 above a certain limit
- the use of mean CO_2 over a year (or other lengthy period)
- time above relative humidity thresholds
- simple pre-calculated multipliers for use in energy calculations.

However, IAQ Metrics vary from country to country and even if they have metrics in common (e.g., cumulative CO_2 above a certain level) the levels and target values are different. Similarly, the implementation in energy calculations also varies (e.g., using different times of the year for evaluation purposes). These differences make discussions about appropriate ventilation levels difficult, adds burden to manufacturers who have to go through multiple product approval procedures and it is a restraint on ventilation system innovation due to having to address multiple performance targets. Therefore, there is the need for a common metric, associated to a common evaluation method and the use of common target values. There is also a clear potential for the use of real-time controllers for IAQ but changes to energy calculation procedures would be required.

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