Energy savings and exposure to VOCs of different household sizes with a smart ventilation system

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1 ABSTRACT

Assessment methods to assess smart ventilation, in most countries focus only on comfort as criteria for the indoor air quality (IAQ), (Guyot et al., 2019). This is an issue as in doing so, pollutants that are known to cause harm to the human health are not taken into consideration while the exposure to VOCs will be elevated if the smart ventilation system lowers the ventilation flowrates to save energy (De Jonge and Laverge, 2021). This research addresses the question what the impact of changing family sizes would be on the individual exposure to unhealthy pollutants for a smart ventilation system that only uses comfort related parameters to control the ventilation system. By introducing sources of Volatile Organic Compounds (VOCs) into a Modelica building energy and IAQ model of a typical Belgian apartment the occupant-dependent (CO_2 and RH) smart ventilation can be assessed for non-occupant dependent pollutants (VOCs). For a given smart ventilation system, ten different households, with varying sizes and occupants are simulated.

The results show that the presence of other family members influences the exposure to VOCs of an individual. For the ten cases, the minimum DALY count is 14.75yr and maximum is 17.72yr. They also show that the energy use of the building can be quite different although the only changing parameter in the simulation are the occupants. For the ten cases, the minimum energy use is 731kwh and maximum is 1319kwh.

When designing a simulation-based assessment framework for residential ventilation, the occupant's behavior will always be an unknown factor to consider. The results indicate that in developing a simulations-based assessment framework, it will be best to not assume just one household as in doing so, the system performance for is not properly checked with regards to health and energy use during the lifetime of the system and the expected variation in household types and sizes. The results in this paper confirm the necessity of a stochastic approach for assessing a smart ventilation system based on health-related pollutants (VOCs).

2 KEYWORDS

Smart ventilation, Volatile Organic Compounds (VOC), Health assessment, Energy use, DALY

3 INTRODUCTION

As there is a growing importance in energy efficient ventilation systems, one approach to minimize the energy use related to (fan energy) or caused by the ventilation (increased heating or cooling demand) is to replace conventional ventilation systems that supplies the nominal airflow rate continuously with smart ventilation systems (Durier et al., 2018). Smart ventilation systems use sensors or other means to continuously assess the actual need for ventilation and adapt the ventilation flowrates accordingly as doing so will lower the energy use of the ventilation system.

The issue lies in the fact that today's stand-alone residential smart ventilation systems sold in the EU typically focus on maintaining the same level of comfort with regards to Indoor Air Quality (IAQ). To do so, the humidity levels need to be kept within certain boundaries as well as the CO_2 levels that for this purpose is used as indicator for human bio-effluents. This is an issue as in doing so, pollutants that are known to cause harm to the human health are not taken into consideration while lowering the ventilation rates to save energy can elevate the exposure to these unhealthy pollutants (De Jonge and Laverge, 2021).

The current ways to assess smart ventilation systems are described by Guyot et al. (Guyot et al., 2019). These assessment frameworks use IAQ simulations to predict the performance. Based on the results of the simulations, it is assessed if a certain control algorithm can meet the minimum requirements and a score (indicative of the energy saving potential) is given to the ventilation system. Such assessment frameworks define a specific set of inputs for the IAQ predictions.

One of such inputs is the size of the household and the type of occupants. For smart ventilation systems focused on comfort, this is proven to be an important aspect (Caillou et al., 2014) as the number of occupants, will impact the CO_2 concentration, which will impact how/when the ventilation airflow rates are increased: occupant-dependent smart ventilation is assessed based on occupant-dependent pollutants.

An exception is the principle of ‘equivalence’ in the ASHREA standard 62.2. The governing idea of this method is to assume a fictive constant non-occupant dependent pollutant source and compare the exposure to this pollutant for a reference system and a smart ventilation system. It should be noted that this method is described for a 1-zone IAQ model. The fictive pollutant source makes abstraction of the actual pollutant sources and their dynamic behavior, not making it able to quantify the harmfulness of the indoor air.

In a scientific paper by Sherman et al. describing the original conception of the equivalence method. The authors discuss the downside of the original method and mention an alternative method for which the harmfulness is quantified using Disability Adjusted Life Years (DALYs) (Sherman et al., 2012).

This research addresses the question what the impact of changing family sizes would be on the individual exposure to specific unhealthy pollutants, the associated health effects and contribution of the different contaminants on the total harm: assessing occupant-dependent smart ventilation using specific non-occupant dependent pollutants.

This is an important question in the development of a new assessment framework which does include exposure to specific unhealthy pollutants and the further development of robust smart ventilation control algorithms. IEA EBC Annex 86: “Energy Efficient Indoor Air Quality Management in Residential Buildings” also points out the necessity of this topic as it addresses caveats in how smart ventilation systems should be assessed and developed (IEA EBC, 2021).

4 METHODS & MODELS

To address the research question, a simulation study is done. A combined thermal and IAQ model of the Belgian reference apartment is made using Modelica. In this model, the nominal ventilation system is replaced by a smart ventilation system and VOC emissions from building materials, furniture and activities are added.

4.1 Simulation environment

The modelling language Modelica is used to model the case study building. The thermal, BES and airflow model is modelled using the open-source IDEAS package. This library is an associated library of the IBPSA project 1 library (De Jonge et al., 2021; Jorissen et al., 2018). These models are complimented with proprietary Modelica models for modelling additional airflow paths, the sources of VOCs and the effects of moisture buffering. Additionally, specific models were developed to calculate the performance indicators during run-time.

4.2 Building model

The building model used for this study is a typical Belgian apartment also used in previous studies concerning (smart) ventilation in Belgium (Caillou et al., 2014; Laverge et al., 2011; Laverge and Janssens, 2013). The walls are modeled as insulated brick cavity walls with the insulation thickness set to match the Belgian standard with regards to necessary U-values: 0.24W/m^2.K. Only two out of the four orientations are outer walls, all others, as well as the floor and ceiling are connected to other heated spaces and assumed adiabatic. Combined with the large south facing windows for living and kitchen, this apartment can be assumed a low-energy dwelling.

Figure 1 shows the plan of the apartment including the furniture that is considered a source of VOCs in this study.

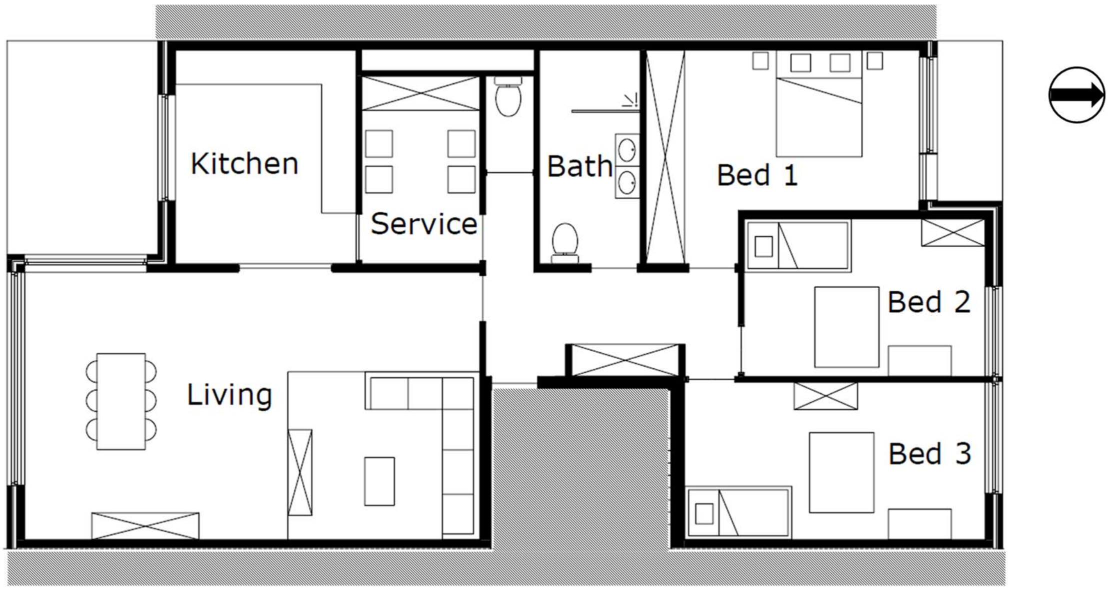

Figure 1 - Floorplan of the modelled apartment including the furniture that is considered a source of VOCs (Ghijsels, 2022)

Table 1 Room floor areas and nominal airflow rates according to NBN D50-001 (BIN, 1991)

	Floor Area	Nominal Airflow
		Supply
Livingroom	42.5 m^2	108.32 m^3/h
Bedroom 1	17.0 m^2	43.92 m^3/h
Bedroom 2	13.2 m^2	35.26 m^3/h
Bedroom 3	16.4 m^2	38.88 m^3/h
		Extraction
Kitchen	13.5 m^2	60 m^3/h
Bathroom	7.5 m^2	60 m^3/h
Toilet	2 m^2	30 m^3/h
Service room	7.7 m^2	60 m^3/h
Hallway	10.8 m^2	16 m^3/h

4.3 Pollutants

Ghijsels et al. (Ghijsels et al., 2022) defined a shortlist of pollutants of concern for Belgian dwellings based on two criteria: 1) is the pollutant present in the Belgian dwellings according to the measurement campaign of Stranger et al. (Stranger et al., 2012), 2) and is the measured concentration surpassing or close to health guidelines found in literature. Based on these criteria the following list of VOCs of concern was defined:

- Benzene
- Formaldehyde
- Naphthalene
- Limonene
- Toluene
- Nitrogen dioxide (NO_2)
- Ozone (O_3)

In the same study, sources and/or source schedules were defined for these sources. Ghijsels et al. also pointed to PM2.5 as additional pollutant of concern, but this is not part of the scope of this research.

4.4 Smart ventilation system

The smart ventilation system under investigation is based on the nominal Belgian, balanced ventilation system with heat recovery (System D) with the nominal ventilation rates and the ventilation system design according to the Belgian standard for residential ventilation NBN D50 (Belgisch Instituut voor Normalisatie and BIN, 1991). The heat recovery is modelled with a constant efficiency of 85%.

The ventilation flowrates of the smart ventilation system are varied according to the set of rules in Table 2. The exhaust airflow rates are adjusted according to the either RH, presence or CO_2 sensors. The total supply airflow rate is adjusted to always keep the total apartment supply airflow rate equal to the total apartment exhaust airflow rate, ensuring a balanced system. Nominal airflow rates are considered 100%.

Table 2 Description of the smart ventilation control algorithm

	Control parameter	**Ventilation rate**
Bathroom & Service room	RH < 30%	15%
	30% < RH < 65%	30%
	65% < RH < 95%	60%
	95% < RH	100%
Bathroom	+Δ2% RH in less than 5min (1timestep)	30min at 100%
Toilet	Presence	100%
	No presence < 15min after presence	100%
	No presence > 15min after presence	15%
Kitchen	Δ450ppm < CO_2	15%
	Δ450ppm < CO_2 < Δ550ppm	Linear
	Δ550ppm < CO_2	100%
Livingroom & Bedrooms	Total supply airflow = Total exhaust airflow Flowrates of each supply changed proportionally	15%-100%

4.5 Occupant schedules

For the typical Belgian apartment (4.2) with a set of pollutants (4.3) and a certain smart ventilation system (4.4). Ten different simulations are done, each with a different household size. The occupants are introduced into the simulation environment as detailed (5-minute interval), weekly repeating schedules. Based on their activity level, there CO_2 and humidity production by breathing increases or decreases. Additionally, activities that produce humidity and/or VOCs (e.g., taking a shower, cooking) are considered. The schedules are based on the work by (Heijmans et al., 2007) and are adapted by Ghijsels (Ghijsels, 2022) to include VOC emissions of the pollutants of concern.

Table 3 Households considered in the simulation study

Occupants	**Household**									
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
Working Adult	**X**	**X**	**X**		**X**	**X**		**X**	**X**	**X**
Stay-at-home Adult	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Child going to school 1			**X**	**X**	**X**	**X**	**X**		**X**	
Child going to school 2		**X**			**X**	**X**	**X**	**X**	**X**	**X**
Child not going to school (Baby) 1			**X**		**X**		**X**			
Child not going to school (Baby) 2					**X**	**X**				
Household size	**2**	**3**	**4**	**2**	**6**	**5**	**4**	**3**	**4**	**3**

Table 3 shows the different types of occupants and how they are combined into households, of different sizes. The households are chosen to always have the stay-at-home adult as one of the occupants. This occupant is the topic of later analysis, as it allows the quantification of the change in exposure due to other people also present in the house.

5 PERFORMANCE INDICATORS

To quantify the IAQ performance with regards to health, the Disability Adjusted Life Years (DALYs) attributed to exposure to the different contaminants (4.3) of the stay-at-home adult is calculated using the same equation as in De Jonge et al. (De Jonge et al., 2022) which is based on the ID and IND method described in the paper by Logue et al (Logue et al., 2012). The results for the stay-at-home adult are extrapolated to 100.000 people as is commonly done for DALYs.

Table 4 lists the input values used in the calculation of the DALYs. For the ID method, these values are adopted from Huijbregts (Huijbregts et al., 2005) and represent the mean value. For the IND method, the 5% confidence interval values are used from Logue et al., table 2 (Logue et al., 2012).

Table 4 Values used for the DALY calculation

ID method	**∂Daly/∂Intake Carcinogenic (yr. kg^{-1})**	**∂Daly/∂Intake Noncarcinogenic inhalation (yr. kg^{-1})**
Benzene	5.8e-3	3.1e-3
Formaldehyde	7.6e-1	-
Naphthalene	1.1e-2	6.1e-2
Limonene	3.9e-3	-
Toluene	2.2e-4	4.7e-3

IND method	**y_0**	**β**	**Daly/Incidence**
Nitrogen dioxide (NO2)	0.0095	1e-06	0.0004
	0.0034	0.001	0.0004
	0.8	0.002	0.0004
Ozone (O3)	0.00018	0.003	0.0004
	0.00021	0.003	0.0004
	0.00058	0.002	0.0004
	0.00024	0.002	0.0004
	0.00077	0.001	0.0004

The energy use indicator of the ventilation system is the sum of two energy uses, the total heating energy use of the building and the total electrical fan energy use. The heating system is a room-based idealized heating system which provides the nominal heating power to the room only when someone is present and when the room temperature drops below the temperature setpoint Tset-1°C, it stops heating when the room temperature reaches Tset+1°C. The temperature set-points of the rooms are lowered during the night-time. This approach will quantify the total heating energy use instead of only looking at the ventilation heat losses allowing for a better estimate of the heat losses as it also considers the dynamic effects of passive heat gains (e.g., solar heat gains, heat dissipation by the occupants). Heat dissipation of appliances and other electrical devices are not included in the model.

6 RESULTS

As an example, the result for case A for 1 year are shown in Figure 2.

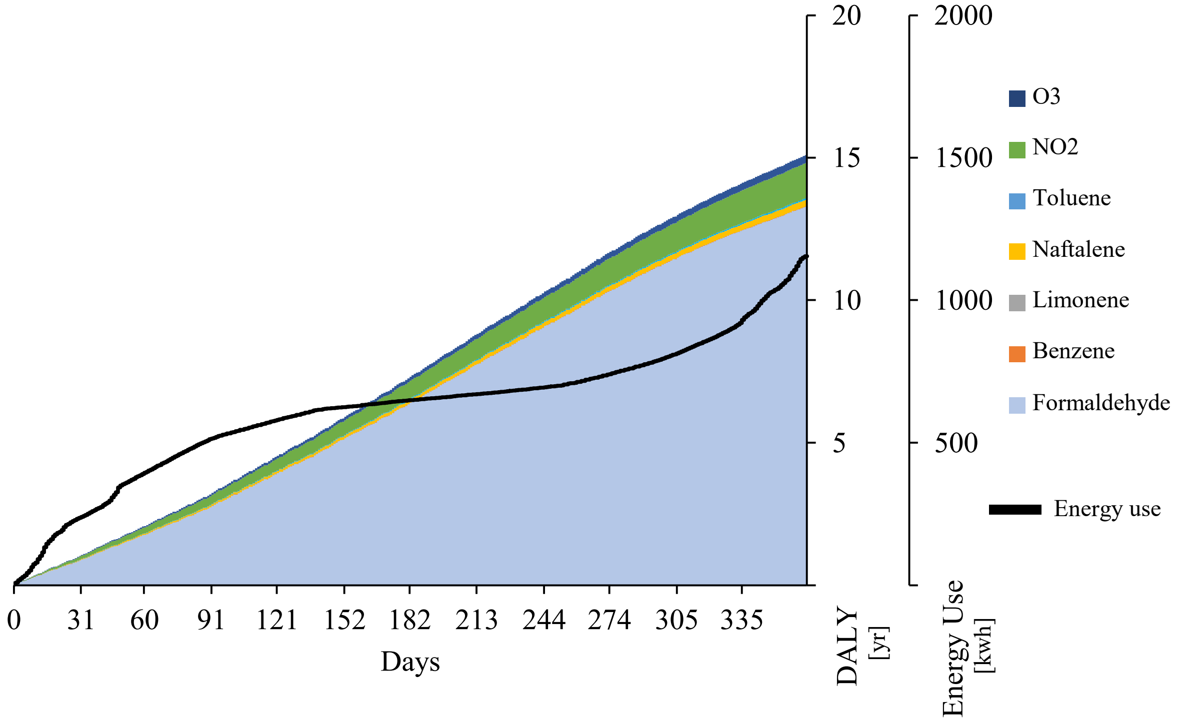

Figure 2 – DALYs of the stay-at-home adult and the energy use for case A

It shows the cumulative energy use throughout the year (second axis) and a stacked area chart of the DALYs accumulated during the simulated period for the different VOCs considered in this study (first axis). The point where the total amount of DALYs touches the right axis is the total accumulated DALYs for the stay-at-home adult (15.09 DALY). The point where the cumulative energy use touches the right axis is the energy use indicator of that case (1154 kWh).

Figure 3 summarizes the results for case A-J, it shows the DALY results of the stay-at-home adult for each of the household variations as well as the values for the energy use indicator. The horizontal subdivision shows the impact of the different pollutants on the total DALY count. Of the considered VOCs, formaldehyde shows to have the largest impact of total DALYs with a minimum share of 86.36% for case I.

There is no correlation between the DALYs of the stay-at-home adult and the household size (correlation=-0.15), this indicates that the actual occupancy pattern of the other occupants is a more deciding factor with regards to the total exposure to VOCs then solely the number of occupants in the household. The family type, size and schedule affect the exposure of an individual in that household. For the ten cases, the average is 15.84 DALY with a standard deviation of 0.8 or a relative standard deviation of 5%. To compare the absolute value of DALYs to other causes then exposure to contaminants, one needs to consider the uncertainty in the input values to calculate the DALYs and source emissions rates. However, for the purpose of comparing different scenarios as done in figure 3, the uncertainty in the input would be of equal size and origin scaling the results proportionally. The minimum DALY count of 14.75yr is noted for case I, and the maximum of 17.72yr if noted for case J. The additional CO_2 emissions by the additional child going to school in case I compared to case J triggers the smart ventilation system quicker, increasing the ventilation flow rate, which in turn results in lower formaldehyde exposure and a lower DALY count.

With regards to the energy use, large variation in the total energy use can be noted because of the differences in occupancy. For the ten cases, the average is 987kWh with a standard deviation of 152kWh or a relative standard deviation of 15%. The average energy use is A minimum energy use of 731kwh is noted for case E and a maximum of 1319kwh is noted for case D.

Interestingly, the highest energy use is obtained for the case with only two occupants and the lowest for six occupants. This is the result of the high energy performance (4.2, 4.4) of the building. As the heat losses of the building are minimal, the impact of the heat dissipation of the occupants becomes apparent in the resulting energy use as it counters part of the needed heating energy. Although one would expect higher ventilation heat losses due to a higher occupancy to lead to higher energy use on a yearly basis. For this building and smart ventilation (including the heat recovery), the overall energy use is lower for the higher occupancy households (correlation=-0.90). This is not necessarily the case for other combinations of buildings, smart ventilation systems and climate conditions (e.g., for hot climate condition where cooling dominates the needed energy use).

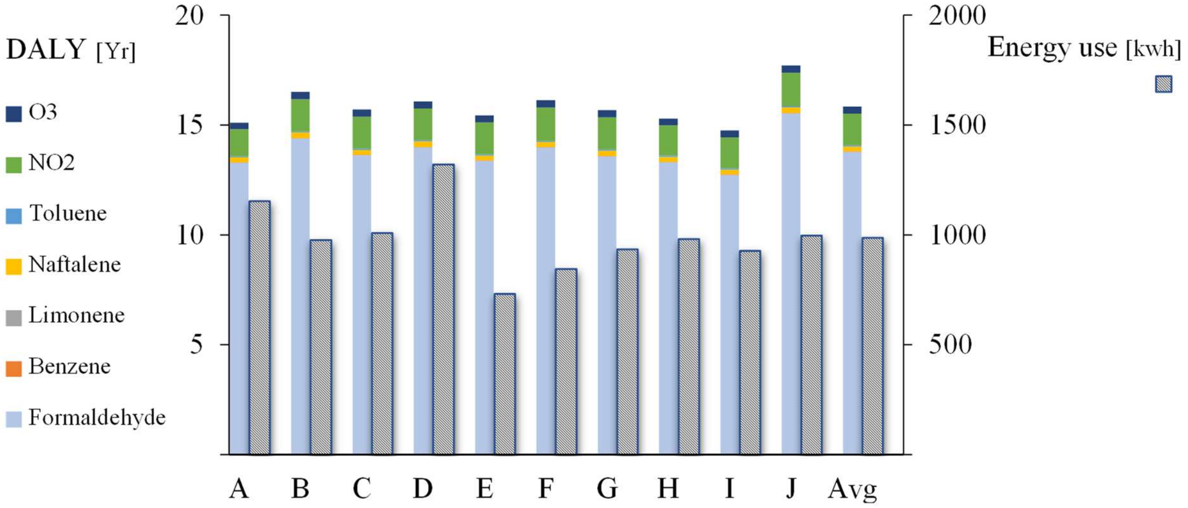

Figure 3 - Overview of the total DALYs for the stay-at-home adult of each case, including a horizontal subdivision of the attributed DALYs due to each pollutant (left axis) and the associated energy use of the same case (right axis)

7 CONCLUSIONS

When designing a simulation-based assessment framework for residential ventilation, the occupant's behavior will always be an unknown factor to consider. Not only does one family evolve over time but also inhabitants of a building can change.

As expected, the results indicate that when only the household size and composition is varied. The presence and behavior of other occupants will influence the total DALYs of an individual in the household as well as the energy use of the household. For the VOCs considered in this study and for the ten cases a difference in 5% relative standard deviation was found but no correlation with the number of occupants. For the energy use, a relative standard deviation of 15% was found and a negative correlation with increasing family size. The VOC emission rates were kept constant in this study, but one can expect to find large variations in source emissions rates in reality.

The result indicates that in designing a simulations-based assessment framework, it will not be possible to assume just one household type and size. This conclusion should be supported by a stochastic simulation study which does considers and quantifies the uncertainty of the input parameters of the DALY calculation, source emission rates and a better representation of the possible household sizes and types.

A possible approach for a simulations-based assessment framework would be to develop a stochastic set of occupants with varying household sizes and rate the system based on the set of results rather than just one household. Such an approach is in line with the current comfort assessment for the Belgium that makes use of a Monte-Carlo approach (Caillou et al., 2014).

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9 REFERENCES

Belgisch Instituut voor Normalisatie, BIN (1991). Ventilatievoorzieningen in woongebouwen (NBN D50-001).

Caillou, S., Heijmans, N., Laverge, J., Janssens, A. (2014). Méthode de calcul PER: Facteurs de réduction pour la ventilation à la demande 141.

De Jonge, K., Ghijsels, J., Cony, L., Laverge, J. (2022). Quantification of harm due to formaldehyde exposure in multi-zone simulation, Presented at the Indoor Air 2022, Kuopio, Finland, p. 2.

De Jonge, K., Jorissen, F., Helsen, L., Laverge, J. (2021). Wind-Driven Air Flow Modelling in Modelica: Verification and Implementation in the IDEAS Library, Presented at the Building Simulations conference 2020.

De Jonge, K., Laverge, J. (2021). Modeling dynamic behavior of volatile organic compounds in a zero energy building. International Journal of Ventilation 20, 193–203. https://doi.org/10.1080/14733315.2020.1777012

Durier, F., Carrié, R., Sherman, M.H. (2018). What is smart ventilation? Ventilation Information Paper.

Ghijsels, J. (2022). Beoordelingsmethode voor een gezonde binnenluchtkwaliteit bij residentiële vraaggestuurde ventilatiesystemen. Ghent University, Ghent, Belgium.

Ghijsels, J., De Jonge, K., Laverge, J. (2022). Health and energy assessment of a demand controlled mechanical extraction ventilation system, Presented at the Clima 2022, REHVA 14th HVAC World Congress, Rotterdam, The Netherlands.

Guyot, G., Walker, I.S., Sherman, M.H. (2019). Performance based approaches in standards and regulations for smart ventilation in residential buildings: a summary review. International Journal of Ventilation 18, 96–112. https://doi.org/10.1080/14733315.2018.1435025

Heijmans, N., Van Den Bossche, N., Janssens, A. (2007). Berekeningsmethode gelijkwaardigheid voor innovatieve ventilatiesystemen in het kader van de EPB-regelgeving. WTCB, Ghent University.

Huijbregts, M.A.J., Rombouts, L.J.A., Ragas, A.M.J., Meent, D. van de (2005). Human-toxicological effect and damage factors of carcinogenic and noncarcinogenic chemicals for life cycle impact assessment. Integrated Environmental Assessment and Management 1, 181–244. https://doi.org/10.1897/2004-007R.1

IEA EBC (2021). IEA EBC Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings. URL https://annex86.iea-ebc.org/ (accessed 6 April 2022).

Jorissen, F., Reynders, G., Baetens, R., Picard, D., Saelens, D., Helsen, L. (2018). Implementation and verification of the IDEAS building energy simulation library. Journal of Building Performance Simulation 11, 669–688. https://doi.org/10.1080/19401493.2018.1428361

Laverge, J., Janssens, A. (2013). Optimization of design flow rates and component sizing for residential ventilation. BUILDING AND ENVIRONMENT 65, 81–89. https://doi.org/10.1016/j.buildenv.2013.03.019

Laverge, J., Van Den Bossche, N., Heijmans, N., Janssens, A. (2011). Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. Building and Environment 46, 1497–1503. https://doi.org/10.1016/j.buildenv.2011.01.023

Logue, J.M., Price, P.N., Sherman, M.H., Singer, B.C. (2012). A Method to Estimate the Chronic Health Impact of Air Pollutants in U.S. Residences. Environ Health Perspect 120, 216–222. https://doi.org/10.1289/ehp.1104035

Sherman, M.H., Walker, I.S., Logue, J.M. (2012). Equivalence in ventilation and indoor air quality. HVAC&R Research 18, 760–773. https://doi.org/10.1080/10789669.2012.667038

Stranger, M., Verbeke, S., Täubel, M., Laverge, J., Wuyts, D., Geyskens, F., Verbeke, L., Poelmans, D., Boonen, F., Lauwers, J., Brouwere, K.D., Hyvärinen, A., Janssens, A., Ingelaere, B. (2012). Clean Air, Low Energy – Exploratory research on the quality of the indoor environment in energy efficient buildings: the influence of outdoor environment and ventilation 346.