DEVELOPMENT OF AN EVALUATION METHODOLOGY TO QUANTIFY THE ENERGY POTENTIAL OF DEMAND CONTROLLED VENTILATION STRATEGIES

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ABSTRACT

Demand controlled ventilation (DCV) is seen more and more as a promising way to limit the energy consumption due to ventilation in buildings. However DCV is always a compromise between decreasing the ventilation flow rates and assuring the indoor air quality (IAQ). Ventilation requirements are usually expressed as required air flow rates in the ventilation standards and regulations. Up to now, no consensus for an absolute criterion of IAQ exists in the international scientific community. Quantifying the energy potential of DCV strategies taking into account the indoor air quality is still a big challenge. This paper describes a preliminary study for the development of such an assessment method for DCV strategies in the context of the regulation for the energy performance of buildings in Belgium.

This method was based on numerical simulations using the CONTAM software, with a Monte Carlo approach and representative occupation profiles.

An important question in this study was the choice of the reference system and/or flow rate used to quantify the energy potential of DCV strategies. Different possible references have been compared and discussed. In the absence of an absolute IAQ criterion and because manual regulation strategies cannot be considered as DCV, we propose to quantify DCV strategies by comparing the DCV strategy to be tested with a system, working at constant flow rate, achieving the same IAQ-level as the tested DCV system.

Different DCV strategies have been evaluated using this methodology. The following types of detection have been studied: CO2 or presence detection in the living spaces, and/or relative humidity (RH) detection in the service spaces. The regulation strategies ranged from very complex, with local detection and local regulation in each room independently, to very crude, with central detection and central regulation for the whole dwelling, and a series of intermediary strategies.

The main results can be summarized as follows. Applying this methodology to a large range of different DCV strategies, the simulation results lead to reduction factors of 0.61 for a complete DCV system combining CO2 detection in the living spaces and RH detection in the service spaces, 0.64 for the DCV system with only CO2 detection, and around 1 for DCV system with only RH detection in the service spaces. DCV strategies with only RH detection in the service rooms showed a poor energy potential because this kind of detection is not sufficient to control the IAQ in the living spaces. In contrast, DCV strategies with only CO2 detection in the living spaces gave a higher energy potential, depending also on the number of living spaces equipped with a detection sensor.

KEYWORDS

Manually regulated ventilation systems, CO_2 detection, relative humidity detection, presence detection, Contam simulations

1 INTRODUCTION

1.1 Context and objective

Demand Controlled Ventilation (DCV) is one of the promising solutions to decrease the energy impact of the building ventilation. The aim of DCV is to automatically adapt the ventilation flow rates to the ventilation needs in the building. By decreasing the ventilation flow rates, DCV also possibly influences the indoor air quality (IAQ). DCV is then always a compromise between energy savings (lower flow rates) and IAQ (higher flow rates). In the context of the energy performance of buildings (EPB), taking this trade off into account is crucial to carefully quantify the potential of energy savings for DCV systems.

The aim of this study was (1) to develop a methodology to quantify the energy savings of DCV and (2) to apply this methodology to a range of different DCV strategies as complete as possible, in order to quantify de energy savings of these DCV strategies in the form of reduction factors (value lower or equal to 1). To achieve this aim, numerical simulations using the software Contam have been carried out.

1.2 What is DCV?

First of all, a DCV system is a ventilation system, aiming to assure a sufficient air exchange rate of the building in order to maintain a sufficient level of IAQ at all times.
Specifically, a DCV system is an automatic control system aiming to modulate the ventilation flow rates by adapting the ventilation flow rates to the real, varying ventilation needs in the building. To achieve this, a DCV system is composed of:

- One or several sensors (CO_2, humidity, etc.) to measure the ventilation needs in the building,
- One or several regulation devices (adjustable fans, control valves, etc.) to regulate the ventilation flow rates in the building.

1.3 Origin of the energy potential of DCV

The energy potential of DCV is related to the real ventilation needs which are sometimes lower than the ventilation requirements for which the building has been designed:

- Lower real occupancy compared to the design capacity of the building (for example 2 occupants are living in a dwelling designed for 4 occupants);
- Variable occupancy in time (for example the occupants are not present during the day because they are at work or at school).

The key goal of DCV is to achieve flow rate reduction due to lower ventilation needs and DCV should be evaluated as such, independently of other ventilation parameters, such as:

- Effect of natural ventilation versus mechanical ventilation;
- Effect of the airtightness of the building and possible interactions between ventilation and in/exfiltration or adventitious ventilation.

Although some of these aspects of ventilation systems are sometimes discussed and evaluated together with DCV, they should be considered separately. In order to evaluate DCV independently from these others aspects, the evaluation of DCV was carried out in the following conditions:

- Mechanical supply and exhaust system (the ventilation system which provides the most controlled flow rates),
- Airtight building envelope (avoiding interaction between ventilation and airtightness),
- Model dwelling situated on one floor (avoid effect of buoyancy related adventitious ventilation).

2 METHODOLOGY

2.1 Modelling

The performances of the reference and DCV ventilation systems were evaluated using numerical simulations in the multi-zone airflow simulation package Contam[1]. The modelling used in this study was based on those used up to now in the context of EPB procedure in Belgium (equivalence procedure for innovative products), which is described in details in the following references (Heijmans et al, 2007[2]; Laverge et al, 2011[3]) and summarized as follows.

The model dwelling has been adapted and Table 1 lists the dimensions (m^2) and design ventilation flow rates of the spaces in the model dwelling. For the results presented in this paper, the building envelope was airtight.

Table 1: Composition of the model dwelling

Spaces	Dimension (m^2)	Supply flow rate (m^3/h)	Exhaust flow rate (m^3/h)
Living room	30	108	
Kitchen	13.5		60
Laundry	7.7		60
Toilet	1.6		30
Hall	10.9		16
Bathroom	7.5		60
Sleeping room 1	12.2	44	
Sleeping room 2	9.8	35	
Sleeping room 3	10.8	39	
TOTAL	104	226	226

To take the sensitivity of the simulation results to variations in the input data into account, a Monte Carlo approach has been used in this study. In this approach, instead of fixing 1 value for each input data, a distribution is determined for the key parameters and multiple simulations are carried out with different values of these parameters. In this study, this approach was carried out with 100 simulations with distributions of input data, such as different occupancy profiles. The number of occupants in the dwelling varies from one to six (1: 3%, 2: 21%, 3: 31%, 4: 32%, 5: 10%, 6: 3%), with an average of 3.34 persons per building.

2.2 IAQ criteria

In dwellings, the main reasons to ventilate are:

- To evacuate polluted air due to human occupancy for comfort and health reasons,
- To evacuate moisture produced by human activities such as cooking, baths and showers, clothes drying, etc., to avoid moisture and mould problems.

For the first ventilation rationale, CO_2 concentration is usually used as tracer of the human exposure to unpleasant IAQ. A first criterion is therefore based on the CO_2 exposure of the occupants. The cumulative CO_2 concentration above 600 ppm to which the occupants are exposed during their time of residence in the dwelling is used in this study. For the second ventilation rationale, the relative humidity is a useful indicator. The second IAQ criterion is based on the risk of high humidity levels on thermal bridges. The monthly averaged relative humidity on a thermal bridge with a temperature factor of 0.7 cannot be higher than 80%, which is a typical threshold for higher risk of mould development.

Two other criteria were also used in the study but not detailed in this paper: dispersion of odours due to the use of the toilets and exposure to pollutant emissions from building materials and furniture.

The main outputs from the simulations are (1) the total average ventilation heat loss, (2) the total exposure of the occupants to CO_2, and (3) the relative humidity in the service spaces.

Thanks to this method, the performance of different DCV strategies can be compared to different reference ventilation systems.

3 RESULTS AND DISCUSSION

3.1 Reference systems to quantify DCV

The most important question of this study was the choice of the reference system and/or flow rate used to quantify the energy potential of DCV strategies. This choice is particularly complex because DCV is always a compromise between flow rate reduction and IAQ. However, up to now, no consensus for an absolute criterion of IAQ exists in the international scientific community. Different possible references have been compared (see Figure 1):

- A mechanical supply and exhaust system working permanently at the design flow rates as required in the EPB regulation in Belgium for the model dwelling (red spot 100 % in the figure), as a result of the simulation methodology used in this study;
- The same system working at the flow rate used in the EPB calculation in Belgium for the model dwelling, which is around 150 m³/h (red arrow in the figure);
- Mechanical supply and exhaust systems working permanently at a constant flow rate, ranging from 100% to 30% of the design flow rate as required in the EPB regulation in Belgium for this model dwelling (blue curve in the figure), as a result of the simulation methodology used in this study.

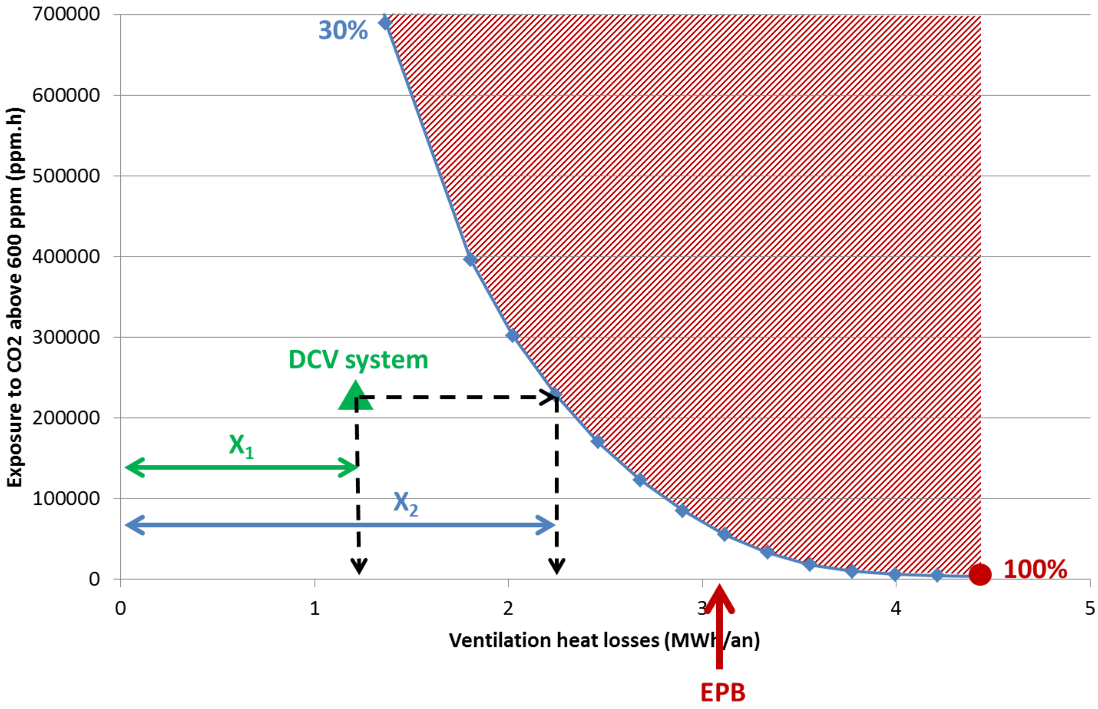

Figure 1: Comparison of different possible references: mechanical supply and exhaust system working at 100 % of required flow rate (red spot 100%), the flow rate used in the EPB calculation in Belgium for the model dwelling (red arrow), and the curve of different mechanical supply and exhaust systems working permanently at a constant flow rate, ranging from 100% to 30% of the required flow rate (blue curve).

As in most of the ventilation regulation and standards, there is no requirement on the IAQ in the ventilation regulation in Belgium, neither does it prescribe an average operational flow rate, but there are requirements on the flow rates for the design capacity of the ventilation systems.[4] The required flow rate (see red spot 100% in the figure) corresponds to a minimum capacity of the ventilation system, but at the same time, it is allowed to regulate the ventilation by adjusting, the flow rates, manually or automatically. The flow rate used in the EPB calculation in Belgium is around 2/3 of the required design flow rate (see red arrow in the figure), and takes already into account a certain regulation of the flow rate, such as manual regulation for example, as an estimate of the average operational flow rate.

The blue curve presented in Figure 1 for a mechanical supply and exhaust systems working permanently at a constant flow rate, ranging from 100% to 30% of the required flow rate, shows that a simple fixed reduction of the flow rates allows already a certain reduction of ventilation heat losses, by degrading the IAQ first very slightly (down to flow rates of around 60%) and then more significantly (flow rate between 60% and 30%). However, it is clear that such a fixed regulation of the flow rates is not a DCV system because DCV means, by definition, an **automatic** regulation of the flow rate. Nevertheless, a DCV system that does not performs better than such a fixed reduction seems of little value.

Required flow rate as reference.

One could consider that the required flow rate (red spot 100% in the figure) should be the reference to quantify DCV strategies. Such an approach is used in the current methodology to evaluate DCV in Belgium (but with additional interpolation between the results of the different ventilation systems, natural or mechanical, allowed in the ventilation regulation in Belgium).
But the main limitation of this approach is that there is no IAQ requirement in the ventilation regulation. A given DCV strategy can then provide a lower IAQ (and a lower flow rate) in this figure, while this strategy is perfectly authorized by the ventilation standard in Belgium. In the absence of an absolute IAQ criterion, this approach therefore leads to more favourable reduction factors for DCV strategies decreasing drastically both the flow rate **and** the IAQ.
A simple fixed reduction evaluated with this methodology and reference could lead to large energy savings, up to around 50%! However it would not be convincing to attribute such favourable reduction factors to a simple manual regulation system, because the calculation of ventilation heat losses in Belgium takes already into account a certain regulation of the flow rate, for example with manual regulation. This approach therefore leads to an embarrassing contradiction.

Flow rate used in EPB calculation as reference.

One could then consider the flow rate used in EPB calculation (red arrow in the figure) as reference to quantify DCV strategies, because this flow rate assumes implicitly a certain reduction of the flow rates, for example thanks to manual regulation strategies. Nevertheless, this only offsets the absolute value of the reduction factor, without addressing the problem of neglecting IAQ in the assessment.

Curve of systems with fixed flow rate reduction as reference.

Finally one could consider quantifying the DCV strategies by comparison with the curve of mechanical supply and exhaust systems working permanently at flow rates from 100% to 30% of the required flow rate (blue curve in the figure).
In this approach, the manual regulation strategies become the reference and correspond logically to a reduction factor equal to 1.0 (default value).This approach takes into account not only the flow rate reduction but also the IAQ provided by the DCV strategy to be tested. That is why this approach has been adopted in this study. The following arguments are also in favour of this approach:

- Most of the ventilation systems today on the market are equipped, as standard, with a manual regulation (for example a switch with 3 positions) and most AHU units allow to adjust the total flow rate in several steps.

- The flow rate used in the EPB calculation in Belgium takes already into account a certain reduction of the flow rates, for example using manual regulation.
- To be really effective, a given DCV strategy should be able to reduce the flow rate compared to a system working permanently at a constant flow rate and providing an equivalent IAQ.

It is particularly important to repeat at this point that the different ventilation systems used in this reference curve are systems working permanently at a constant flow rate. They are not systems manually adjusted by the occupants according to their needs.

This curve allows comparing a DCV system with a system, working at constant flow rate, giving the same IAQ than the DCV system tested. In the following of this study, the DCV systems are evaluated by comparison with this curve and the reduction factor of a given DCV strategy is calculated by X_1/X_2 as illustrated in Figure 1.

3.2 Tested DCV strategies

Different DCV strategies have been investigated and can be classified according to the following parameters:

- Type of **detection**: type of sensor, spaces where detection takes place (living spaces and/or service spaces), local detection (sensor in each space) or centralised detection (sensor in a plenum for example), etc.
- Type of **regulation**: regulation of the supply and/or the exhaust flows, local regulation (the flow rates are adjusted in each space) or centralised (the flow rates are adjusted at the fan for example), etc.

The types of sensor simulated in this study were:

- For the living spaces: CO_2 sensors or presence detection;
- For the service spaces: humidity (RH) detection in the kitchen, the bathroom and the laundry, and presence detection in the toilets.

For each DCV strategy to be tested, different variants of the regulation algorithms have been tested, to check the impact of, for example, the setpoint (for example 950 ppm CO_2), the shape (eg. linear, hysteresis, PID) and the minimum/maximum flow rates (for example 10/100% or 30/100%). The investigation of these variants allowed to identify additional conditions corresponding to each DCV strategy to assure a sufficient effectiveness (for example, conditions on the threshold, the minimum/maximum flow rates, etc.). For the different types of algorithms tested, the main influencing parameters have been found to be the threshold values in terms of flow rates and detected concentrations (for example 950 ppm for CO2 or 70% for RH), rather than the shape of the relation between the detected concentration and the flow rate.

3.3 Maximum potential of DCV

The most complete DCV system investigated combines:

- CO_2 detection locally in each living space, and local regulation of the supply flow rate in each living space;
- RH detection in each service space (presence detection in toilets), and local regulation of the extract flow rate in each service space.

According to the methodology used in this study, and compared to a system working permanently at a constant flow rate and giving the same IAQ, the average reduction factor for this most complete system was 0,61. This result is somewhat higher than but comparable to reduction factors mentioned in other references. For example, the most favourable reduction factor for a DCV system (similar to the one tested in this study) is 0,52 in the EPB regulation in The Netherlands (standard NEN 8088). [5] In the context of the preparation of the Ecodesign

Directive for ventilation units, the value of 0,50 is also mentioned as the most favourable reduction factor (for multi-variable DCV) in the draft of Directive. [6]

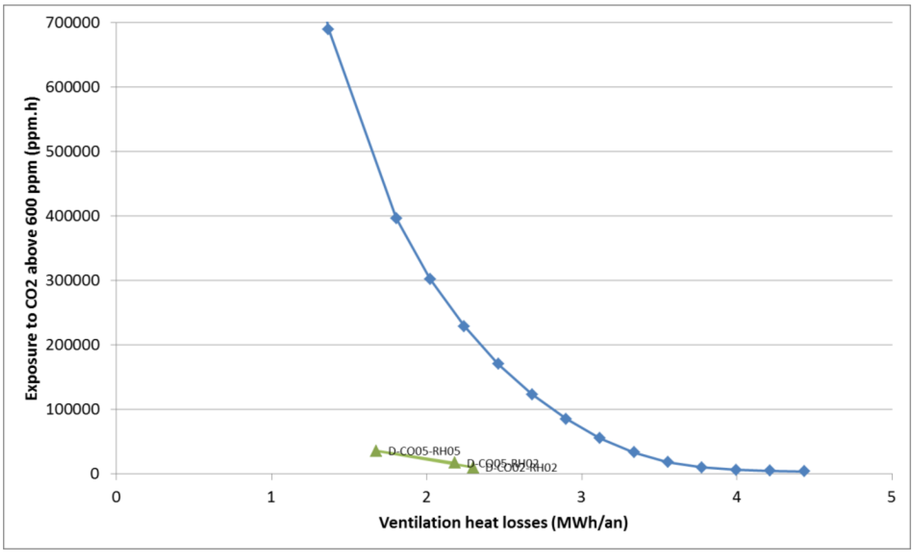

Figure 2: Result of DCV strategies combining CO_2 in the living spaces (local detection and local regulation) with RH in the service spaces (local detection and local regulation). The blue curve is the reference.

3.4 DCV with only CO_2 detection in the living spaces

The most complete DCV system with only detection and regulation in the living space combines:

- CO_2 detection locally in each living space, and local regulation of the supply flow rate in each living space;
- Total flow rate in the service spaces adjusted to the total flow rate for supply in the living spaces.

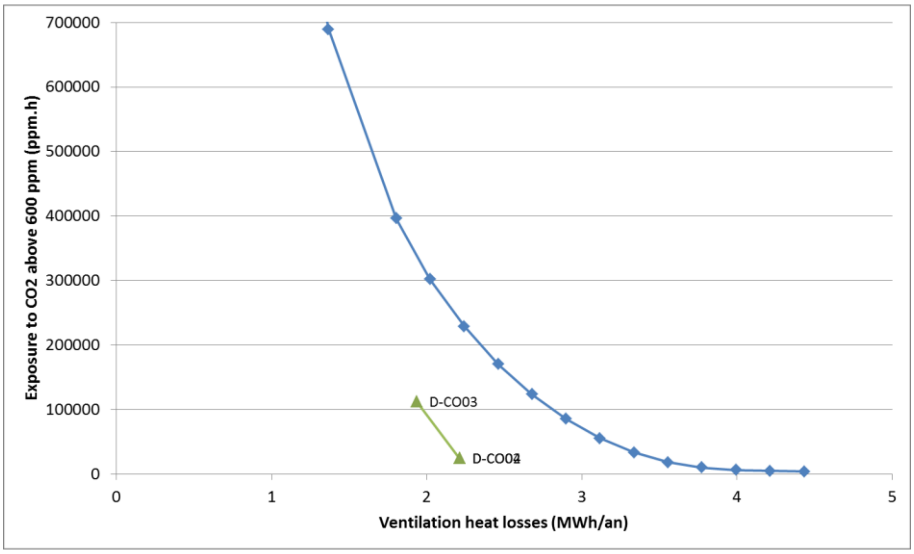

Figure 3: Result of DCV strategies with CO_2 in the living spaces (local detection and local regulation). The blue curve is the reference.

The DCV systems with only CO_2 detection in the living spaces showed an important potential of energy savings compared to a system working permanently at a constant flow rate and giving the same IAQ. But they showed also a higher risk for the humidity criteria in some cases. For the CO_2 criteria, these systems are, as expected, quite effective because the regulation is directly based on the IAQ detected in the living spaces although most of the occupancy time is concentrated in these spaces. Nevertheless, excessive reduction of the flow rates can lead to systems that cannot meet the humidity criterion, while the CO_2 criterion is easily fulfilled. Thus, to meet the humidity criterion and limit the risk of mould development, the results showed that a minimum flow rate of 30-35% for the supply flow rates (compared to the required flow rates) is necessary. The average reduction factor obtained for the DCV systems satisfying the humidity criteria was 0,64.

3.5 DCV with only presence detection in the living spaces

For the detection of the need in the living spaces, presence detection was also investigated as an alternative to CO_2 detection. The results of the simulations showed that the DCV strategies with presence detection are less effective than those with CO_2 detection, with reduction factors 33% higher compared to those for CO_2 detection. The lower performance obtained for the presence detection can be explained by the binary working of the presence detection (“on” or “off”), while the CO_2 detection takes into account variation of demand during occupancy, for example as a function of the number of persons in the space.

3.6 DCV with only RH detection in the service spaces

The most complete DCV system with only RH detection in the service spaces combines:

- RH detection in each service space (presence detection in toilets), and local regulation of the extract flow rate in each service space.
- Total flow rate in the living spaces adjusted to the total flow rate for extraction in the service spaces.

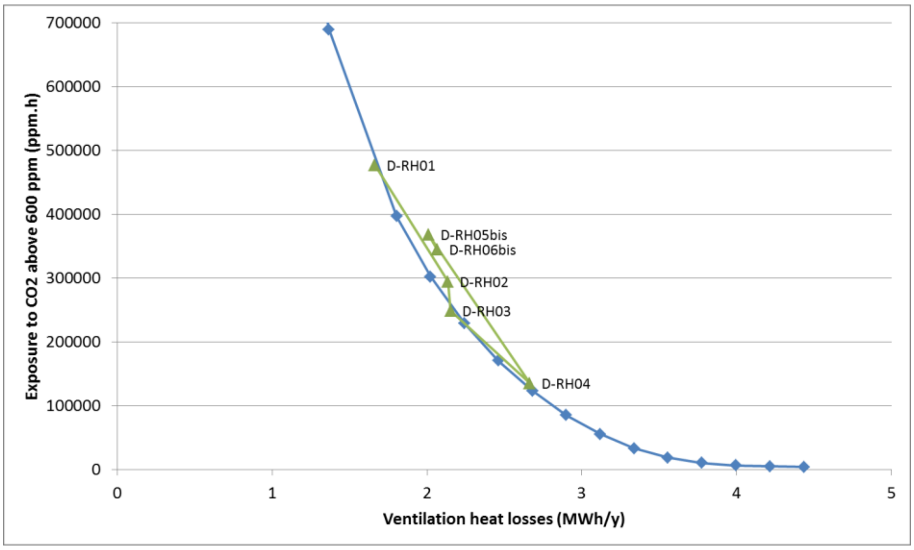

Figure 4: Result of DCV strategies for RH in the service spaces (local detection and local regulation). The blue curve is the reference.

According to the methodology used in this study, and compared to a system working permanently at a constant flow rate and giving the same IAQ, the average reduction factor for the DCV strategies with only RH detection in the service spaces was around 1. This means no advantage compared to a system working permanently at a constant flow rate and giving the same IAQ. This result is maybe not as surprising as it seems and can be explained among other by the too weak link between the RH detected in the service spaces and the human occupancy in the living spaces. This type of DCV strategies is mainly working when humidity is released in the services spaces (shower, cooking, etc.). But it is working on the lowest regime when there are little or no humidity sources, during periods of possibly higher occupancy in the living spaces, for example during the night. In contrast to this DCV strategy with RH only, the systems working permanently at a constant flow rate (the reference curve) assure permanently minimum ventilation:

- By supplying outdoor air to the living spaces, assuring sufficient IAQ for the occupants;
- By evacuating continuously humidity from the service spaces.

3.7 Intermediate DCV strategies

Besides the most complete DCV strategies (local detection and local regulation) presented in § 3.3 to § 3.6, different intermediate DCV strategies have been investigated with a lower number of sensors and moving from local regulation to zonal and centralised regulation. Based on the simulation results, the most promising intermediate DCV strategies were identified as follows (results presented for CO_2 detection in the living spaces).

Table 2: Results for the most promising intermediate DCV strategies with CO_2 detection in the living spaces. Hatched zones indicate irrelevant combination of detection and regulation.

Type of detection in the living spaces	**Type of regulation in the living spaces**	**Reduction factor**
Locally : One sensor or more in each space	Locally	0.64
	2 zones (day/night) or more	0.70
	Centralised	0.80
Partially locally : One sensor or more in each sleeping room	Locally	▨
	2 zones (day/night) or more	▨
	Centralised	0.88
Partially locally : One sensor or more in the living room and one sensor or more in the sleeping room	Locally	▨
	2 zones (day/night) or more	0.73
	Centralised	1.03
Other or no detection in the living spaces	aucune, locale, par zone, ou centrale	1.00 = default value

3.8 Influence of the type of ventilation system (natural versus mechanical)

The results presented above are for the mechanical supply and exhaust system (type D in Belgium). To evaluate the influence of the type of ventilation system (for example the natural ventilation system, type A; or the mechanical exhaust system, type C), DCV systems of type A have been compared to a reference curve of type A, and DCV systems of type C have been compared to a reference curve of type C. The results of the simulations showed that the reduction factor, determined by this way, were close to each other whatever the system type (A, C or D) for a given DCV strategy. The difference between the system types was lower than 10%, sometimes positive, sometimes negative.

4 CONCLUSIONS

This study aimed to develop a methodology to quantify the energy savings of DCV strategies. In the absence of an absolute IAQ criterion and because manual regulation strategies cannot be considered as DCV, it was proposed to quantify DCV strategies by comparing the DCV strategy to be tested with a system, working at constant flow rate, achieving the same IAQ-level as the tested DCV system.

Applying this methodology to a large range of different DCV strategies, the simulation results lead to reduction factors of 0.61 for a complete DCV system combining CO_2 detection in the living spaces and RH detection in the service spaces, 0.64 for the DCV system with only CO_2 detection, and around 1 for DCV system with only RH detection in the service spaces.

5 ACKNOWLEDGEMENTS

This study was funded by the Brussels Capital Region, which is one of the 3 Regions in Belgium, responsible for the EPB regulation.

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