ANNEX **86**

EBC

Energy in Building and Communities Programme

ST4 Report - Ensuring performance of smart ventilation

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international cooperation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.).

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely ‘Objectives’ and ‘Means’. These two groups are distinguished for a better understanding of the different themes.

Objectives: The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of ‘low tech’, robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible; the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means: The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from ‘living labs’ to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the ‘objectives’ themes are final goals or solutions (or part of) for an energy efficient built environment, while the ‘means’ themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)

Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
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Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (*)
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale (*)
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements (*)
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Annex 73: Towards Net Zero Energy Resilient Public Communities (*)
Annex 74: Competition and Living Lab Platform (*)
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables (*)
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Annex 93: Energy Resilience of the Buildings in Remote Cold Regions
Annex 94: Validation and Verification of In-situ Building Energy Performance Measurement Techniques
Annex 95: Human-centric Building Design and Operation for a Changing Climate
Annex 96: Grid Integrated Control of Buildings
Annex 97: Sustainable Cooling in Cities
Annex 98: Flexibilization and Optimization of Heat Pump Systems in Existing Buildings through Secondary-Side Digitalization
Annex 99: Air Cleaning for Sustainable and Resilient Buildings

Working Group – Energy Efficiency in Educational Buildings (*)
Working Group – Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group – Annex 36 Extension: The Energy Concept Adviser (*)
Working Group – HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group – Cities and Communities (*)
Working Group – Building Energy Codes

Table of content

1. Introduction

Smart ventilation, as defined by the Air Infiltration and Ventilation Centre (AIVC) (F. Durier et al., 2018), is a dynamic process that continually adjusts the ventilation system in time and, optionally, by location to provide the desired indoor air quality (IAQ) benefits while minimizing energy consumption, utility bills, and other non-IAQ costs such as thermal discomfort or noise. Traditional ventilation systems often operate at a constant air flow rate, leading to unnecessary energy consumption and suboptimal air quality (Walker et al., 2014). This definition underscores the importance of responsive and adaptive ventilation systems that can optimize their own performance based on various factors including air quality, occupancy, and outdoor conditions or electricity grid needs. Smart ventilation includes a wide range of systems currently available in literature and on the market depending on the type of sensing parameters (CO_2, humidity, occupancy, etc.), the type of sensing combinations, the type of installation (centralized/decentralized) and the types of control algorithms. In residential buildings, smart ventilation systems use advanced controls and sensors to adjust ventilation rates based on real-time data, thereby improving both energy efficiency and IAQ (Guyot et al., 2017). Studies have shown that smart ventilation can reduce energy use attributable to ventilation by up to 60% without compromising, and sometimes even improving, IAQ (Guyot et al., 2018a). Countries such as Belgium, France, and the Netherlands have already integrated smart ventilation strategies into their regulatory frameworks, promoting their adoption and market availability (Guyot et al., 2018b). This simple, robust approach has been used in the non-residential sector for several decades. However, recent technological advances, which have brought down the price of sensors, controllers and electronically commutated fans, are paving the way for greater use of smart ventilation in the residential sector.

The quality of ventilation systems is an issue of interest as the literature shows that ventilation is often badly designed, installed or used, achieving lower performances than expected (Boerstra, 2012; Caillou et al., 2012; Jobert and Guyot, 2013; Guyot et al., 2017). It is important to identify the critical issues specific to smart ventilation systems. Examples include sensor quality testing, actuator durability, and sensitivity to boundary conditions, as well as the durability of building performance. With smart ventilation, we generally allow lower airflows at certain times with decreased demands regarding IAQ (no occupancy, low emissions, etc.), but we need to ensure, even more than with other ventilation systems, that the planned airflows are always correctly delivered, throughout the building's lifetime.

Subtask ST4- *Ensuring performance of smart ventilation* focuses on the practical conditions and necessary scientific support that ensure efficient (energy efficiency and IAQ), reliable, cost-effective and robust design and implementation of intelligent ventilation, updating the data published in 2017-2018 cited above.

Subtask ST4 was divided into four activities:

1. **A4.1 Rating existing smart ventilation strategies**. This part was the essential component of ST4, as it included substantial work both on the scientific and regulatory state of the art, and on the definition and realization of a common exercise.
2. **A4.2 Quality control of implementation**. This part used some results from the common exercise, as well as data from in situ campaigns documenting the real performance (and faults) of smart ventilation strategies, and data from certain countries with specifications for sensor accuracy when integrated into intelligent ventilation systems.
3. **A4.3 Durability of smart ventilation systems and components**. This part focused on review of studies dealing with durability of the sensors and the components presented in literature including laboratory tests and in situ measurement campaigns.
4. **A4.4 Occupant interaction**. This activity collected data about the impact of interactions between the occupant and the system on the (perceived) performance and acceptability.

This ST4 report combines three Annex 86 deliverables:

D4.1. Review report on IAQ and energy performance of smart ventilation and presentation of a performance-based approach for smart ventilation - divided into two sub-reports:

D4.1a. A literature review on smart ventilation performance in residential buildings.
D4.1b. State-of-the-art on the use of performance-based approaches for residential ventilation in 2024.

D4.2. Investigation report: IAQ and energy performances, durability and occupant interaction of smart ventilation strategies - divided into two sub-reports:

D4.2a Rating existing smart ventilation strategies – testing the usability of performance indicators for smart ventilation strategies – this report is further constituting a part of Annex 86 deliverable D4.
D4.2b Accuracy, durability and occupant interaction in smart ventilation strategies (Short investigation report)

D4.3 Inspection protocols for stand-alone smart ventilation systems in residential buildings (Short investigation report).

2. D4.1. Review report on IAQ and energy performance of smart ventilation and presentation of a performance-based approach for smart ventilation

2.1. D4.1a Smart ventilation in residential buildings: a literature review

Authors: Yu Wang, Daniela Mortari, Manfred Plagmann, Nathan Mendes, Gaëlle Guyot

2.1.1. Introduction

This document reviews smart ventilation strategies in residential buildings, focusing on IAQ and energy efficiency. The review covers developments in smart ventilation from 2017 to 2023, highlighting the benefits of these systems in residential buildings. The key questions addressed are:

- What strategies have been investigated for smart ventilation systems in residential buildings?
- How effective are these smart ventilation strategies in improving IAQ, thermal comfort, and minimizing energy consumption?

The review is conducted within the scope of the International Energy Agency Energy in Buildings and Community (IEA EBC), Annex 86, focusing on subtask 4, which emphasizes the necessity of reviewing existing smart ventilation strategies. The aim is to analyse these strategies' effectiveness in improving indoor environmental quality without compromising occupants' health or minimizing energy consumption.

2.1.2. Methodology

A systematic review was performed according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Statement) recommendations (Liberati et al., 2009). The search process aimed to answer the following questions: How much is the indoor environmental quality improved, and how much energy savings are achieved with the use of smart ventilation in residential buildings compared to a reference system? The electronic databases used to perform the search were the Web of Science, Scopus, and AIVC collections. The search was conducted in August 2023, covering articles published from January 2017 to August 2023, using search terms that included combinations related to ventilation, indoor air quality, and energy savings or energy consumption.

The initial search retrieved 803 articles. After removing duplicates and postprocessing, 73 articles were reviewed in full text. Ultimately, 44 articles were considered relevant and included in the final review. A bibliometric analysis was then conducted to assess the development and trends in smart ventilation research. This analysis examined the evolution of publications by geographic location, year, and keyword correlation.

2.1.3. Preliminary analysis of literature

The reviewed studies were categorized based on their methodology, with 78% being simulation studies, 11% experimental setup studies, and 11% in-situ studies. The studies focused on various parameters for ventilation control, including occupancy, relative humidity (RH), carbon dioxide (CO_2), particulate matter (PM2.5), and outdoor conditions. Most studies were conducted on single-family detached houses and apartment-units representative for the residential building stock.

Different calculation methods and parameters were used to form the ventilation performance indicators and assess smart ventilation performance. Most of these performance indicators fell into categories such as indoor air quality, comfort, energy savings, and ventilation change. Specific metrics like CO_2 levels, temperature, Relative Humidity (RH), ventilation flow rates, and Disability-Adjusted Life Years (DALYs) were used either to form these indicators or as indicators themselves. The theory of equivalent ventilation has been introduced to assess the IAQ resulting from different ventilation systems. This equivalent ventilation theory is a key aspect of all smart ventilation studies, conducted at Lawrence Berkeley National Laboratory, USA included in the present review.

The simulation studies varied from one day to one year. The ventilation systems studied ranged in complexity from exhaust-only to decentralized and centralized balanced mechanical ventilation with heat recovery. Different occupancy patterns and pollutant generation scenarios were observed in simulation studies.

These reviewed studies were published in various journals, with "Energy and Buildings" and the "Journal of Building Engineering" being the most frequent. Sixty-one percent of the reviewed papers were conducted in Belgium, France, and the United States. When analysing the co-occurrence of keywords in these reviewed studies, the evolving trends in smart ventilation publications reveal a shift. Publications from 2017 to 2021 focused on themes such as CO_2 and humidity controlled ventilation, energy savings, and building-generated pollution, while publications after 2022 emphasize themes such as health, pollutant- controlled ventilation such as volatile organic compounds (VOCs) and $PM_{2.5}$, performance-based assessments, decentralized ventilation, and the use of data-driven methods and/or the Internet of Things (IoT) to develop ventilation strategies and improve the ventilation performance.

2.1.3.1. Occupant behaviour, and pollutant generation scenarios

The occupant's behaviour has a significant impact on ventilation performance, as it affects both the magnitude and timing of pollutant emissions, whether bio-effluents or pollutants from indoor activities such as cooking, showering, and cleaning, among others. Understanding occupant behaviour enables the prediction of occupant exposure to pollutants. Many efforts have been devoted to addressing occupant behaviour in residential buildings, including monitoring the occupancy, developing occupant behaviour models, and applying those models in building performance simulation (Balvedi et al., 2018; Franceschini and Neves, 2022). The occupancy pattern data used by authors were often defined according to standards (Carbonare et al., 2020, 2019) or derived from time-use survey data (Klaas De Jonge and Laverge, 2022; Baptiste Poirier et al., 2021a). When analysing the occupancy patterns used in these reviewed studies, we observed significant variations related to the number of occupants (ranging from 1 to 4), the time spent at home, their activities at home, and the changing schedules for weekdays and weekends.

The pollutant generation scenarios used in simulation studies, including human bioeffluents and their main human activities, are summarized in

Table 2-1. In this review, humidity is considered as a pollutant. In

Table 2-1, the emission rate column shows the values or ranges used in different studies. As can be observed, the variations are not limited to values or ranges. The studies differ from each other also in units used. This variation in pollutant generation scenarios results in distinct outcomes in ventilation system performance, making it impractical to compare ventilation strategies.

2.1.3.2. Ventilation system performance indicators

The most common indicators to evaluate ventilation performance can be categorized into five groups: IAQ, energy savings, thermal comfort, ventilation and health impacts, as presented in Figure 2-1. Additionally, other indicators, such as building material condensation, mould development, annual cost analysis and financial payback time of a ventilation system, are also used to assess ventilation performance.

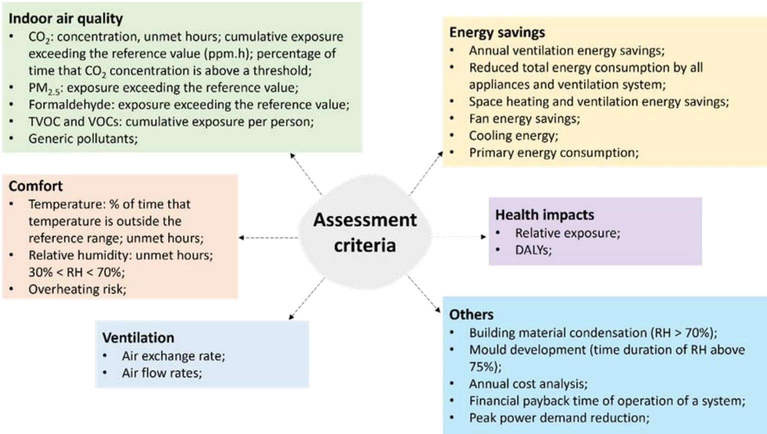

Figure 2-1 Performance indicator summarized from the reviewed simulation studies

Table 2-1 Pollutant and contaminant emission generation scenarios used in simulation studies

Pollutants and contaminants		**Emission rate**	**Reference**
CO_2 (bio-effluent)	Adult awake	12 L.h^{-1}, 14.4 L.h^{-1}, 16 L.h^{-1}, 18 L.h^{-1}, 19 L.h^{-1}, 10 mg.s^{-1}, 8.5 mg.s^{-1}, 0.25 L.min^{-1} varying from1.86 e-4 m^3.s^{-1} to 9.69e-4 m^3.s^{-1} depending on the activity level, varying from 15 dm^3.h^{-1} to 35 dm^3.h^{-1} depending on the activity level	(Van Gaever et al., 2017) (Pecceu et al., 2018) (Baptiste Poirier et al., 2021a) (Walker et al., 2021) (Ghijsels et al., 2022) (De Jonge et al., 2022) (Carbonare et al., 2020) (Belmans et al., 2019) (Filis et al., 2023) (Kim et al., 2022) (Müller and Dębowski, 2020) (Rojas, 2022) (Shin et al., 2018)
	Adult asleep	10 L.h^{-1}, 15 L.h^{-1}, 6.5 mg.s^{-1}, 1.65e-4 m^3.s^{-1}, 10 dm^3.h^{-1}, 0.20 L.min^{-1}	
	Child awake	6.5 mg.s^{-1},12 L.h^{-1}, 12.6 L.h^{-1}, 9 L.h^{-1}	
	Child asleep	4 mg.s^{-1}, 8 L.h^{-1}	
H_2O (bio-effluent)	Adult awake	55 g.h^{-1}, 15 mg.s^{-1}, 45 g.h^{-1}, 40 – 45 g.h^{-1}	
	Adult asleep	40 g.h^{-1}, 9 mg.s^{-1}	
	Child awake	10 mg.s^{-1}, 41.3 g.h^{-1}, 35 g.h^{-1}	
	Child asleep	6 mg.s^{-1}	
H_2O (human activities)	Cooking	1. morning and noon 0.5 L.s^{-1} (10min); evening 0.6 L.s^{-1} (10min) + 1 L.s^{-1} (10 min) + 1.5 L.s^{-1} (10min), 2. Breakfast 1512 g.h^{-1}, lunch 2268 g.h^{-1}, dinner 2844 g.h^{-1}, 3. 140 mg.s^{-1}, 4. 500 g.h^{-1}, 5. Breakfast 50 g/person, lunch 150 g/person, dinner 300 g/person, 6. $1.33 \cdot 10^{-4}$ kg.s^{-1}	(Van Gaever et al., 2017) (Baptiste Poirier et al., 2021a) (Ghijsels et al., 2022) (De Jonge et al., 2022) (Carbonare et al., 2020) (Belmans et al., 2019) (Filis et al., 2023) (Johnston et al., 2020) (Kim et al., 2022)
	Dishwashing	130 mg.s^{-1}, 200 g.h^{-1}	
	Shower	0.5 L.s^{-1} per shower (10min), 1440 g.h^{-1}, 330 mg.s^{-1}, 500 g.h^{-1}, 300 g/shower/person, $7.22 \cdot 10^{-4}$ kg.s^{-1}	
	Laundry room	0.06 L.s^{-1} (12h), 252 g.h^{-1}, 250 g.h^{-1}, Laundry + dry 136.8g/h, 200 g/laundry, 1000 g/drying	
H_2O plants		3 g.h^{-1}	
VOCs Proportional to the floor area		From 4.5 µg.h^{-1}m^{-2} to 23.6 µg.h^{-1}.m^{-2}	
$PM_{2.5}$ from cooking		1). 0.0208 mg.s^{-1}, 2). From 1.26 mg.min^{-1} to 2.55 mg.min^{-1}, 3). Per activity: 70 µg.min^{-1} – vacuuming 10 µg.min^{-1} - oven 283 µg.min^{-1} – grilled, 1483 µg.min^{-1}- fried	
Generic contaminant		18 µg/m^2/h	(Walker et al., 2021)
Formaldehyde		3.06 µg.h^{-1}.m^{-2} for furniture (wood), 4.50 µg.h^{-1}.m^{-2} for doors (wood), 3.00 µg.h^{-1}.m^{-2} for cushion, 4.27 µg.h^{-1}.m^{-2} for carpet	(Klaas De Jonge and Laverge, 2022)
Benzene		1.40 µg.h^{-1}.m^{-2} for furniture (wood), 2.00 µg.h^{-1}.m^{-2} for cushion, 0.21 µg.h^{-1}.m^{-2} for carpet	

Naphthalene	5.68 μg.h^{-1}.m^{-2} for furniture (wood) and 0.47 μg.h^{-1}.m^{-2} for carpet	
Toluene	11.00 μg.h^{-1}.m^{-2} for Cushions, 0.20 μg.h^{-1}.m^{-2} for carpet, 0.5 μg.h^{-1}.m^{-2} for gypsum	
Limonene	1912 μg.h^{-1}.m^{-2} for cleaning, 24.8 μg.h^{-1} for dishes1200 μg.h^{-1} for shower (soap/shampoo), 2000 μg/event for deodorant	
Naphthalene	3.76 μg.h^{-1} Shower (soap/shampoo)	

2.1.4. Ventilation control strategies and performance

The performance of the ventilation system is discussed based on the methods used in the studies, such as simulation, experimental, and in-situ studies

2.1.4.1. Simulation studies

In simulation studies, the performance is discussed in categories based on the control parameters used to develop the ventilation strategy.

Occupancy based control strategies

In this review, three studies have explored occupancy-based ventilation control strategies, and all three studies applied equivalent ventilation theory and the relative exposure (RE) concept. Clark et al. (2019) assessed the IAQ and energy savings of three occupancy-based ventilation strategies for residential buildings located in four California climate zones. Results showed that when ventilation is completely turned off during the unoccupied period, the occupants experience a peak in pollutant exposure upon re-entering the environment due to increased accumulation of pollutants during the off period. Additionally, the energy consumption required for ventilation to recover air quality makes this strategy unviable. The addition of a pre-occupancy flush period by turning on the ventilation 1 hour or 2 hours prior to the occupants returning home proved to be the best strategy in terms of energy savings and exposure to peak pollutants, which can result in up to 60% energy savings for the 2-story buildings with an ACH50 of 5. Two additional studies, (Walker and Less, 2018) and (Walker et al., 2021), investigating occupancy-based strategies, both conducted under American climate conditions, found that energy savings of up to 30% were achieved. These savings depended on factors such as the occupancy schedule, climate, ventilation type, emission generation, and other assumptions.

Outdoor conditions-based strategies

In this review, six studies focused on this aspect. Less et al. (2019) conducted a study on two single-family dwellings in four California climate zones to evaluate six outdoor temperature-based strategies and found that these strategies achieved up to 33% ventilation energy savings while maintaining the equivalent IAQ compared to the constant ventilation system. Ambient temperature-based controlled ventilation is less effective in regions with low diurnal or seasonal temperature swings. More energy savings are obtained from buildings located in regions with higher heating demands, and from buildings with less-airtight envelopes, as observed across simulation cases with 1, 3, and 5 ACH_{50}. Young et al. (2020) investigated the potential of an outdoor temperature-based strategy to temporarily curtail building ventilation systems and reduce peak power demand and found that it achieved 0-30% peak energy savings while maintaining the daily and annual RE of 1.0.

In addition to the outdoor temperature-based strategy, (Parker et al., 2018) evaluated a smart ventilation system controlled by outdoor temperature and moisture, and this strategy was validated by laboratory experiments conducted in Florida, USA, to demonstrate the potential cooling energy savings. De Jonge et al. (2022) conducted a study in a typical Belgian apartment unit, assuming that outdoor air quality is not always better than IAQ; consequently, it may sometimes be unsuitable for diluting indoor pollutants. Compared with the ventilation strategy only based on IAQ, the control algorithm considering both IAQ and outdoor air quality achieved 44% of the energy savings and reduced about 10% of the total DALYs count. However, the trade-off was exposure to high levels of indoor CO2 (De Jonge et al. 2022). Considering outdoor air quality in ventilation design is necessary, especially in regions with pollutants exceeding indoor levels, such as traffic related air pollutants. (Kim et al., 2020) developed a conditional-based ventilation strategy based on both outdoor PM2.5 concentrations and indoor PM2.5 generation rates, resulting in a 70% reduction in power consumption while maintaining IAQ within acceptable thresholds. This strategy includes ventilation filtration to filter ambient PM2.5 before bringing air indoors and recirculate filtration control to dilute indoor PM2.5 when ambient air is unsuitable for ventilation. The outdoor PM2.5 concentrations and indoor PM2.5 generation rates were also used to develop the ventilation strategy in another study (Kim et al., 2022), which applied a data-driven approach to identify the optimal ventilation schedule and achieved 45.5% energy savings compared to on/off controlled ventilation.

Ventilation for cooling

Using ventilation as a strategy for cooling is a well-known concept. Here we examine studies that have examined new approaches to providing ventilation cooling. In this review, five studies discussed this aspect: three on hybrid ventilation for cooling and two on smart ventilation for cooling. A hybrid ventilation system combines or alternates natural and mechanical ventilation to balance IAQ, user comfort, and energy efficiency. Hybrid ventilation is also referred to as mixed-mode ventilation (MMV) in some of the reviewed studies. (Belmans et al., 2019b, 2019a) showed that mixed-mode ventilation performed as well as demand-controlled systems (DCV) systems in winter in terms of energy consumption and IAQ achieved. However, in summer, it can minimize energy consumption to achieve good thermal comfort by reducing mechanical ventilation and increasing free cooling natural ventilation. (Grygierek and Ferdyn-Grygierek, 2022) combined natural with mechanical ventilation, evaluating different ventilation strategies in a Polish semi-detached house and found that the natural ventilation system combined with automatic window opening resulted in the highest number of thermal discomfort (overheating of rooms) hours. (Cakyova et al. 2021) found that applying hybrid ventilation with night ventilation through window openings (turning off the CAV system at night) reduced energy demand by 28% compared to constant mechanical ventilation. (Kim et al., 2017) proposed an integrated comfort control strategy that integrates air conditioning, a humidifier, and a ventilation system by considering the outdoor temperature and RH to ensure indoor thermal comfort and energy savings. The results showed that the integrated comfort control strategy presented a good result in terms of comfort ratio, and reduced energy consumption by 10% to 30%.

Strategies based on indoor conditions: temperature, humidity, CO2, VOCs, formaldehyde (HCHO), PM2.5, and occupancy

This section includes the highest number of studies, with 20 detached single-family houses, apartment buildings, and multiunit buildings, all conducted in European countries and climates. Four studies focused on decentralized ventilation systems, while the remaining 16 investigated centralized ventilation systems.

For decentralized ventilation systems, (Carbonare et al. 2019) proposed two comfort-oriented control strategies based on the façade integrated room-based ventilation unit. On average, 10% energy savings were achieved, compared to the commonly used linear and step control strategies. In another simulation study on façade integrated room-based ventilation units, (Carbonare et al. 2020) evaluated four control strategies, namely linear, steps, comfort-oriented, and fuzzy control utilizing measurements of indoor relative humidity and CO_2 concentration. The fuzzy controlled strategy achieved about 25% energy savings compared to a constant airflow strategy and about 12% energy savings compared to a step-controlled DCV system. (Smith and Kolarik 2019) simulated and assessed a manifold of fans that connects to an air-handling unit to control the supply airflow to each room based on measurements in that room (i.e. zonal control). The results showed that this system was effective in saving energy and maintaining IAQ targets related to CO_2, RH, and temperature, where 74% savings in fan energy consumption compared to a constant air volume system were achieved. CO_2 only exceeded the limit in the bathroom, where it did not have CO_2-based control. (Filis et al., 2023) conducted a study to compare the widely used mechanical extract ventilation (MEV) and the room-based ventilation units (with constant airflow rate) under three French climatic conditions. The study demonstrated that, compared to constant-MEV, energy savings in space heating demand ranged from 61% to 85% for room-based ventilation units, and from 44% to 75% for RH-MEV. However, this study did not account for energy consumption by fans, which was higher for room-based ventilation units compared to exhaust-only systems.

For centralized systems, (Poirier et al. 2021) employed five indicators to demonstrate the IAQ achieved through DCV systems. These indicators include: CO_2 cumulative exposure (thresholds of 1000 *d* ppm.h), humidity from the health perspective (percentage of time spent by an occupant with RH outside of the range 30% to 70%), humidity from a condensation risk perspective (percentage of time with RH above 70%), cumulative formaldehyde exposure (threshold of 9 *d* µg m^{-3}.h), and cumulative $PM_{2.5}$ exposure (threshold of 10 *d* µg m^{-3}.h), where d represents the simulation duration in hours (h). Simulation studies during the heating season in Lyon, France, showed that among the constant-MEV, constant balanced mechanical ventilation, and humidity-based DCV systems, none of them achieved all five proposed IAQ indicators. The $PM_{2.5}$ targets were not reached under any of the ventilation strategies (Baptiste Poirier, Guyot, Woloszyn, et al. 2021; B. Poirier, Guyot, and Woloszyn 2021). Another study conducted by (Poirier et al. 2022) applied the proposed five IAQ indicators to assess the performance of five DCV systems in a newly renovated Danish apartment building and found a similar result: none of the investigated ventilation systems were able to achieve the targeted $PM_{2.5}$ indicator. The MVHR resulted in a better IAQ in terms of CO_2 and formaldehyde exposure. However, none of the DCV and non-DCV systems investigated achieved an acceptable formaldehyde exposure when the emission rates were in the medium and high scenarios. (Evola et al., 2017) evaluated the energy (both total energy and primary energy) and financial convenience of RH-controlled MEV and RH-controlled MVHR in three Italian cities: Milan, Rome, and Catania. They found that in colder climates, the MEV system provides lower energy savings compared to MVHR systems; however, generally, MEV systems have a shorter payback time compared to MVHR systems.

Han et al. (2022) applied statistical methods (clustering and genetic algorithm) to build numerical models based on real-time monitored data from an experimental house to identify indoor CO_2 patterns and estimate fan energy consumption. The model was subsequently used to control an existing smart ventilation system. This proposed ventilation strategy achieved a 7.8% energy savings for CO_2-based DCV. The control algorithm, the location of sensors, and the number of sensors impact the performance of the ventilation systems. Rojas (2022) found that balanced MVHR, controlled by one single CO_2 sensor located in the common exhaust within the MVHR unit, did not outperform the constant MVHR regarding the IAQ especially when the dwelling is not fully occupied. Faure et al. (2018) demonstrated how the distribution of leakage across the building envelope affects the performance of ventilation systems and highlighted the importance of a multiple sensor-based DCV strategy in mitigating the effects of uneven air leakage distribution to achieve the desired IAQ.

The performance of DCV under the humid continental climate in Poland was explored (Müller and Dębowski, 2020; Sowa and Mijakowski, 2020). Müller and Dębowski (2020) highlighted the importance of considering the operating cost when setting up a ventilation system. They estimated that the annual operating cost, which includes the running costs of the two fans and the energy required to heat the supply air to 20 °C in a Polish single-family house, was found to be twice as high for keeping the maximum CO_2 concentration below 600 ppm compared to maintaining them below 800 ppm. Sowa and Mijakowski (2020) analysed a RH-based DCV system installed in an eight-floor multiunit residential building in Poland. They conducted a whole building simulation, including 23 apartment units for a full heating season. They found that all three ventilation options (passive stack ventilation, RH-controlled ventilation, and RH-controlled ventilation with a roof-mounted exhaust fan) resulted in average airflow rates below the Polish standard. Using RH-controlled ventilation with a roof-mounted exhaust fan, the ventilation rate was higher, and no unwanted backflows occurred. In addition, under this option, the energy needed to heat the ventilation air is 21% lower than passive stack ventilation.

Jones et al. (2017) simulated three DCV strategies for detached houses and flats, which represent a large portion of the United Kingdom housing stock. The three ventilation strategies all use mechanically extracted air controlled either by RH or both CO_2 and RH at the local level. Supply air was either uncontrolled (i.e., makeup air induced by the exhaust) or controlled by local RH. The simulation results revealed that all ventilation systems can achieve similar IAQ compared to continuous exhaust. Among the three evaluated strategies, the one with uncontrolled supply and local CO_2 and RH controlled mechanical extract achieved the highest reduction in both ventilation heat loss and fan electricity consumption. Van Gaever et al. (2017) assessed four ventilation systems in a single-story detached Belgian dwelling and found that the local CO_2-controlled, or combination of CO_2 and water vapor content-controlled ventilation systems with air supply to the living rooms and bedrooms and air exhaust from wet rooms (kitchen, bathroom, toilet, and laundry), was the most effective ventilation strategy in terms of controlling CO_2 and RH exposure and to reduce the airflow rate. Pollet et al. (2017) compared the IAQ and energy loss due to ventilation among three ventilation strategies. The simulation results showed that, compared to conventional MEV, adding extraction to bedrooms or to all habitable rooms improved IAQ in habitable rooms but increased ventilation heat losses. Furthermore, extract volumes from wet rooms should always exceed those from bedrooms for such a ventilation system to prevent reverse airflow.

Formaldehyde as a control variable in a DCV system with heat recovery was assessed in Danish homes with the aim of investigating the impact of building generated pollutants on the energy demand (Johnston et al., 2020). Simulation results showed that having a minimum ACH of 0.22 h^{-1} is necessary to protect the occupants from HCHO harm (maintaining the HCHO below 0.1 $mg.m^{-3}$). A minimum background ventilation rate of 0.3 $l{\cdot}s^{-1}{\cdot}m^{-2}$ and DCV systems using HCHO as a control variable can prevent harmful levels of HCHO in these homes.

The recent novel development in the field of DCV is assessing ventilation performance through the health implications of exposure to different indoor pollutants under different ventilation strategies, expressed as DALYs. (De Jonge and Laverge, 2022) estimated that the total dynamic DALYs during a year due to exposure to five indoor VOCs pollutants (HCHO, Benzene, Limonene, Naphthalene, and Toluene) for a working adult, living in a typical Belgian apartment, were 2.2 years when the household was ventilated by a constant mechanical ventilation system as required by Belgian ventilation regulation and 8.6 years when the dwelling was ventilated by the RH, CO_2 and presence based DCV system. The energy consumed, including both the space heating and fan electricity consumption, was 2307 kWh for the constant mechanical ventilation and 1008 kWh for the DCV. In other words, a 1300 kWh energy savings is a trade-off with a 6.3-year loss in DALYs. Two additional simulation studies (De Jonge et al., 2023; Klaas De Jonge et al., 2022) conducted by the same team of authors, based on the same Belgian apartment building, discovered a similar result: while DCV results in significant energy savings, it also causes an increase in the sum of DALYs. The extent to which pollutant most impacts the total DALYs depends on which pollutants are considered as pollutants of concern in the model.

2.1.4.2. Experimental studies

Five studies were identified that directly measured contaminants. (Rahnama et al., 2023) designed a ventilation system that incorporated the heating system aiming to eliminate the need for separate heating systems and satisfy different room temperature requirements and airflow rates in all zones. Experimental results showed the ability of the system to achieve and maintain individual room temperatures, while ensuring the required airflow rate to meet IAQ requirement (based on minimum airflow rates per square meter), though it did not address the RH or CO_2 levels.

Laffeter et al. (2019) tested a ventilation system that incorporates a heat exchanger supplied with water from a reversible heat pump to preheat or precool the supply air. The conditioned air is supplied to the dry rooms, circulates through the door's undercuts, and is extracted from every wet room. The supply airflow rate varies according to the indoor RH and outdoor absolute humidity. Experimental results showed that this ventilation system significantly improved air exchange rates, maintaining CO_2 levels below 1000 ppm throughout the entire period from 1 a.m. to 5 a.m. in the bedroom. In addition, this ventilation system increases the supplied air temperature by 10 °C to 25 °C above the outdoor air temperature (5 °C and 20 °C) and contributes to 25% to 40% of the household total heating power demand during the heating season. Shin et al. (2018) investigated the effectiveness of a CO_2-controlled ventilation system with energy recovery in a mock-up experiment in a Korean apartment unit. Results showed that a living room-based control can maintain the overall CO_2 concentration in the entire unit at acceptable levels during nighttime hours. The ventilation energy consumption would be reduced if the CO_2 were dispersed through keeping bedroom doors open.

Pantelic et al. (2023) experimentally evaluated eight algorithms in a fully furnished residential unit with a floor area of 32.6 m^2 to assess how IoT-enabled sensors can control cooking-emitted pollutants, specifically $PM_{2.5}$. Results showed that single intervention, such as PM-activated stove hood or portable air cleaners (PACs), significantly improved integrated $PM_{2.5}$ concentrations when properly sized. Source control with a stove hood was more effective than removing the particles using PACs. This study also highlighted the importance of sensor locations for the rapid detection of cooking-emitted $PM_{2.5}$ concentrations. Another study based on IoT was conducted by (Chiesa et al., 2019) who developed and tested an IoT platform to monitor both the indoor and outdoor environments, including CO_2, TVOC, temperature, and RH, and optimise the ventilation to ensure an acceptable indoor environment. Positive results of using this platform were demonstrated over a test period of one hour, showing that this ventilation system can maintain CO_2 levels below 1000 ppm, VOC levels below 0.087 ppm, and keep RH within the range of 40% to 70%. However, their platform was not equipped with a heat recovery unit, nor was it equipped with a filter, so energy loss is inevitable, and the IAQ may deteriorate if it is used in areas where the outdoor air is polluted.

2.1.4.3. In-situ studies

This review includes five in-situ studies, all of which investigated the performance of demand controlled mechanical exhaust ventilation (DCMEV). Three of these studies assessed commercially available systems one manufacturer- for this publication named System 1 (Derycke et al., 2018) and System 2 (De Maré et al., 2019; Lokere et al., 2019). The remaining two studies did not specify the name of system's manufacturer (Jardinier et al., 2018; Sutter et al., 2022). Systems 1 and 2 supply fresh air to the habitable rooms via self-regulating window ventilation grills. The air then moves to wet rooms through doors by door grilles, where it is extracted. The extraction rates are controlled based on factors such as the presence of people, humidity, CO_2 and VOCs. Both System 1 and 2 incorporate SmartZone technology. The system is referred to as 'with SmartZone' when it extracts air from both bedrooms and wet rooms, and 'without SmartZone' when it extracts air only from wet rooms, without extraction from the bedrooms.

De Maré et al. (2019) analysed data from 350 Belgian dwellings with DCMEV systems, which maintained RH within acceptable ranges and kept CO_2 levels below 950 ppm in bedrooms. Lokere et al. (2019) monitored 900 Belgian dwellings with DCMEV systems, effectively controlling indoor moisture levels and reducing the risk of mold growth. Derycke et al. (2018) compared DCMEV and MVHR systems in passive houses, finding that both systems showed similar IAQ and energy consumption, but DCMEV had lower fan electricity consumption and overall running costs. Sutter et al. (2022) compared CO_2 and TVOC-controlled MEV systems in 29 Belgian households, noting that TVOC-controlled ventilation had higher airflow rates and was effective for activities generating TVOCs. Jardinier et al. (2018) evaluated RH-controlled MEV systems in French apartments after nearly 10 years, observing that most instruments remained functional, but regular maintenance was lacking.

2.1.5. Discussion and conclusions

Performance analysis revealed that smart ventilation strategies generally improved thermal comfort by maintaining acceptable temperature and humidity levels. Most studies showed positive effects on IAQ, with reduced pollutant concentrations and better control of CO_2 and humidity levels. The use of DALYs to estimate health impacts of exposure to indoor pollutants highlights the importance of balancing energy savings with IAQ to minimize harm to occupants. Energy savings varied widely, with some studies reporting savings of up to 85%, though discrepancies in simulation settings and reference systems made cross-study comparisons difficult.

Challenges and limitations included variability in simulation inputs, such as differences in occupancy patterns, pollutant generation scenarios, and building characteristics, which affected the results. Furthermore, the lack of standardization in assessing smart ventilation performance made comparisons challenging. The reference systems and buildings used in simulations significantly affect reported energy savings, and it is crucial to account for both space heating demand

and auxiliary consumption of the ventilation system, including fan electricity consumption. Additionally, assumptions about building envelope airtightness are crucial to simulation outcomes and should be carefully considered.

Future research should focus on in-situ studies, the impact of smart ventilation on health and energy consumption, and the performance of smart ventilation in the context of climate change. It is also important to find a balance between health and energy savings, investigating the performance of sensors in ventilation systems, and exploring the impact of urban heat islands and varying microclimatic conditions on the effectiveness of smart ventilation systems. Research should also aim to minimize carbon emissions, maximize cost-benefit, and improve indoor environmental quality.

This study evaluated 44 papers published from 2017 to 2023, on smart ventilation in residential buildings. Most smart ventilation strategies respond to RH and/or CO_2 levels, with some considering occupancy, outdoor conditions and indoor pollutants (i.e. HCHO and VOCs). The use of DALYs to estimate the health impact of indoor pollutants is a new development, emphasizing the importance of balancing energy savings with IAQ. The new developments also include performance-based assessment, decentralized ventilation units, data-driven approach to form the optimal strategy, financial analysis of the ventilation system, and the IoT-enabled devices and sensors. Belgium, France, and the US are the top three countries where smart ventilation studies have been conducted. Single-family houses and apartment units are the most investigated building types. Over the past seven years, smart ventilation concepts have been applied to ventilation for cooling and hybrid ventilation.

The analysis of IAQ indicators has revealed that in addition to the most widely used parameters of RH and CO_2, other IAQ parameters have been used to indicate the air quality, for example, HCHO, $PM_{2.5}$, and TVOC. The challenge related to the diversity of input data and the performance indicators was highlighted. The energy savings from smart ventilation strategies vary widely, ranging from -24% to 85%. However, discrepancies in simulation settings and reference systems made cross-study comparisons difficult. More in-situ studies to evaluate the performance of simulated ventilation strategies and assess their practicality are needed. A standardized approach to assessing ventilation performance, including consistent simulation input data, performance indicators, and results reporting is also needed.

2.2. D4.1b State-of-the art on use of performance-based approaches for residential ventilation in 2024 (published in REHVA Journal)

Authors: Gaëlle Guyot, Valérie Leprince, Baptiste Poirier, Jakub Kolarik

2.2.1. Introduction – Towards an innovative basis of thought for building ventilation

The context of climate change and the need to save energy has required rethinking the ventilation and the air change rates in buildings, because of their increased impact on thermal losses. Indeed, ventilation plays a crucial role estimated around 30-50% of the energy delivered to buildings, becoming an even higher part in high-efficient buildings (Liddament and Orme, 1998, AIVC FAQ).

Indoor air quality (IAQ) is another major area of concern in buildings which is influenced by ventilation. Because people spend most of the time in residential buildings (Klepeis et al., 2001) and 60-90% of their life in indoor environments (homes, offices, schools, etc.) (Klepeis et al., 2001; European Commission, 2003; Brasche and Bischof, 2005; Zeghnoun et al., 2010; Jantunen et al., 2011), indoor air quality is a major factor affecting public health. Logue et al. (2011b) 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.

Thus, by optimizing airflows where and when needs are higher, a smart ventilation system can truly improve IAQ while significantly minimizing energy consumption (François Durier et al., 2018; G. Guyot et al., 2018a).

An innovative basis of thought in order to conciliate energy and IAQ in buildings can be proposed for buildings, in the following order:

1. **Sufficiency**: the best $L.s^{-1}$ (airflow) is the one we do not need (because the pollutant sources have been reduced and are strictly limited)
2. **Aeraulic efficiency**: the right $L.s^{-1}$ is the one renewed at the best time and at the best location (smart ventilation)

3. **Air cleaning & filtration**: if the two first steps don't meet IAQ objectives, filtration of air inlet and/or air cleaning are needed.

2.2.2. A majority of prescriptive ventilation regulations & associated issues

IAQ performance-based approaches are seldom used for the design of ventilation systems in buildings. Instead, prescribed ventilation rates have been used. As a result, standards and regulations, such as ASHRAE 62.2-2022, EN 16798-1 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 the 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 such as cooking, showering, house cleaning, etc.

Several issues can be highlighted with prescriptive regulations, notably in our global context towards energy efficient buildings and the three axes proposed on the innovative basis of thought for ventilation.

- With the same level of ventilation airflows, you can reach a wide range of IAQ performance indicators, as shown by instance in (Guyot et al., 2019). In this article, the authors calculated that just by changing the assumptions concerning the distribution of air leakage with the same ventilation air flow rates, a 40% difference could be obtained in the average concentration of formaldehyde inside certain bedrooms over the course of a heating season.
- With a lower average ventilation airflow, you can even improve the level of IAQ, which is the exact principle of smart ventilation in general. A recent literature review reported that the performance of smart ventilation strategies gives a range of energy savings of 10-40% (associated with the reduced ventilation airflows) nearly always associated with an improved IEQ (Wang et al., 2024). It confirms results from another review performed in 2018 (G. Guyot et al., 2018a).

2.2.3. Performance-based approaches for smart ventilation & barriers

In order to conciliate energy saving and indoor air quality issues, interest in smart ventilation systems has been growing due to performance-based approaches. These systems often need to be compared to either constant-airflow systems ("equivalence approaches") or fixed IAQ metrics thresholds

A paper published in 2018 offers a review of performance-based approaches for residential ventilation, which had only been found in use in four countries (France, Spain, Belgium and The Netherlands) and one ASHRAE standard around the world, often for the assessment of smart ventilation strategies (G. Guyot et al., 2019, 2018b). At this time, most of these approaches were based on CO_2 and/or humidity-based performance indicators, or a fictive pollutant.

Poirier et al. (2021d) explained the three different steps of performance-based approaches: 1. Definition of a relevant set of performance indicators; 2.Definition of all the inputs needed for their computation; 3.Definition of the process and assumptions for the modelling stage (Figure 2-2, source: Poirier et al., 2021).

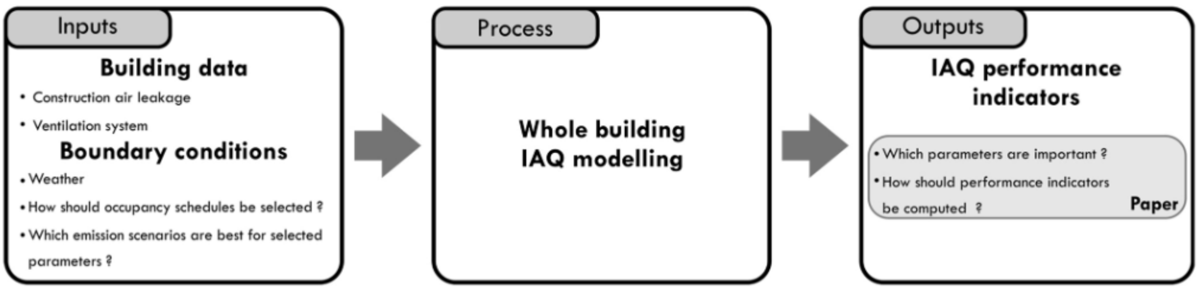

Figure 2-2 Schematic diagram illustrating a performance-based approach for ventilation at the design stage of a residential building

Associated scientific barriers (lack of data) can be listed below:

- What is the smallest set of relevant performance indicators?
- What are the levels of requirements (threshold values)?

- What is the level of performance of reference (constant airflow) systems? And must this level be used for fixing threshold values?
- What are the scenarios to be used as input data: occupancy patterns – emission scenarios – exposure profiles at the room scale?
- What is the proper level of detail of the modelling required at the design stage of a building, notably on air leakage distributions, deposition/resuspension phenomena, chemical reactions and dependencies, etc.?
- How can assumptions made on input data and modelling influence the output? Some answers have been provided with sensitivity analysis works (Poirier et al., 2024a, 2024b).
- How to balance IAQ and energy (or other non IAQ) in output results aggregation from performance-based approach for design and/or decision making?

2.2.4. What is new in 2024?

This paper gives an updated overview of how the performance-based concept has been developed and used in research projects since 2018, and how it has been transposed in standards and regulations since. In order to update the knowledge published in 2018 (G. Guyot et al., 2019, 2018b) highlighting only four countries (France, Spain, Belgium and The Netherlands) and one ASHRAE standard.

Since 2018, new research has been published and collected, notably in the context of the IEA-EBC Annex 86 - Energy Efficient Indoor Air Quality Management in Residential Buildings (2022-2025) with a series of deliverables to be published shortly. In this Annex, the preliminary scheme developed by (Baptiste Poirier et al., 2021d) based on 5 indicators including relative humidity, CO_2, formaldehyde and $PM_{2.5}$ along with associated input data on emission scenarios (Baptiste Poirier et al., 2021b) has been extended and tested in a common exercise performed in 5 countries (France, Denmark, Belgium, Brazil, and Austria).

In our international context in 2024, IAQ and energy are still issues of interest. Nevertheless, other aspects should be included in the performance indicators. An efficient ventilation system should dilute and remove indoor air contaminants, thus improving IEQ, preventing the build-up of pollutants and excessive moisture or pathogens/viruses, without needlessly wasting energy heating or cooling incoming air, considering environmental and climate changes (heatwaves, pollution peaks, pandemics, …).

In the revised European standard prEN 15665:2024 – Ventilation for buildings – Ventilation systems in residential buildings – design, the section 11 is dedicated to describing the “Performance assessment method” into 11.1-General approach; 11.2-Primary ventilation requirements and performance indicators; 11.3-Calculation method and assumptions.

A new addendum was proposed to the standard ANSI/ASHRAE 62.2- Ventilation and Acceptable Indoor Air Quality in Residential Buildings (Jones, 2023; Jones et al., 2024). A new metric named “harm intensity” is proposed with an associated requirement: the “harm budget”. This proposal is based on the choice of 3 contaminants of concern: $PM_{2.5}$, formaldehyde, and nitrogen dioxide. Indeed, the harm caused by those three pollutant accounts for ~83% of all harm caused by each of the 45 contaminants in residential dwellings. This proposal has not been voted yet.

The existing performance-based regulation in Spain has been updated and interesting feedback is available since 2018 (García-Ortega and Linares-Alemparte, 2024; Linares-Alemparte and García-Ortega, 2024). Two indicators based on CO_2 are still used. Associated energy savings have been estimated to be between 20 and 100%.

In France, although a performance-based method was already in use since the 80’s for humidity-based ventilation, which equips over 90% of new residential buildings, the concept is going to be extended to all types of ventilation with the recent French law (Leprince et al., 2023; Leprince and Poirier, 2024), based on the following statement “*Air renewal, shall be such as, in normal condition of use, the indoor air pollution does not endanger health and security of occupants and that condensation is avoided, except temporarily*”. Twelve performance indicators could be used in this future performance-based approach: two based on CO_2, three based on relative humidity, two based on a fictitious pollutant representing constant emissions, two based on another fictitious pollutant representing cooking emissions and three based on air renewal, which remains an intermediate indicator that can be assessed more affordably in most cases and is independent of sources.

In Poland, the use of smart ventilation is still rare in 2024 despite some humidity-based ventilation, the same type as in French systems. In the regulation, ventilation requirements can have exception for a given building if it is proven that energy savings can be obtained. The calculation method and the whole procedure have been described by Sowa et al. (2013).

In Ireland, new regulations for building, including ventilation aspects, were published in 2019 and 2022, with requirements on air leakage and ventilation performance. The first NSAI (National Standard Authority of Ireland) Agreement Certificate for ventilation systems was awarded in 2021 for AERECO humidity-based ventilation systems.

2.2.5. Conclusion

This is not a new topic, but it's not going away any time soon either. A number of scientific hurdles remain, despite the research carried out as part of the IEA-EBC Annex 86 project. Secondly, as regards the national standards and regulations that are responsible for transferring this research into the real world, feedback from Spain and France highlights all the remaining barriers: political barriers, as well as technical barriers such as the issue of regular inspections to check that the expected performance is achieved throughout the life of the ventilation system.

3. D4.2. Investigation report: IAQ and energy performance, durability and occupant interaction of smart ventilation strategies

3.1. D4.2a Rating existing smart ventilation strategies – testing usability of performance indicators for smart ventilation strategies

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3.1.1. Introduction and background

Evaluating the performance of smart ventilation systems involves several approaches (G. Guyot et al., 2019; Baptiste Poirier et al., 2021d). One common approach is the use of performance-based metrics, which assess the system's ability to maintain IAQ. In most cases, the ability of the system to provide simultaneous minimization of energy consumption is also assessed. Key metrics include the concentration of indoor air pollutants, mostly represented by CO_2 (although the CO_2 is not really a pollutant, but rather an indicator of outdoor air supply), volatile organic compounds, air humidity levels, and energy use. Additionally, the concept of "equivalent ventilation" can be employed, which allows for the anticipation of future ventilation needs and retroactive compensation for previous ventilation needs (BSR/ASHRAE, 2016). According to (Wang et al., 2024), evaluating the effectiveness of smart ventilation systems under various conditions happens mostly using computer simulations. Utilization of experiments or combination of experiments with simulations is rare.

Despite the promising benefits, smart ventilation systems face several challenges. One of the most important challenges is the fact that the regulatory landscape for smart ventilation is still evolving, and there is a need for standardized guidelines and performance criteria to ensure consistent and effective implementation (G. Guyot et al., 2019).

One of the key objectives of the collaborative research project entitled “Energy Efficient Indoor Air Quality Management in Residential Buildings”, performed under the framework of the International Energy Agency (IEA), IEA EBC Annex 86, has been to build an internationally based performance-based approach for assessing smart ventilation multicriteria performance, in order to allow the generalization of such promising solutions in residential buildings.

The present report demonstrates the application of an internationally applicable performance-based approach for the assessment of residential ventilation performance, including smart as well as traditional ventilation strategies. First, we aim to create a generally acceptable rating scheme- a set of performance indicators for assessment of residential ventilation. Secondly, we investigate its applicability with a common exercise conducted by experts in six countries (France, Denmark, Belgium, Italy, Austria, and Brazil) with different design contexts, simulation software, smart ventilation strategies, building geometries. The analysis of results shows: (1) how a performance-based approach using different performance indicators can be used to assess the performance of smart ventilation strategies in different countries and (2) how these smart strategies perform compared to standard ones.

3.1.2. Methods

3.1.2.1. A general method in two steps – Construction and Applicability

The first step was the development of an internationally based “rating scheme” or “performance-based approach”. Before the second Annex 86 meeting in Athens, a “homework” questionnaire was sent to all Annex 86 participants in order to identify the relevant performance indicators to use and the identified barriers. Eight experts send an answer from seven countries (UIBK-Austria, SINTEF-Norway, Buildwise-Belgium, KU Leuven-Belgium, CETIAT-France, LBNL – USA, TUe-The Netherlands, CSIC-Spain). During a series of meetings and workshops, an international consensus was obtained with the selection of a set of performance indicators, using the available literature as well as an expertise of the team members and the work performed during the IEA-EBC Annex 68 project (Abadie and Wargocki, 2017; Cony

Renaud Salis et al., 2017; Cony-Renaud-Salis et al., 2019). Then, a working group was established to create a common description of the simulation study to be conducted by each participant. The description included details of the workflow, to be followed by each participant, list of target contaminants to be simulated and the required output data. Besides the output data, each participant had to fill out forms collecting the standard simulation input information (e.g. occupancy schedules, pollutant emission rates and information about simulated ventilation control strategies).

The second step consisted in testing this rating scheme in different national or regional contexts. The project participants from seven research institutions in six countries agreed to participate in this common exercise. The participants were free to use an existing simulation case including building geometry, type of simulation software, weather data, etc. The task was to conduct a performance analysis of the different ventilation strategies for the case, with both standard and smart approaches to control and use the predefined set of performance indicators to assess these strategies. We gave the participants a free choice to select the case as well as the ventilation strategies studied. The only condition was that they provided all the required information and that they selected one strategy, preferably standard (not smart), as a reference. The common set of performance indicators constituted the framework for the analysis which looked at the data from two main angles:

- Usability of the indicators to describe a relation between the smart ventilation strategies and a "reference case", which had a country specific relevance.
- A general qualitative analysis of the usability of the performance indicators. This analysis comprised of a synthesis of experiences, observations, identified barriers and challenges reported by all involved participants in a dedicated formular.

3.1.2.2. Target contaminants and collected data

Table 3-1 summarizes the contaminants to be included in the simulation studies of the performance of ventilation. There were four obligatory contaminants and one optional contaminant.

Table 3-1 Contaminants/parameters to be included in the simulations

Contaminant/parameter	**Reasoning behind the choice of the contaminant**
Carbon dioxide (CO_2)	Emitted by humans and pets, indicates emission of bioeffluents, if the bioeffluents dominate the indoor emission can be used as a surrogate for IAQ, indicator of ventilation. In limited amount emitter also by indoor combustions (e.g. gas cookers).
Relative humidity	Emitted by humans and pets as well as occupancy related activities and processes. Low relative humidity leads to irritation of mucous membranes, discomfort and increased transport of viruses. High relative humidity can result in condensation on constructions and consequent mould growth.
Particulate matter $PM_{2.5}$	Main indoor sources of particles include combustion of all kinds, printing, use of cosmetics (lacquers, sprays), erosion of coating materials, presence of occupants and occupants' activities. Cooking emissions are major sources. Health impact of $PM_{2.5}$ has been demonstrated on major among other pollutants in indoor environments (Jones, 2023; Logue et al., 2011a; Baptiste Poirier et al., 2021d). PM2.5 emissions are rather localized in time and in location. In some locations, outdoor air can also be a source of PM2.5.
Formaldehyde	Formaldehyde is a common pollutant found in all residential buildings and its health impact is important among other pollutants in indoor environments (Jones, 2023; Logue et al., 2011a; Baptiste Poirier et al., 2021d). Formaldehyde emissions are rather evenly distributed in time and in location, when they are due to buildings materials, products and furniture.
Fictive pollutant (optional). constantly and continuously emitted in each zone	The procedure is being developed for the new version of ASHRAE 62.2 standard and in the French national framework, it can be complimentary to the 4 other parameters.

The following data were collected with a time-step in the range of 10-15 min:
- The concentration of raw time-series data, at least for CO_2 and relative humidity, in all rooms
- The contaminant concentrations of raw time-series data, at least for PM2.5 and formaldehyde and for two occupants (as occupants should differ in their presence patterns in particular rooms).

The calculation period has been defined as the entire period of ventilation operation, depending on the context: either the typical heating period when there is no cooling with outside air supply - the heating period can extend to the “fee floating” period when neither heating nor cooling is used; or the whole year if there is a cooling system with outside air supply and a heating system, or the typical cooling period in countries where there is no heating period.

3.1.2.3. Selection of 13 performance indicators

All the ventilation strategies must be evaluated by the performance indicators described in Table 3-2.

Table 3-2 Description of the 13 performance indicators selected

Performance Indicator	Unit	Description
DALY	[years.10^5](*)	The total health impact is the sum of all DALYs (Dynamic Disability-Adjusted Life Years). The calculation was based on approach by (K. De Jonge and Laverge, 2022)
E_{CO2}	[ppm.h]	Normalized cumulative exposure when concentrations are higher than 1000 ppm in a room.
P_{CO2}	[ppm]	95^{th} percentile of the CO_2 exposure concentrations.
T_{RH}	[%]	Percentage of time spent out of the humidity range of 25-60% (EN 16798 category II)
E_{HCHO}	[µg m^{-3}. h]	Cumulative formaldehyde occupant exposure.
$E_{fictive}$	[µg m^{-3}. h]	Cumulative fictive occupant exposure.
$E_{PM2.5}$	[µg m^{-3}. h]	Cumulative $PM_{2.5}$ occupant exposure.
$E_{HCHO\ acute}$	[µg m^{-3}. h]	Maximum of the formaldehyde cumulative occupant exposure over 1h.
$E_{fictive\_acute}$	[µg m^{-3}. h]	Maximum of the fictive cumulative occupant exposure over 1h.
$E_{PM2.5\_acute}$	[µg m^{-3}. h]	Maximum of the $PM_{2.5}$ cumulative occupant exposure over 1h.
ACH	h^{-1}	Average building air changes per hour due to ventilation.
E_{losses}	[kJ]	Ventilation heat loss
E_{elec}	[kJ]	Energy consumption of the fan(s)

(*) Disability-adjusted life years (DALYs) lost in a group of 100 000 people.

3.1.2.4. Collection of input data and modelling assumptions

Every participant must describe all the entry data and assumptions used to calculate the selected performance indicators. This includes entry data: detailed occupancy patterns and emission scenarios (multizone) for CO_2, humidity, formaldehyde, $PM_{2.5}$, fictive pollutant, weather files, simulation period, and outdoor pollution data. This includes the modelling assumptions and data, notably on moisture absorption/desorption, PM deposition/resuspension, air leakage values and distributions, position of internal doors and windows and associated models, penetration factors for PM, formaldehyde dependences, wind pressure / microclimate around the building, etc.

3.1.2.5. Description of smart and reference ventilation strategies

Eleven smart ventilation systems were selected for the simulations, which could be classified into 3 categories:

- Humidity controlled mechanical exhaust-only ventilation (**MEV-rh**).
- Mechanical balanced ventilation with heat recovery and humidity control at the apartment level (**MVHR-rh**).
- Mechanical balanced ventilation with heat recovery and humidity + another parameter (CO_2 or VOC generally) control at the room level (**MVHR-rb;** rb=”room based”)

Behind the same name of category (MEV-rh, MVHR-rh and MVHR-rb), there are several systems, with different type of sensors, and/or location of sensors, and/or setpoints, and/or airflows.

We decided to use the constant airflow ventilation strategies (**-cav**) for each contributor separately as the reference systems. Again, despite the identical name (MEV-cav or MVHR-cav), the reference system is different for each participant (Table 3-3).

Table 3-3 Description of the studied smart ventilation strategies and associated reference ventilation strategies for every participant to the common exercise

Contributor	Smart ventilation system	Reference system
Cerema	MVHR_rb	MVHR_cav
	MEV_rh, MEV_rb	MEV_cav
DTU	MVHR_rb, MVHR_rb1	MVHR_cav
	MEV_rh0, MEV_rh1	MEV_cav
KUL	MVHR_rb	MVHR_cav
	MEV_rb	MEV_cav
PUCPR	MEV_rb	MEV_cav
UGENT	MVHR_rb	MVHR_cav
UIBK	MVHR_rb	MVHR_cav
EURAC	MEV_rb	MEV_cav

3.1.2.6. Analysis of data - new criteria for normalizing the results

All the output performance indicators calculated by the contributors were regrouped and homogenized. The units of the results were checked carefully to ensure that the assessed performance can be correctly compared. Because every contributor used a different reference ventilation system/strategy as well as boundary conditions, it was not the intention to perform a direct comparison among the cases from different contributors. Instead, the trends represented by particular ventilation strategies for individual contributors were studied. In some cases, there were huge differences in the order of magnitude of performance indicators. This made it difficult to represent the absolute results data on the same scale. To tackle these issues, we proposed to calculate a relative direction of the indicators with a new criterion named Indicator's Relative Direction (IRD). This criterion allows us to focus on the relative performance of a smart ventilation system in comparison to a reference ventilation system.

$$IRD_{sys} = 100.\frac{I_{sys} - I_{ref}}{I_{sys} + I_{ref}}$$

Equation 3-1

With IRD, in percentage [%], the relative direction of ventilation system *sys,* for a given performance indicator *I,* in comparison to the reference ventilation system *ref.*

3.1.3. Results

The comparison of the performance results between all the contributors is not straightforward due to the number of performed indicators and the diversity of modelled ventilation systems. We divided the results analysis into three short sections. First, a general overview of all the data is provided, followed by the data detailed by contributor and lastly by performance indicator.

3.1.3.1. Overview of results data – participants, strategies, basic data

Figure 3-1 presents all the results provided by the contributors across the 13 performance indicators. Each contributor corresponds to a unique color: EURAC (light green) , UIBK (purple), UGent (blue), PUCPR (bluegreen), KUL (yellow), Cerema (orange), and DTU (red). The marker is different depending on the ventilation system.

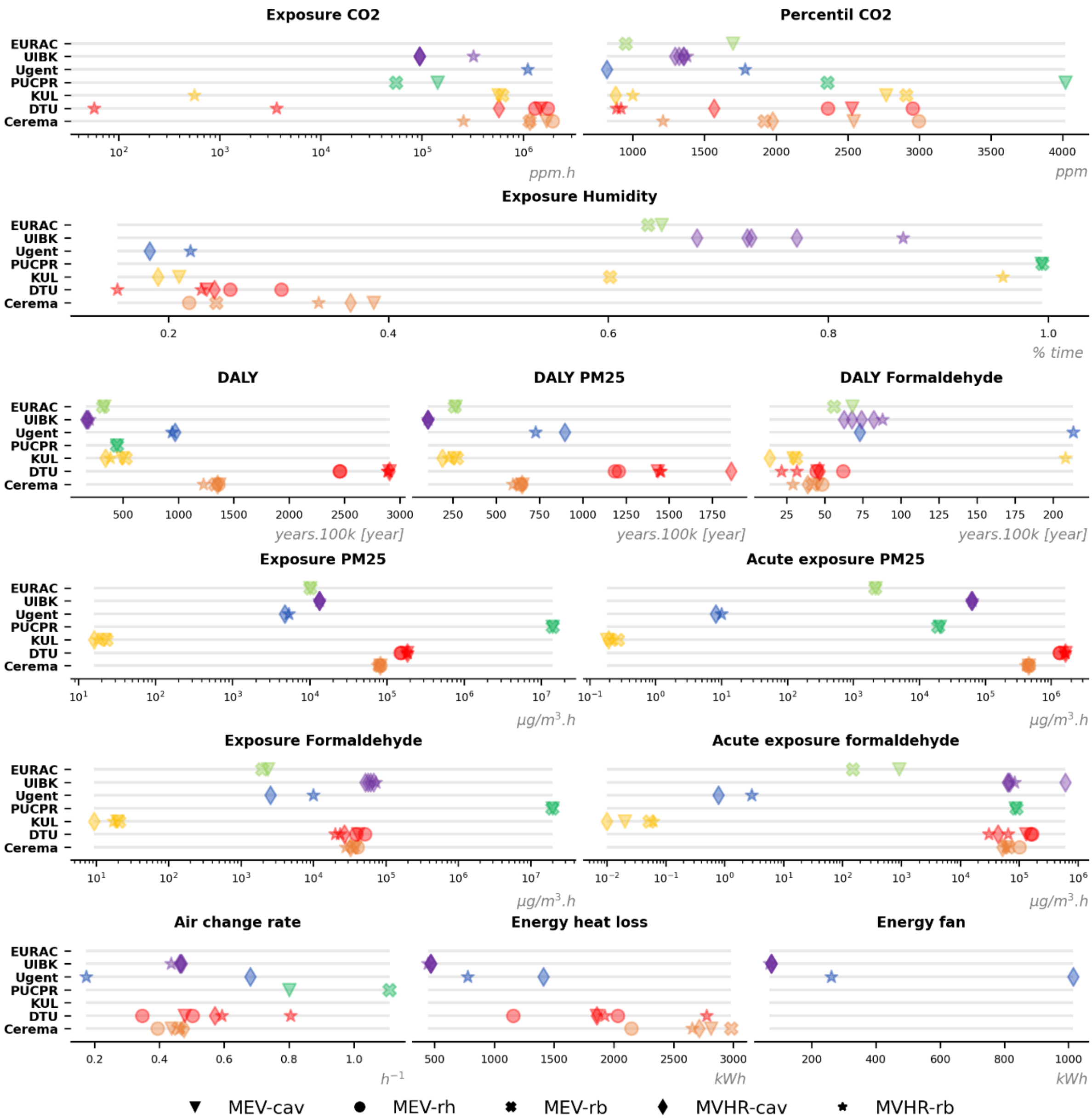

Figure 3-1 Overview of all data provided by the contributors

The results for CO_2 exposure range between 10^2 and 10^7. The cases from DTU and Cerema present the highest values. The second indicator, 95th percentile of exposure concentrations ranges, for most cases, between 1000 – 3000 ppm with MEV systems representing the highest values. Higher levels were observed only for PUCPR with MEV-cav, with results over 4000 ppm and we can observe that KUL MVHR system performed better than KUL MEV. Regarding RH, UGent, DTU and Cerema were between 20% and 40 % of the time out of the [25% - 60%] range, while EURAC, UIBK and PUCPR were out 60-100% of the time, PUCPR, 100% of the time. The results of KUL cover the whole range between 2% to almost 100% of the time out of the [25% - 60%] range. The total DALY results are similar for EURAC, PUCPR and KUL between 300 to 600 DALYs.100k people, UIBK has the lowest values under 200 DALYs.100k people where UGent and Cerema have higher results between 1000 and 1440 DALYs.100k. Lastly, DTU results are the highest ones with values over 2300 DALYs.100k people. Almost the same patterns can be observed between the contributors results for the pollutant exposure indicators to formaldehyde and PM. KUL have the lowest exposures results, EURAC, UIBK, UGent are mostly in the middle range and PUCPR, CEREMA and DTU have the highest ones.

The average air change rate is mostly between $0.3h^{-1}$ and $0.8h^{-1}$ except for UGent (MVHR–rb) which performs the lowest rate at $0.17h^{-1}$ and PUCPR (MEV-rb) the highest one at $1.1h^{-1}$. It shows that smart ventilation strategies can provide a quite large range of air change rates depending on the systems. For an ACH of the same order of magnitude, Cerema has the highest heat losses, while UIBK achieves the lowest. The heat losses of DTU and UGent are intermediate and comparable, slightly lower for UGent. These differences can be explained by different weather and climate conditions and/or the temperature set point in the heating system. Lastly, some results were obtained on yearly fan energy consumption.

3.1.3.2. Relative performance direction-IRD by contributor

Figure 3-2 represents the IRD (Equation 3-1) by contributor, for all indicators. The colour of the plotted result indicates if the relative direction is negative (better performance in comparison to the reference) in green, or positive in red (worst performance in comparison to the reference). Boxplots represent the median, 1st quartile, 3rd quartile and outliers (detailed in Table 3-4). The boxplot serves solely for a comparison of the spread of IRD across the different contributors. In general, we can conclude that smart ventilation strategies have:

- **Always better performance** for EURAC simulations with results in average -7.9 %.
- **Generally, the performance** of the Cerema, DTU, PUCPR, and UIBK simulations was better, with results between -2.3 % and -5.5 %.
- **Generally, the worst performance** was for the UGent and PUCPR simulations, with results on average 9.14% higher.
- **Always the worst performance** for the KUL simulations, with an average of 15.5 % higher results.

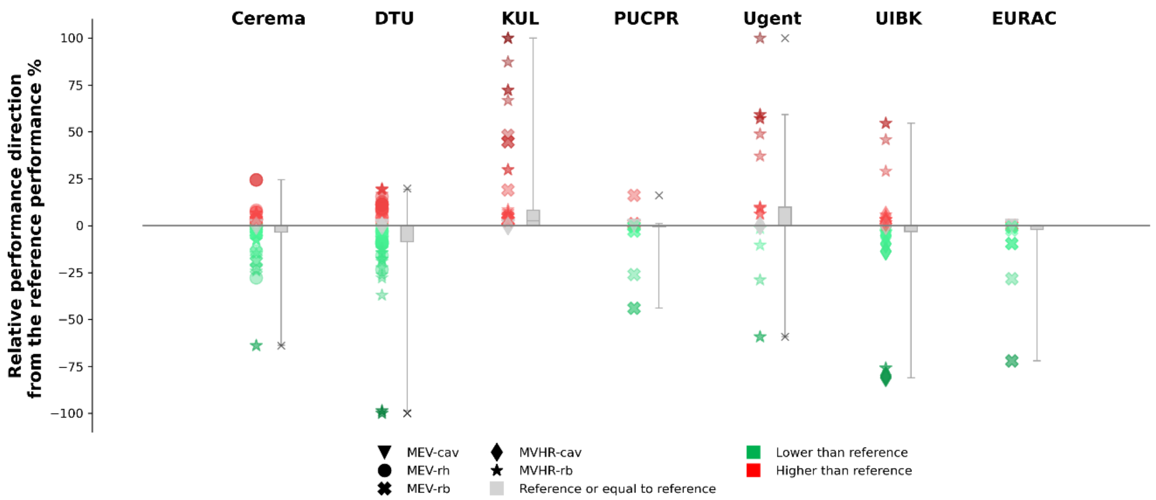

Figure 3-2 Relative performance direction-IRD" by contributor

Table 3-4 Detailed statistical results for IRD

	Cerema	DTU	KUL	PUCPR	UGent	UIBK	EURAC
count	95.00	114.00	50.00	28.00	33.00	100.00	26.00
mean	-2.31	-5.17	15.54	-3.67	9.14	-5.48	-7.91
std	11.95	20.50	28.33	12.84	32.06	24.15	19.81
min	-63.91	-100.00	0.00	-43.97	-59.20	-81.13	-71.95
25%	-3.38	-8.51	0.00	-0.36	0.00	-3.10	-1.97
50%	0.00	0.00	2.52	0.00	0.00	0.00	0.00
75%	0.00	0.00	8.28	0.00	9.86	0.27	0.00
max	24.57	19.82	100.00	16.23	100.00	54.72	0.17

3.1.3.3. Relative performance direction-IRD by performance indicator

The plotted points in Figure 3-3 are the relative performance direction named IRD (Equation 3-1), already plotted in Figure 3-2, but classified by indicators separately for all the contributions.

We can observe that:

- The CO_2 exposure and 95th percentile indicator gives rather similar indications, but the exposure has the ability to highlight the frequency of high concentrations (CO_2 > 1000 ppm).
- There is a reduction of the total DALY indicator for smart ventilation in main cases except for KUL results, as already discussed in the previous part. It shows potential benefits of such strategies to improve the IAQ in comparison with their reference constant airflows strategies.
- In detail, the total DALY as well as the DALY form $PM_{2.5}$ and DALY from HCHO result in the same ranking as given by $PM_{2.5}$/HCHO exposure indicators. The colour and relative direction are the same. Only the $PM_{2.5}$/HCHO acute exposure indicators highlight different tendencies, in comparison with the DALY indicator.
- Air change rates and energy benefits give the same ranking in all cases.

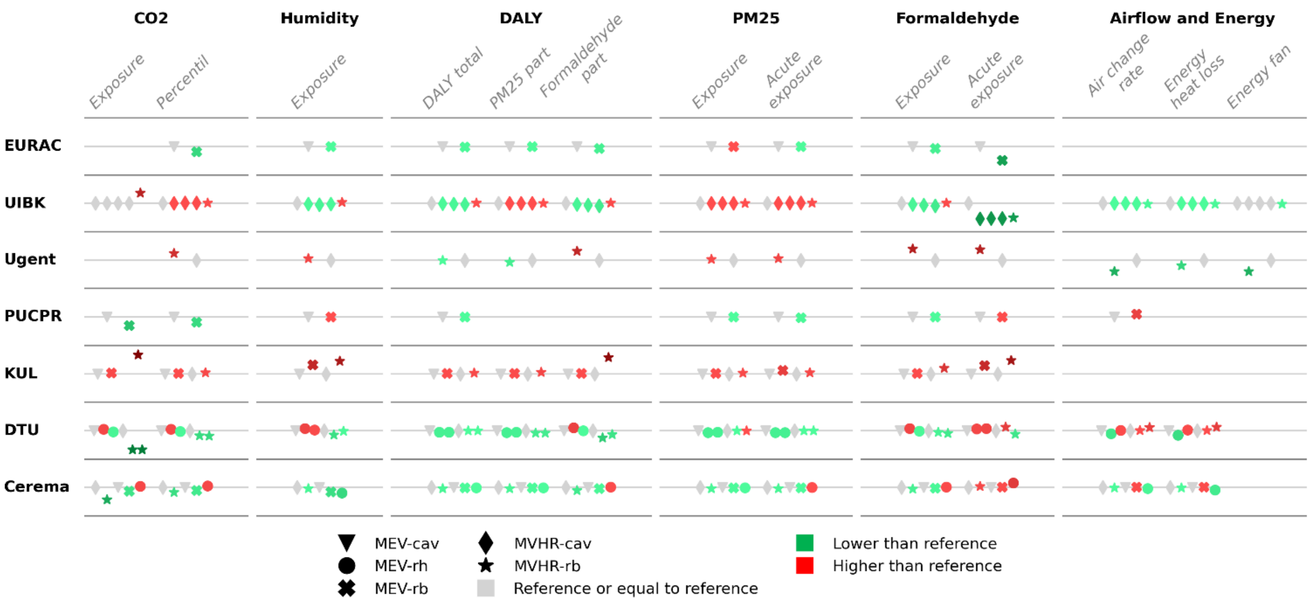

Figure 3-3 Relative performance direction-IRD" by performance indicator

It is clear that IDR, with its colour code (green and red). could be used for a decision-making process. Indeed, for each specific context of the contributor, we can easily observe the performance of a system depending on which aspect of the performance is prioritized. For example, the MVHR-rb system of UGent shows good relative performance for energy-based indicators (green) and offers high IAQ regarding the total DALY indicator. This good performance is, however, contradicted by worse relative performance (red) for CO_2 and humidity-based indicators, and for $PM_{2.5}$/HCHO exposures. In opposition, the MVHR-rb system of Cerema and DTU offers good relative performance (green) on IAQ based on CO_2, total DALY, but with higher energy losses/demands for DTU (and not for Cerema).

3.1.4. Conclusions and perspectives

An internationally based performance-based approach has been developed for assessing smart ventilation performance using multicriteria approach. This approach was tested and used in a common exercise conducted by experts in six countries with different design contexts, simulation software, smart ventilation strategies and building geometries. The analysis of results performed by indicator and by contributor show in different countries: (1) how a performance-based approach using different performance indicators can be used to assess performance of smart ventilation strategies and (2) how these smart strategies perform compared to standard ones.

With respect to the usability of the indicators, our results show that not all indicators need to be used. For example, the DALY and exposure indicators point in the same direction and therefore only one of them could be used. The same can be concluded about air change rate indicator and the energy demand indicators. It must be confirmed by more simulations in future work.

Another step of analysis in this common exercise is being conducted using more standardized conditions to compare performance of these different smart strategies under different climatic and boundary conditions, using identical building model and modelling tools.
Despite the promising benefits, smart ventilation systems face several other technical challenges such as the reliability and accuracy of sensors used to monitor airflows and/or contaminants. Current pollutant sensors, for instance, are not always robust or accurate enough for reliable residential ventilation control. There are also concerns

regarding potential system malfunctions (e.g. zero-drift, lack of calibration), which can lead to suboptimal performance (Zhao et al., 2022) and regarding the long-term performance of sensors and systems in general.

3.2. . D4.2b Accuracy, durability and occupant interaction in smart ventilation strategies

Short investigation report

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3.2.1. Durability, Long term performance, and accuracy of sensors

Durability of building performance is a crucial issue to be addressed. With smart ventilation, we generally allow lower airflows at some times or places when and where needs are low (no occupancy, low emissions, etc…), so we must ensure that airflows reliably change to higher level when ventilation needs are greater. The result is that we must ensure, even more than with other ventilation systems, that expected ventilation airflows are still correctly provided, over the building's life. Questions include:

1. The accuracy and durability of the different components of the ventilation system itself, as well as the sensors. These can be tested in lab conditions.
2. The long-term performance of systems and impact of maintenance and occupant interaction. They can be assessed with *in-situ* monitoring campaigns.

During the project, three main inputs were collected on this topic:

- Background and literature review describing current state-of-the-art regarding durability and long-term performance.
- Results of 13 years operation of humidity-based systems in France from the project called '*Performance 2'* project, which was focused on the two aspects detailed above.
- Feedback from requirements for sensors in place in Belgium.

3.2.1.1. State of the art review

First, a summary of the state of the art was performed during the French Performance 2 project and published in (Mélois et al., 2023) regarding the long-term durability of ventilation performance in buildings. **It confirms the lack of data and the need for new research studies on the long-term performance of ventilation systems and components for sustainable buildings.**

The Scopus, Google Scholar and the airbase database of the AIVC were used as bibliographic databases. We observe a problem of terminology regarding expression "long-term". In the context of building IEQ, "long-term" is often defined as the timescale of 1 year or even less. Nevertheless, the lifetime of any product of ventilation systems is considered to be much shorter than the lifetime of a building (Seuntjens et al., 2022). If a building's technical services lifetime has often been assessed between 7 and 15 years (Estaji, 2017; Gosling et al., 2013), other authors consider a much longer lifespan for ventilation systems: 15 to 20 years (Feist et al., 2020), even 25 years (Durmisevic, 2006). Therefore, we would need data on the "long-term" durability of the performance for ventilation systems, which should be considered for more than 3-4 years.

We found only three papers dated after 2017 providing detailed data on the long-term durability of ventilation systems. It seems that the topic has not given much attention in recent decade. Considering earlier publications, work by Sonne et al. (2015) addressing durability by quantifying effectiveness and failure rates can be mentioned. Furthermore, studies by Balvers et al. (2012) and Hill (1998) also indirectly deal with durability issues. Some of recent studies, consider even the assumption that DCV ventilation dysfunctions or failures should have been reported by the occupants and should not happen due to the fact that the buildings are newly built and any kind of technical problems were normally covered by the 5 year-guarantee (Simanic et al., 2019).

(Feist et al., 2020) provides data on the durability of fabric components of ventilation systems on four occupied passive houses built 25 years ago, equipped with balanced ventilation with heat recovery, which have been intensively monitored (200 sensors) over a 5-year period. Their inspections focus on the supply ventilation ducts. Even if the ducts have never been cleaned during the 25 years, they observe by visual and camera inspection in the supply ducts and by microbiological analysis in the laboratory a perfect hygiene status of the ventilation supply air duct network, with no evidence of increased germ density or mould contamination. This study provides no data about the ATDs (Air Terminal Device). Authors write "There is no reason why the basic components (ducts, cases, filter boxes and counter-flow heat exchangers) could not be used for 50 years". Tenants themselves can easily service these filters; with these filters installed, the extract/ supply air ducts only need to be cleaned once within 10 years.

Howarth (2001) provides a study in 26 dwellings over 6 years on the reliability of radon reduction techniques, one of them being based on ventilation. 11 of the 17 ventilation systems operated for more than 50,000 hours without any problems being reported. They show that the failure rate of fans tends to increase over time, but this is normal as the fans approach the end of their life.

Pallari M-L and Luoma M (1993) propose a follow-up study on long-term performance of residential ventilation carried out in 1992-1993 on nine of the buildings studied in the 1980's, equipped with various heating and ventilation systems, but no DCV ventilation. The regular maintenance included changing filters every third to sixth month and cleaning of ducts and ATDs when necessary. The authors identified the control valves did not function as designed. The measured exhaust ventilation rates dropped in the range 15%-94% except in one building where it increases by 9%. The authors noted dirty supply ATD with insufficient filtering. They concluded that the normal maintenance work was not always of good quality (dirty fans and filters) and not sufficient in the long-term, because airflow and pressure conditions of the buildings tend to change due to occupants' interaction and dirty ATDs.

If we focus solely on sensors, the literature also highlights a lack of data on durability of sensors (Anastasiou et al., 2022; Malings et al., 2020; Sá et al., 2022; Zhang and Srinivasan, 2020). The need for periodic calibration of CO_2 sensors was stressed in the literature, which contains several accounts of sensor drift over time (Fisk et al., 2006; Kesselring et al., 1993).

3.2.1.2. "Performance 2" project – Long term performance of humidity-based ventilation

Humidity-based DCV systems have been widely used in France for 35 years and are considered as a reference system, including for low-energy residential buildings. The on-going "Performance 2" project delivers feedback from 13 years of on-site operation in twenty-two social housing apartments. The project was based on two main activities: 1. Laboratory studies, to address the issue of durability of the sensors and the components. 2. In situ measurement campaigns to assess the robustness of the ventilation components and sensors to their use/lack of maintenance by occupants. The initial project was a large-scale monitoring of thirty new occupied apartments in two buildings in France equipped with this DCV system, which extended from 2007 to 2009. Thirteen years later, the buildings were re-visited, and the monitoring system was turned back on with the intention to assess the ventilation system performance after a prolonged in-situ functioning period. Then, the ventilation system components were collected and tested in laboratory facilities: as collected, after cleaning, and finally after a light rehabilitation. Despite largely insufficient levels of maintenance, 100 % of the exhaust units and air inlets not purposely degraded by the occupant, still reacted as expected to humidity. A good relationship was found between the visual maintenance level and the limitation of maximum airflow for each Air Terminal Device (ATD): an average limitation of -10.6 m^3/h has been evaluated for ATDs presenting a "Bad" level of maintenance whereas the average limitation was only -2.2 m^3/h for ATDs showing a "Good" maintenance state. Finally, after cleaning and refurbishing, but without touching the hygroscopic sensor/actuator, the ATDs still meet the specifications and are very close to their original characteristics. Detailed results are available in (Mélois et al., 2023).

3.2.1.3. Accuracy requirements in Belgium for sensors used in smart ventilation

In Belgium, the regional Energy Performance of Buildings (EPB) regulations allow a possible reduction of ventilation heat losses for energy performance calculation in case of the use of Demand control ventilation (DCV). A reduction factor (f_{reduc}) is applied depending on the number and types of sensors (CO_2, RH, etc) and the control extent (room by room control, control by zone, central control). Minimum and maximum airflow rates are defined based on the sensor types and control configurations.

For these reduction factors to be applicable, the regulation has defined **requirements on the accuracy of the sensors**. These requirements are:

- CO_2: ± 40 ppm +5% of the actual value between 300 and 1200 ppm (absolute concentration)
- RH: ± 5 percentage points between 10% RH and 90%RH

These tolerances were established based on airflow simulations conducted using the CONTAM software. First, DCV systems were simulated to evaluate whether the resulting indoor air quality (IAQ) was satisfactory, using indicators such as CO_2 exposure and an RH-based metric. Subsequently, the f_{reduc} factors were calculated by comparing the average airflow rates of the DCV systems to those of a reference system.

To assess the impact of sensor accuracy, additional simulations were performed by introducing a bias in the sensor measurements. The IAQ indicators from these simulations were then compared to those obtained using ideal sensors. The final tolerances represent a trade-off between the sensitivity of IAQ to sensor accuracy and the performance characteristics of commercially available sensors.

The protocol for testing the sensors' accuracy is detailed in the EPB Database procedure for each type of product and for DCV systems (CSTC and UGent, 2020).

In short, RH and CO_2 sensors accuracy must be measured in hermetically closed environments with fixed CO_2 concentration (or RH), known concentration obtained by calibrated CO_2 gas (bottles, etc) or saline solution (for RH), Tested for at least two concentrations / RH values, Reaction time must be lower than 5 min.

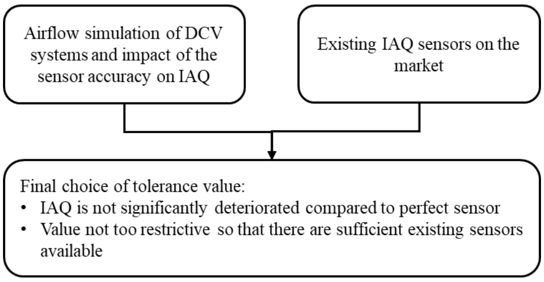

Figure 3-4 Determination of sensor tolerance in Belgium

3.2.1.4. Others

A new project is starting at the Technische Hochschule Rosenheim (presented at Singapore meeting) but data and results are not available now.

3.2.2. Occupant interaction

The question of the interaction between the occupant and the ventilation system is an interesting issue rarely treated in literature. Sarran (2021) mentions that examinations of occupant interaction with building systems reveal several non-physical factors influencing occupant satisfaction with these systems. Sarran states that: "occupants' understanding of the technology and their perceived control over the indoor environment were key to their acceptance of technical installations". According to the author, this influenced the proper operation of these systems. According to Sarran (2021a), occupants' perception of indoor environmental quality in homes was correlated to their perception of the usability of technical installations. Regarding smart ventilation, the following questions are of interest: What is the impact of interactions between the occupant and the smart system on the (perceived) performance and acceptability? How can some options proposed by some ventilation products, with a possible visualization of the performance (giving the user the ability to assess whether the system performs as intended), impact the performance or the fault detection?

During the IEA-EBC Annex 86 project, it has not been possible to collect data from involved partners regarding this issue, except the results presented in the prior section. The aforementioned questions remain unanswered and should be focused upon during future studies. However, some data can be obtained from studies not directly focused on smart ventilation, but on mechanical ventilation with heat recovery in general. In a questionnaire study carried out in a social housing complex consisting of 2007 single-family houses, of which 1305 were retrofitted between 2014 and 2019, Sarran et al. (2021) and Sarran (2021) focused on obtaining feedback from occupants of low-energy retrofitted houses concerning the indoor environmental quality (IEQ) and the building systems in their homes. The authors describe how occupants interact with mechanical ventilation to avoid discomfort (mostly draft). These interactions resulted from an annoyance towards faulty operation of mechanical ventilation, coupled with a perceived lack of control over it. Interactions included taping/ blocking the ventilation inlets or adjusting the diffuser plates (installers despite advice not to do so). In certain cases, occupants disconnected the power switch corresponding to ventilation to avoid air dryness, to limit draft, or to save energy. Authors conclude that even if occupants noticed that the indoor air quality worsened, they preferred to be in control. So, they could decide whether to prioritize indoor air quality, thermal comfort, energy use, or other factors. Definitely, one can assume that "smartness" of the future ventilation systems in dwellings should also lie in giving the occupants the ability to prioritize their needs without negatively affecting indoor air quality and/or energy efficiency.

3.2.3. Conclusion

In conclusion, there is a need to:

- Secure even more the performances of the smart ventilation systems over the ventilation lifetime – assessed to be around 20/30 years.
- Implement requirements for sensors and actuators accuracy and longevity.
- Secure long-term performance through adapted inspection protocols including a check of sensors and actuators.

Encourage new research on the impact of occupant interaction on smart ventilation performances.

4. D4.3 Inspection protocols for stand-alone smart ventilation systems in residential buildings

Short investigation report

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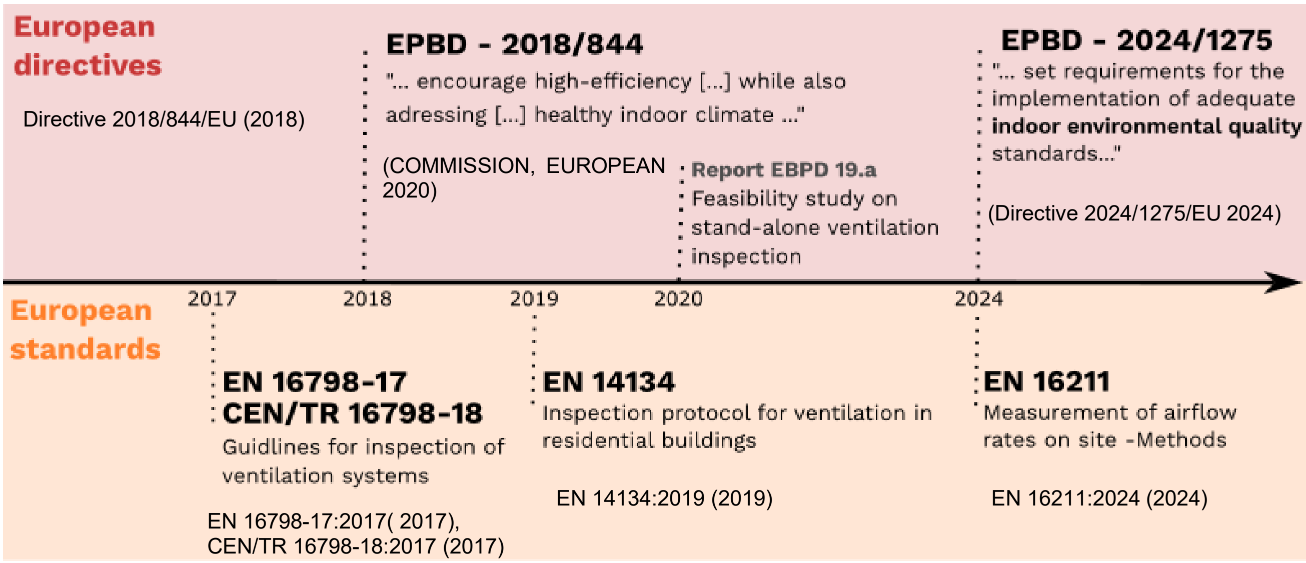
4.1. Introduction

To minimize the energy consumption of buildings while maintaining good Indoor Air Quality (IAQ), smart ventilation (including Demand Control Ventilation, DCV) raises growing interest. These ventilation systems raise new questions concerning their inspection. The present document focuses on the inspection of stand-alone (without heating or air-conditioning) smart ventilation systems in residential buildings. After reviewing the European framework (directives and standards) for ventilation inspection, the reference to smart ventilation in some existing inspection protocols will be gathered. Finally, the points of attention for smart ventilation inspection will be discussed. The last two parts are based on a survey sent to the members of the IEA-EBC Annex 86/ST4, which can be found in Appendix 3.

4.2. European framework for ventilation inspection

The main directives and standards concerning European ventilation inspection are gathered in Table 4-1.

Table 4-1 European framework considering inspection of stand-alone ventilation systems in residential buildings



4.2.1. EPBD – 2018/844

The directive (Directive 2018/844/EU of the European Parliament of the Council of 30 May 2018 (recast). Available at: https://eur-lex.europa.eu/eli/dir/2018/844/oj) mentions addressing healthy indoor climate conditions in the following extract:

"For new buildings and buildings undergoing major renovations, Member States should encourage high-efficiency alternative systems, if technically, functionally and economically feasible, while also addressing the issues of **healthy indoor climate** conditions, fire safety and risks related to intense seismic activity, in accordance with domestic safety regulations."

A technical report about inspection- protocols in residential buildings has been ordered by the Article 19.a. In this report (COMMISSION, EUROPEAN; INIVE; BPIE, 2020), 81 existing regulation standards and guidelines about ventilation systems inspection are collected, and 34 are studied. When these documents involve measurements, there are mainly: airflow measurements, ductwork airtightness, electrical consumption. The IAQ measurements are rarely mentioned.

4.2.2. EPBD – 2024/1275

The EPBD directive (Directive 2024/1275/EU of the European Parliament of the Council of 20 April 2024 (recast). Available at: http://data.europa.eu/eli/dir/2024/1275/oj) (Hogeling, 2024) was revised in July 2024 and will be applied progressively until the 30th May 2026.

It provides a new definition of **Indoor Environmental Quality** (IEQ) and the concept of optimal indoor environmental quality.

Moreover, in Article 13, it sets the following, referring to IEQ as the parameter of interest: "Member States shall set requirements for the implementation of **adequate indoor environmental quality** standards in buildings in order to maintain a healthy indoor climate."

In Article 13 as well, the following sentence is of interest: "Member States shall require non-residential zero-emission buildings to be equipped with **measuring and control devices for the monitoring and regulation of indoor air quality**." This part is dedicated to non-residential buildings, which are out of our scope. Anyway, it shows a growing interest in smart ventilation.

Finaly, Article 23-1 concerning inspection states the following: "Member States shall lay down the necessary measures to establish **regular inspections** of the accessible parts of heating systems, **ventilation systems** and air-conditioning systems, including any combination thereof, with an effective rated output of **over 70 kW.** The effective rating of the system shall be based on the sum of the rated output of the heat generators and cooling generators." This part does not concern individual households, which usually stay below 70 kW. However, it may be applied to multi-family buildings, for which the sum of the power for heating, ventilation and air-conditioning systems may exceed 70 kW. An inspection every 5 years is required if the effective rated output is between 70 kW and 290 kW, and every 3 years if it is above 290 kW (Article 23-3).

4.2.3. European standards

Three European standards and one technical report are relevant for ventilation system inspections.

In EN 16798-17:2017 (EN 16798-17:2017: Energy performance of buildings-Ventilation for buildings-Part 17: Guidelines for inspection of ventilation and air conditioning systems) and CEN/TR-16798-18:2017 (CEN/TR 16798-18:2017: Energy performance of buildings - Ventilation for buildings - Part 18: Interpretation of the requirements in EN 16798- 17 - Guidelines for inspection of ventilation and air- conditioning systems), guidelines are given for inspection of ventilation systems, distinguishing the following steps:

- **Pre-inspection**: consist of consulting the building reference documents mentioning the ventilation system
- **Functional checks:** consist of several visual checks of the system
- **Functional measurements:** consist of airflow and pressure measurements
- **Special measurements:** consist of measurements aimed at explaining any problem detected by the functional measurements

EN 14134:2019 (EN 14134:2019 Ventilation for buildings — Performance measurement and checks for residential ventilation systems) details the inspection protocol for residential buildings, keeping the steps mentioned above. EN 16211:2014 (EN 16211:2024: Ventilation for buildings - Measurement of air flow rates on site - Methods) concerns the method for air flow measurement.

In these standards, no specific part relevant to smart ventilation systems is included. However, the inspection steps used in EN 16798-17:2017 and EN 14134:2019 are basic principles and should also therefore apply to smart ventilation systems inspection as well.

4.3. Reference to smart ventilation in existing protocols

Several protocols to inspect ventilation systems exist, for example 34 and 20 protocols were studied respectively in (COMMISSION, EUROPEAN; INIVE; BPIE, 2020) and (Leprince & Hurel, Inspection of ventilation systems-summary of existing protocols and technical survey, 2021).

To focus on smart ventilation inspection, a survey was conducted among the members of the IEA-EBC Annex 86/ST4, asking for the inspection reference document in different countries and if a part specific to smart ventilation is included. The results are detailed in Appendix 3. The AIVC papers relevant to ventilation systems inspection were also studied (Linares-Alemparte, García-Ortega, & Feldman, 2024) (Coggins, McIntyre, Jones, & McGrath, 2024) (Leprince, Mouradian, & Guyot, Ventilation Information Paper n° 48.2 - Trends in building ventilation requirements and inspection, 2024) (Janssens, De Jonge, De Strycker, & Van Gelder, 2024). The results are presented in Table 4-2.

In this table, it appears that only Belgium and France include a part specific to smart ventilation inspection, when most countries (UK, Netherland, Austria, Denmark, Ireland, Spain) do not mention it.

Table 4-2 Inspection protocols for smart ventilation in different countries (from the survey + AIVC papers (Linares-Alemparte, García-Ortega, & Feldman, 2024), (Coggins, McIntyre, Jones, & McGrath, 2024), (Leprince, Mouradian, & Guyot, Ventilation Information Paper n° 48.2 - Trends in building ventilation requirements and inspection, 2024), (Janssens, De Jonge, De Strycker, & Van Gelder, 2024))

Country	Inspection reference document	Type	Reference to smart ventilation
Belgium (Janssens 2024)	General document : *STS-P 73-1 Systèmes pour la ventilation de base dans les applications résidentielles* Specific documents to compute *f_reduc*, for example for Brussel : *Annexe 1 : Détermination des facteurs de réduction pour la ventilation (pour les systèmes de ventilation à la demande) dans les bâtiments résidentiels (PER)*	Regulatory	**Yes**
France (Leprince et al. 2024)	Protocol RE2020	Regulatory	**Yes**
UK	Building Standards technical handbook 2017: domestic buildings Section 3.14 Ventilation - Mandatory Standard	Regulatory	No
Netherlands	*Dutch building code*	Regulatory	No
Austria	*Passive House certification*	Voluntary label	No
Denmark	*The nationwide VENT scheme*	Other	No
Ireland (Coggins et al. 2024)	*National Standards Authority of Ireland Ventilation Validation Registration Scheme*	Regulatory	No
Spain (Linares-Alemparte, García-Ortega, & Feldman, 2024)	*UNE 171330-2: 2014: Calidad ambiental en interiores. Parte 2: Procedimientos de inspección de calidad ambiental interior.*	Regulatory	No

In Belgium, a parameter corresponding to a reduction factor related to smart ventilation can be taken as default or estimated through an inspection requiring:

- To check which inlet and outlet are regulated and if the user can also manually activate the system
- To measure the air flow and compare it to a minimum value
- To compare the uncertainties of the sensors (by checking the model of the sensors) against reference values.

In France the humidity DCV systems went through an agreement certificate ("*avis technique*") by a public establishment to prove that, between a minimum and maximum pressure at Air Terminal Devices (ATD), the airflow is correctly controlled by humidity, with a mechanical technology (no sensor). The system is then inspected by checking that the pressure at ATD is between the minimum and maximum pressure. Therefore, this is a specific case that can not apply to a DCV with sensors.

In the Netherlands, there is no reference to smart ventilation in the regulatory protocol. However, in practice some consultancy firms (see survey answers) inspect smart ventilation systems by manually setting the maximum airflow rate before airflow measurements and by continuously measuring IAQ parameters (CO_2 & RH).

4.4. Points of attention for an inspection protocol for smart ventilation

Finally, the points of attention to elaborate an inspection protocol for smart ventilation are discussed in this section. The last question of the survey gathered the opinions of the IEA-EBC Annex 86/ST4 members, which served as the primary source of information, alongside the perspectives of the authors and reviewers of this document. The scope of this part is restricted to ventilation systems controlled by IAQ sensors.

Before continuing, it is important to acknowledge that **a ventilation system should be designed with a specific inspection method**. For example, if the maximal airflow rates are to be measured, or if the verification needs to adjust the sensor at a specific setting point, the procedures must be practicable and well described.

Furthermore, the first step for smart ventilation inspection shall always consist of checking the documentation, as mentioned in the European standards (see paragraph 4.2.3, e.g., certification of products, calculation notes, etc.).

4.4.1. Control strategy check: continuous or punctual measurements

To inspect the control strategy, two different principles were identified:

- Means based verification: Measure airflow rates, without measuring the IAQ induced by these airflow rates
- Performance based verification: Measure the IAQ, i.e., the performance of the ventilation system, without measuring the airflow rates that led to this IAQ.

Based on these two principles, four inspection approaches can be distinguished, including four comparison criteria:

- **Installation conformity**: checking of the installation without the control system
- **Control strategy:** verify that the control strategy parameters are respected
- **Manual setting:** “yes” if some manual operation is necessary to proceed to the checking, “no” otherwise (this criterion is important because a manual operation comes with a risk, for example, to forget unsetting it)
- **Time/Cost:** three indicative levels (+, ++, +++).

The four approaches in Table 4-3 are presented in a decreasing level of precision. The two first approaches (1 and 2) are combining the means-based and performance-based principles. Approach 3 is only performance-based and Approach 4 is only means-based.

Approach 1 consists of measuring continuous flow rates and IAQ parameters. This is the only way of correctly checking the control strategy, however it is not realistic nowadays for residential buildings with common measurement devices.

Approach 2 consists of spot measurements of maximal or nominal flow accompanied with continuous IAQ measurement. This approach will indirectly notice any major dysfunction by observing the consequences on the pollutant concentration. Measuring the maximal or nominal flow rate implies manually changing the setting of the ventilation system. It allows the inspector to check that the ventilation system without smart control is functioning correctly. However, it creates a risk of malfunctioning if the original setting is forgotten. This approach has already been used by a consultancy firm in the Netherlands (as reported in the survey).

Table 4-3 Approaches to inspect smart ventilation control

Approach description			Comparison criteria			
Approaches	Measurement	Periodicity	Installation conformity check	Control strategy check	Force manual setting	Time / cost
Approach 1 **Ideal**	Flow rate IAQ measurements	Continuous Continuous	Yes	Yes	No	+++
Approach 2 **Optimal**	Maximal or nominal flow rate IAQ measurements	Spot/discrete Continuous	Yes	Allows to observe major problems	Yes	++
Approach 3 **Performance based**	IAQ measurements	Continuous	Partially	Allows to observe major problems	No	++
Approach 4 **Airflow only**	Maximal or nominal flow rate	Spot/discrete	Yes	No	Yes	+

Approach 3 is entirely performance based and consists of continuous IAQ measurements only. This approach does not require any manual change to the ventilation system settings. However, in case of bad IAQ results, it does not give information regarding the origin of the problem.

Finally, approach 4 is entirely means-based and consists of manually setting the flow rate to a maximal or nominal flow rate. This approach allows the inspector to check that the ventilation system without smart control is functioning as expected but does not give any information on the control strategy. This approach is proposed for DCV inspection in the protocol PromevenTertiaire (ADEME, 2022), which is the reference for non-residential ventilation inspection in France.

4.4.2. Sensors check

The sensors are a specific part of a smart ventilation system and questions are raised about their inspection. Two steps for sensor inspection are distinguished below: the first step should be feasible now while the second step is a long-term perspective.

Step 1: Functional checks: verifying installation/location of sensors

The installation and location of sensors shall be compared to the plans by the inspector. It would allow them to see installation problems and to note which room has ventilation controlled by sensors (for example, if there is a sensor in the living room, pollutant concentrations in the bedrooms are not guaranteed).

Step 2: Functional measurements: sensors accuracy / calibration

The accuracy of a sensor is given by the manufacturer. However, how will it evolve over time? Moreover, calibration is also a challenge. For example, VOC sensors are often characterized with one reference gas, whereas they measure several. For CO_2 sensors, an auto-calibration is often used, assuming that the CO_2 concentration in the room goes down to 400 ppm every week or every two weeks. This creates problems for dwellings that do not have lengthy periods without occupants - such as elderly households, or those with small children. Concerning PM sensors, their accuracy allows them to be used for a qualitative approach to highlight changes in concentrations but not to control ventilation to date. How much detail of sensor verification is necessary? These questions remain unanswered and should be considered in the long term, but they are too advanced for the actual problematics.

4.5. Conclusion

To conclude, inspection of stand-alone smart ventilation systems in residential buildings is rarely practised at the present time. If the share of smart ventilation systems in residential buildings were to increase, their inspection would be a major but necessary challenge. Notably, inspecting the control strategy and the sensors raises a number of challenges. However, the traditional ventilation systems inspection is already complicated, and not always achieved in practice. Another priority will be the improvement of the traditional ventilation systems inspection.

5. Conclusion and perspectives

The literature review on performances of smart ventilation in residential buildings (Deliverable 41a) evaluates 44 papers published from 2017 to 2023, on smart ventilation in residential buildings and shows that new developments have emerged. Belgium, France, and the US are the top three countries where smart ventilation studies have been conducted. Single-family houses and apartment units are the most investigated building types. Over the past seven years, smart ventilation concepts have been applied to some new areas, such as ventilation for cooling and hybrid ventilation. The use of DALYs to estimate the health impacts of operating DCV is also a new development, as it allows for direct health impacts and resulting health care/financial impacts to be analysed. Most studies consider that outdoor air is always cleaner than indoor air and that it is suitable to dilute indoor pollutants, but only a limited number of studies point out that this is not always the case. The analysis of IAQ indicators has revealed that, in addition, to the most widely used parameters of RH and CO_2, other IAQ parameters have been used to indicate the air quality, for example, HCHO, $PM_{2.5}$, and TVOC. The DALYs approach to estimating the health impacts shines a light on the importance of balancing energy savings and the IAQ. The challenge related to the diversity of input data and the performance indicators was highlighted by this literature review. Though the research in this area has rapidly grown, a standardized approach to assessing ventilation performance is lacking, as is the field testing of the proposed strategies.

The state on the use of performance-based approaches for residential ventilation in 2024 (Deliverable 41b) shows that even if the topic is not new in some countries, it will not be going away any time soon either. A number of scientific hurdles are still in place, despite the research carried out as part of the IEA-EBC Annex 86 project. Secondly, as regards the national standards and regulations that are responsible for transferring this research into the real world, feedback from Spain and France highlights all the remaining barriers: political barriers, as well as technical barriers such as the issue of regular inspections to check that the expected performance is achieved throughout the life of the ventilation system.

The common exercise demonstrated that an internationally based performance-based approach is possible and was developed to assess smart ventilation multicriteria performance, as described in the Deliverable 42a. This approach was tested and used in a common exercise conducted by experts in six countries with different design contexts, simulation software, smart ventilation strategies and building geometries. The analysis of results performed by indicator and contributor in different countries showed: (1) how a performance-based approach using different performance indicators can be used to assess the performance of smart ventilation strategies and (2) how these smart strategies perform compared to standard ones.

The short investigation report on Accuracy, durability and occupant interaction in smart ventilation strategies (Deliverable 4.2b) concluded there is a need to:

- Secure even more the performances of the smart ventilation systems over the ventilation lifetime – assessed to be around 20/30 years.
- Implement requirements for sensors and actuators accuracy and longevity.
- Secure long-term performances through adapted inspection protocols including a check of sensors and actuators.
- Encourage new research on the impact of occupant interaction on smart ventilation performances.

The short investigation report on Inspection protocols for stand-alone smart ventilation systems in residential buildings (Deliverable 4.3) concludes that inspection of stand-alone smart ventilation systems in residential buildings is rarely practised at the present time. If the share of smart ventilation systems in residential buildings were to increase, their inspection would be a major but necessary challenge. Notably, inspecting the control strategy and the sensors raises a number of challenges. However, the classical ventilation systems inspection is already complicated, and not always done. Another priority will also be the improvement of the classical ventilation systems inspection.

As a perspective, another step of analysis in the common exercise will be conducted using more standardized conditions in order to compare performances of these different smart strategies under different climatic and boundary conditions, using one identical building model and only one modelling tool.

In the future, it will be necessary to include future climates and pollution scenarios, new indicators such as thermal comfort, and to test the performance of intelligent ventilation strategies with multiple geometries and occupant scenarios, representative of different countries around the world. Next, this research work needs to be transferred to the various national regulations, in collaboration with the various players involved, including building construction and ventilation manufacturers. Finally, the question of how to guarantee initial performance through initial commissioning, and the durability of performance, remains a topical issue.

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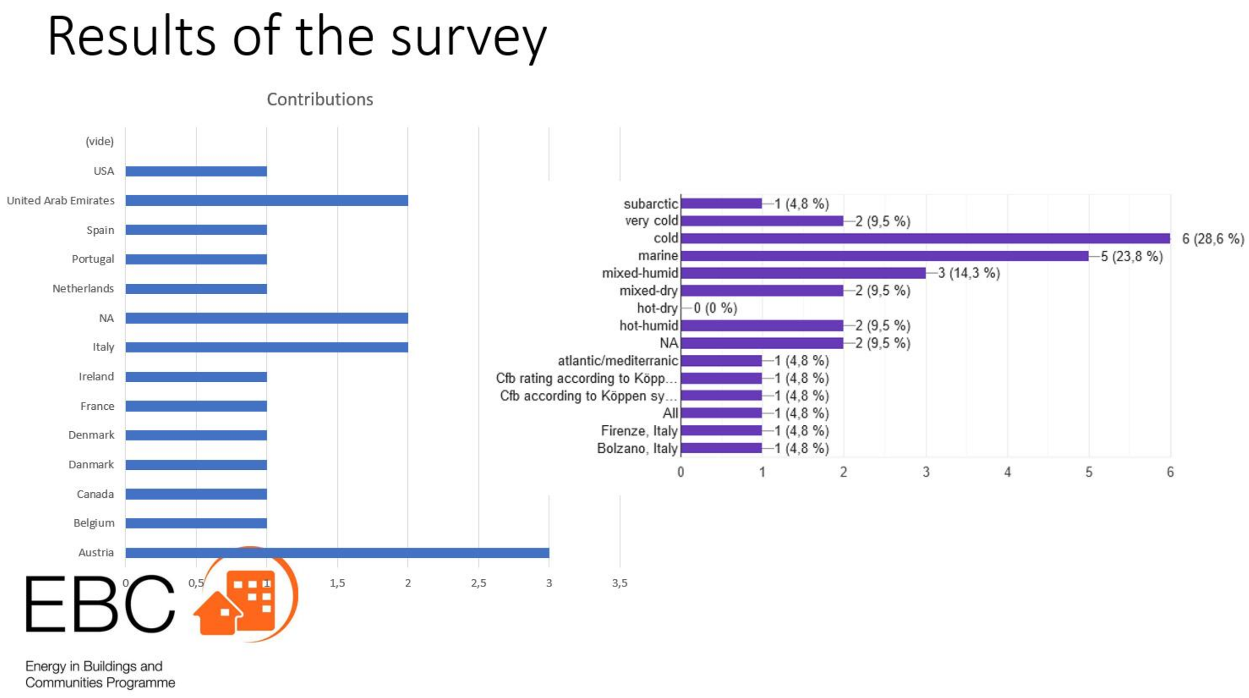
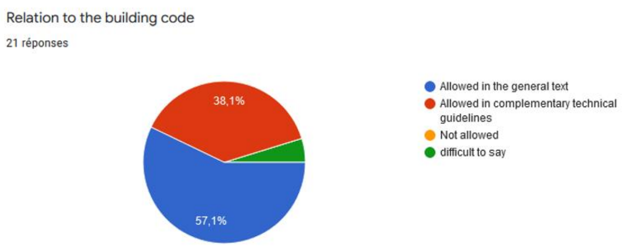
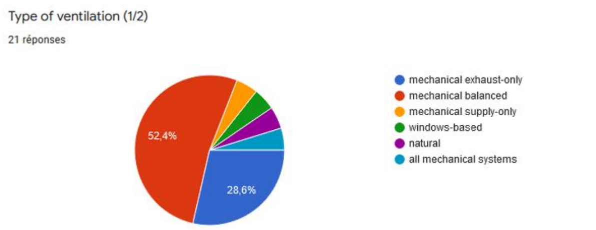
8. Appendices

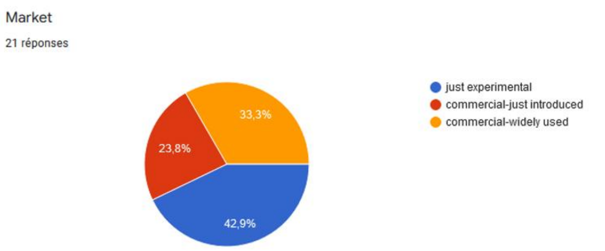
8.1. Appendix 1 - Results of the ST4 survey January 2022

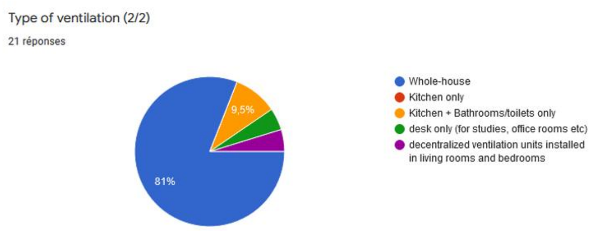
Survey regarding smart ventilation control strategies conducted among Annex 86 participants. Results presented at Annex 86 expert meeting in Athens, May 2022.





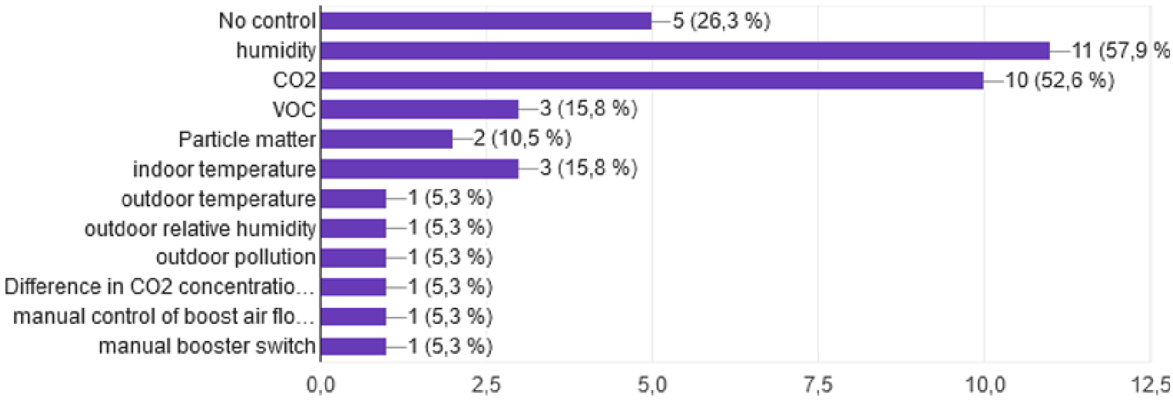






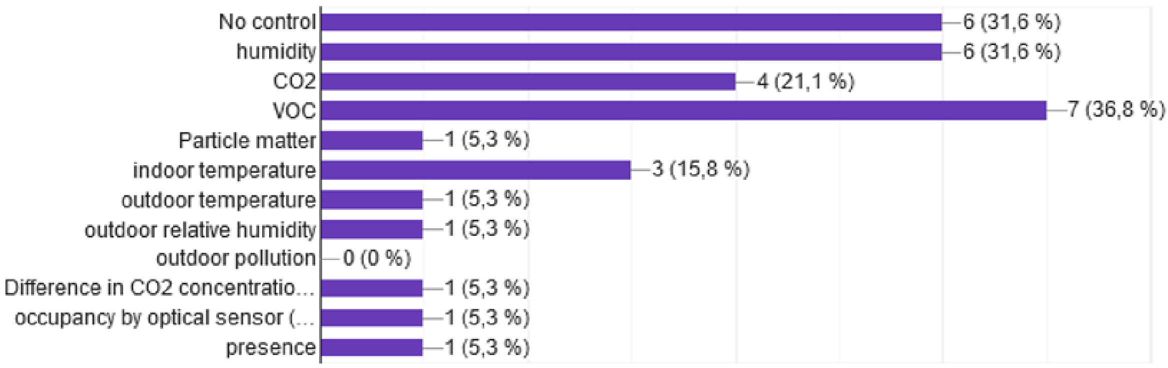
Type of control parameters - kitchen

19 réponses



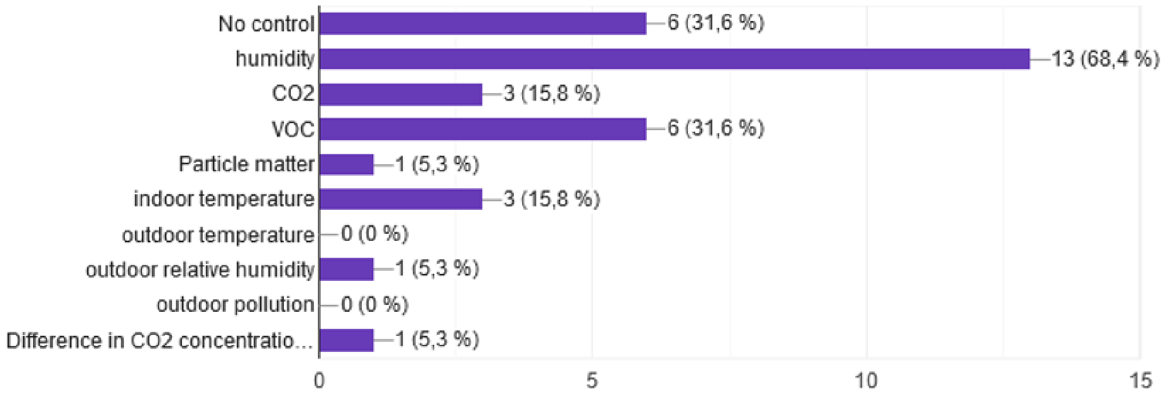
Type of control parameters - toilets

19 réponses



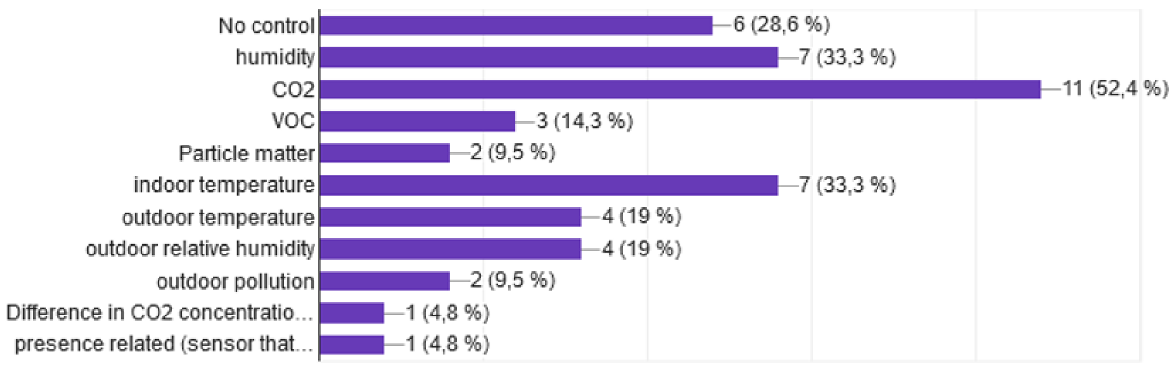
Type of control parameters - bathrooms

19 réponses



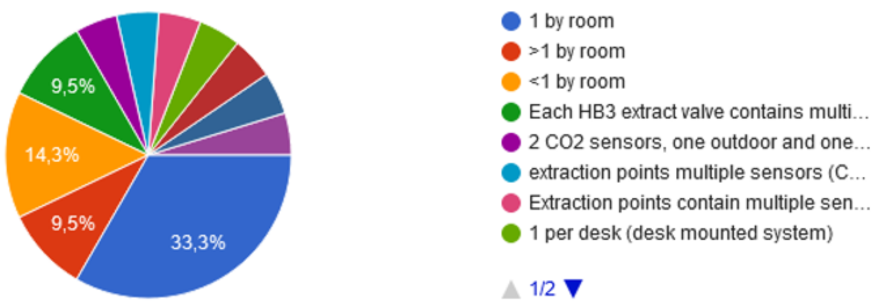
Type of control parameters - bedrooms

21 réponses



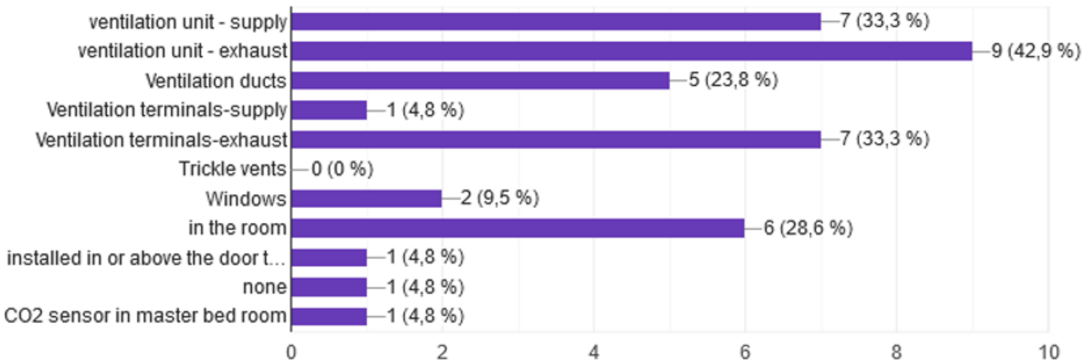
Amount of sensors (for the whole dwelling)

21 réponses



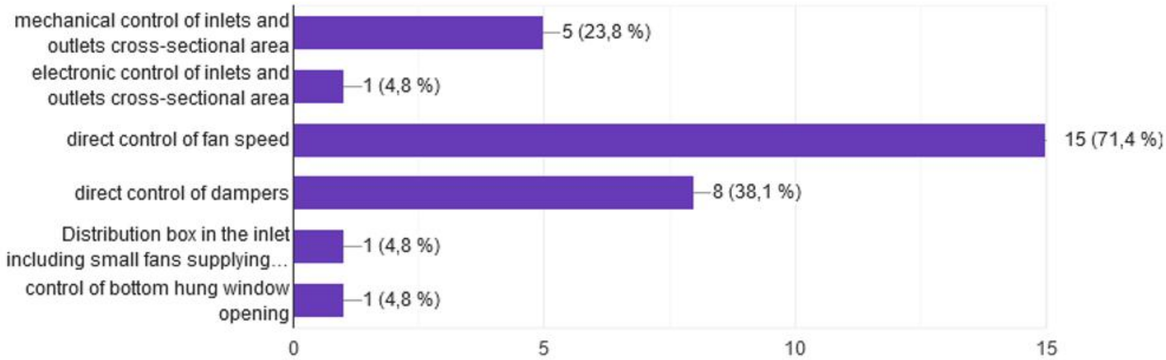
Location of sensors

21 réponses



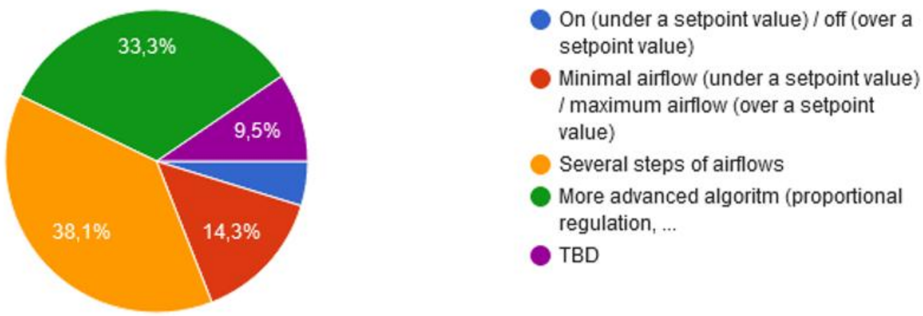
Type of control and components that are controlled

21 réponses



Control algorithm (1/2)

21 réponses



8.2. Appendix 2 - Smart ventilation. First common exercise. Instructions and template for collection

ST4 smart ventilation - 1st common exercise

Instructions & Template for data collection from the common exercise

"Rating existing smart ventilation strategies"

By Gaëlle Guyot, Jakub Kolarik, Hilde Breesch, Klaas De Jonge, Baptiste Poirier, Douaa Al Assaad, Maria Justo Alonso

Instructions

1. Context and objectives

Each country has its specific approach regarding design of residential ventilation. This includes both "standard" ventilation strategies and "smart"[1] ventilation strategies. In this common exercise, we would like (1) to show how different performance-based approaches using different performance indicators can be used to assess performance of "smart" ventilation strategies in different countries and (2) to compare these "smart" strategies with the traditional/standard ones.

The objectives of this exercise are:

- To demonstrate the application of performance-based approach for the assessment of residential ventilation performance, including smart as well as traditional ventilation strategies, across the participating countries.
- To form a basis for creation of generally acceptable rating scheme for performance-based assessment of residential ventilation.
- To investigate its applicability in different countries, design contexts, with different simulation software, smart ventilation strategies, building geometries, etc.
- To conduct a qualitative assessment, identifying the challenges, barriers, advantages and disadvantages regarding application of performance-based evaluation in the context of different countries, their building codes and design-construction traditions. Consequently, to define common trends regarding challenges & barriers as well as benefits.

2. The workflow

For the common exercise, you are free to use an existing simulation case (building geometry, software, weather data, etc…). We would like you to conduct a performance analysis of the (smart) ventilation strategy in this simulation case study and use the performance indicators and methods described below. You can choose "smart" ventilation strategy/strategies; as well as the standard strategy for a reference. What we use in common are the performance indicators. You do the comparison to a "reference case", which has a country specific relevance, and we, as a group, do the qualitative analysis of the usability of performance-based approaches and associated performance indicators. This analysis will include a synthesis of experiences, observations, identified barriers and challenges reported by all involved participants.

3. Contaminants

To be able to produce the desired outputs, the following contaminants should be included (**those marked with (*) are optional, but we strongly encourage simulating as many as possible**):

- CO_2 (human breathing)
- Humidity (human breathing, events)
- $PM_{2.5}$ (Outdoor concentration, events)
- Formaldehyde (Indoor sources, events)
- Fictive pollutant constantly and continuously emitted in each zone (Cf ASHRAE 62.2) (*)

[1] According to the AIVC: "Smart ventilation is a process to continually adjust the ventilation system in time, and optionally by location, to provide the desired IAQ benefits while minimizing energy consumption, utility bills and other non-IAQ costs (such as thermal discomfort or noise). (…)".

4. We need to collect as output data:

1. **The concentrations profiles** (Raw time-series data), at least: CO_2 and relative humidity
   - Preferably In all the rooms
   - at least in
     - the bedroom with the highest occupancy
     - the living room
     - the kitchen
2. **The exposure concentrations profiles** (Raw time-series data), at least:
   - $PM_{2.5}$
   - formaldehyde
   - fictive pollutant

   At least for two occupants (as occupants should differ in their presence patterns in particular rooms).
3. Following performance indicators should be determined (**those marked with (*) are optional, but we strongly encourage determining as many as possible**) (Formulas in Annex 2):
   - DALY (chose one of calculation methods from the Annex 2)
   - CE_{CO2}: cumulative CO2 exposure when exposure concentrations are higher than a threshold ppm in a room
   - P_{CO2}: 95th percentile
   - T_{RH}: % of time spent out of the range [25-60%][2]
   - E_{HCHO}: cumulative occupant exposure
   - $E_{fictive}$: cumulative occupant exposure
   - $E_{PM2.5}$: cumulative occupant exposure
   - E_{HCHO_acute}: maximum of the cumulative occupant exposure over 1hour
   - $E_{fictive\_acute}$: maximum of the cumulative occupant exposure over 1hour
   - $E_{PM2.5\_acute}$: maximum of the cumulative occupant exposure over 1hour
   - ACH: Average building ACH due to ventilation
   - If possible (voluntary), for the ones who can/are interested in (it will be further investigated for the second exercise in one-two years):
     - Energy losses due to ACH ventilation (*)
     - Fan electric consumption over the year (*)
     - Exposure to a pollutant emitted only in toilets (odour) (*)
     - 30 day average RH on a thermal bridge (*)
     - Thermal discomfort indicator (*)
4. **Calculation period**: the whole ventilation operating period depending the contexts:
   - Typical Heating period where there is no cooling with outdoor air supply. The heating period can extend to the "fee floating" period where neither heating nor cooling is used.
   - Whole year if there is a cooling system with outdoor air supply and heating system
   - Typical cooling period where there is no heating period
5. **Time step**: If possible 10-15 min (max. 1 hour).

5. We need that you fill out the tables of Annex 1

6. Where to upload your contributions?

- *The output data listed in [b] :*
  - *On TEAMS : Documents/ ST4 Smart ventilation/Activity 4.1/CommonExercise/Studycases_Output*
- *This document with tables from Annex 1 fulfilled:*
  - *On TEAMS : Documents/ ST4 Smart ventilation/Activity 4.1/CommonExercise/Studycases_Docs*
- *The modelling and scripts files (if you agree):*
  - *On TEAMS : Documents/ ST4 Smart ventilation/Activity 4.1/CommonExercise/Studycases_Files*

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[2] EN 16798 category II

8.2.1. Annex 1 - Tables to use for gathering the data (one table 2.a and one table 2.b per case study):

Contributor (name, country, Institute, date) :

……………………………..……………………………………………

……...

Case Study (name, short description, sim. software used, reference for more details) :

……………………………..……

……...

Inputs

Occupancy patterns : who is where when ?	Example : <table><tr><th>Room</th><th>Occupant 1</th><th>Occupant 2</th><th>Occupant3</th></tr><tr><td>Bedroom</td><td>21h00-6h20</td><td>21h00-6h20</td><td>21h00-6h20</td></tr><tr><td>Bathroom</td><td>6h20-7h00</td><td>7h00-7h40</td><td>20h20-21h00</td></tr><tr><td>Kitchen</td><td>7h00-7h20 12h00-12h40 19h00-20h10</td><td>6h20-6h40 12h00-12h40 19h00-20h10</td><td>6h20-6h40 12h00-12h40 19h00-20h10</td></tr><tr><td>Livingroom</td><td>7h20-8h30 12h40-14h00 20h10-21h00</td><td>6h40-7h00 7h40-8h30 12h40-14h00 20h10-21h00</td><td>6h40-8h30 12h40-14h00 20h10-20h20</td></tr></table>
Emission scenarios for CO2	*Example : CO_2 awake / asleep: 18 / 15 $L.h^{-1}$*
Emission scenarios for humidity	*Example : H_2O awake / asleep: 55 / 40 $g.h^{-1}$* *Breakfast / lunch / dinner: 1512 / 2268 / 2844 $g.h^{-1}$* *During 15 / 30 / 40 minutes*
Emission scenarios for HCHO	*Example : In each room 12$\mu g.h^{-1}.m^2$ (m² floor area)*
Emission scenarios for PM	*Example : Cooking event: 1.91 $mg.min^{-1}$ During 28 minutes, at 12:00 and 18:00*
Emission scenarios for fictive	*Example : In each room 10 $\mu g.h^{-1}.m^2$ (m² floor area)*
Weather file used	*Example : London TRY weather file*
Simulation period	*Example : Heating period from October 15, 00:00 a.m to April 14, 12:00 p.m (French one)*
Outdoor pollution	*Example : We assumed a constant outdoor concentration of CO_2 at 400 ppm; 2.6 $\mu g.m^{-3}$ for formaldehyde based on average concentration in European cities (Bruinen de Bruin et al. 2008) and 10.6 $\mu g.m^{-3}$ yearly average concentration for $PM_{2.5}$ in*

	Copenhagen between 2015 and 2020 calculated from weather data measurement (« Annual AQ statistics » s. d.).
Air leakage distribution	*Example :* *envelope airleakage of n_{50}=1.5h^{-1}, evenly distributed over the envelope depending the ratio of external surfaces,* *evenly distributed airleakage on internal partition walls: q_{50}=1.2 m^3.h^{-1}.m^{-2} (from Guyot et al. 2016 for heavy structures)*
Position of internal doors	*Example : all closed, an undercut of 1 cm² is modelled*
Position of windows	*Example : All closed*
…	
…	

Modelling data

	Model	Associated parameters asumptions / schedules
Moisture absorption/desorption		
PM deposition/resuspension Penetration factor		
HCHO dependence to T°C and RH		
Position of doors and associated models		
Position of windows and associated models		
Wind pressure / microclimate around the building		
Airflows through natural ventilation components		
…		
…		
…		
…		
…		
…		

Description of the ventilation strategies and components

Type of ventilation (whole house ?, mechanical exhaust-only/balanced/supply only, windows-based, etc.)	
Type of control parameter (humidity, CO_2, VOC, outdoor conditions, a combination, etc.)	
Amount of sensors	
Location of sensors (rooms – which rooms?, ducts, …)	
Type of measuring technology for sensors (Ex : CO2 : NDIR), or reference and name of producer, and associated accuracy and range of measurement	
Type of control and components that are controlled (mechanical or electronic of inlets and outlets cross-sectional area, direct control of fan speed, of dampers, …)	
Control algorithm (value of set points + associated airflows + rules, etc…)	
Airflows through mechanical exhaust vents	
Airflows through mechanical suppliers	

Qualitative Feedbacks

Feedback on proposed metrics o What did you like, what didn't you like and why? o Are some of these metrics used in your country? Which ones ? Are they required/incorporated in the building code? o To what extent are these metric relevant given the context you work in. o Are these metric relevant for practice in your country? Will there be expertise and tools available among the practitioners? o Suggestions for expanding the framework? (other IAQ aspects, non-IAQ costs?) o Suggestion for simplification?	*Free answer ….*
List of barriers and problems met during the exercise	*Free answer ….*
List of warnings	*Free answer ….*
List of advantages	*Free answer ….*

Conclusions on the applicability of the method	*Free answer ….*
Major needs	*Free answer ….*
Other important comments	*Free answer ….*

8.2.2. Annex 2 – Formulas for the calculation of performance indicators

Remember the calculation period and time-step are described in 1. Instruction [d]

DALYs

The long-term health effects of indoor air contaminant exposure can be quantified using Dynamic Disability-Adjusted Life Years (DALYs)[3]. The total health impact is the sum of all DALYs, regardless of the method used to calculate the DALYs. Dynamic DALYs can be calculated as:

$$DALYs(t) = \int_{t_0}^{t} \frac{DALYs}{time}(t)$$

$$\frac{DALYs}{time}(t) = EF_{marginal} * IR(t)$$

$$IR(t) = V_{br}(t).C_{exp}(t)$$

Where

- $DALYs(t)$ is the cumulative Dynamic DALYs function
- IR(t) [kg/s] is the Intake rate
- $V_{br}(t)$ is the breathing rate over time, default a value of 16m³/day may be assumed [4] (this parameter can be varied based on the occupant's metabolism).
- $C_{exp}(t)$ is exposure concentration profile
- EF [DALY/kg] is the Effect factor[5] (From ST1, this function is made easier, linear and independent of ID or IND method).

		95% Confidence interval (CI)	
	EF marginal (median) [DALY/kg]	CI_2.5% [DALY/kg]	CI_97.5% [DALY/kg]
PM2.5	118.6111038	28.32760334	502.3125065
Formaldehyde	18.0350555	3.518138613	94.1348335

E_{CO2}: normalized cumulative exposure when concentrations are higher than 1000 ppm in a room

For rooms *r* in the building:

$$E_{CO2\_r} = \frac{\sum_{t=0, occupied\ hours}^{d} (C_{CO2\_r}(t) - 1000).\Delta t}{d}$$

Equation 1

With $C_{CO2\_r}(t)$ the CO_2 exposure concentration (only when the room is occupied) in *[ppm]* in the room *r* at time step *t* , *d* the total duration of the simulation, and Δt the time step of simulation.

[3] 2022/08 - Unpublished so must be treated confidential until correct reference can be made.

[4] U.S. EPA. Exposure Factors Handbook 2011 Edition (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-09/052F, 2011, https://www.nrc.gov/docs/ML1400/ML14007A666.pdf.

[5] P. Fantke *et al.*, "Global Effect Factors for Exposure to Fine Particulate Matter," *Environ Sci Technol*, vol. 53, no. 12, pp. 6855–6868, Jun. 2019, doi: 10.1021/acs.est.9b01800.

P_{CO2}: 95th percentile

The 95th percentile must be calculated of the CO2 exposure concentrations (only when the room is occupied).

E_{RH}: % of time spent out of the range [25-60%]

For rooms *r* in the building:

$$E_{RH\_r} = \frac{100}{d} \sum_{t=0}^{d} \Delta t \begin{cases} if\ RH\_r(t) > 60\% \\ if\ RH\_r(t) < 25\% \end{cases}$$

Equation 2

With $RH_{\_r}$ *(t)* the relative humidity in *[%] of* the room *r* at time step *t*, *d* the total duration of the simulation, and Δt the time step of simulation.

E_{HCHO}: cumulative occupant exposure

For occupants *o* in the building:

$$E_{HCHO\_o} = \sum_{t=0}^{d} C_{HCHO\_r,o}(t).\Delta t$$

Equation 3

With $C_{HCHO\_r,o}$ *(t)* the HCHO concentration in *[µg.m*$^{-3}$*] of* the room *r* where the occupant *o* is at time step *t*, *d* the total duration of the simulation, and Δt the time step of simulation.

$E_{fictive}$: cumulative occupant exposure

For occupants *o* in the building:

$$E_{fictive\_o} = \sum_{t=0}^{d} C_{fictive\_r,o}(t).\Delta t$$

Equation 4

With $C_{fictive\_r,o}$ *(t)* the fictive pollutant concentration in *[µg.m*$^{-3}$*] of* the room *r* where the occupant *o* is at time step *t*, *d* the total duration of the simulation, and Δt the time step of simulation.

$E_{PM2.5}$: cumulative occupant exposure

For occupants *o* in the building:

$$E_{PM2.5\_o} = \sum_{t=0}^{d} C_{PM2.5\_r,o}(t).\Delta t$$

Equation 5

With $C_{PM2.5\_r,o}$ *(t)* the HCHO concentration in *[µg.m*$^{-3}$*] of* the room *r* where the occupant *o* is at time step *t*, *d* the total duration of the simulation, and Δt the time step of simulation.

E_{HCHO_acute}: maximum of the cumulative occupant exposure over 1hour

For occupants *o* in the building:

$$E_{HCHO_{acute\_o}} = max\left(\sum_{t=0}^{1h} C_{HCHO\_r,o}(t).\Delta t\right)$$

Equation 6

With $C_{HCHO\_r,o}$ *(t)* the HCHO concentration in *[µg.m*$^{-3}$*] of* the room *r* where the occupant *o* is at time step *t*, and Δt the time step of simulation.

$E_{fictive\_acute}$: maximum of the cumulative occupant exposure over 1hour

For occupants *o* in the building:

$$E_{fictive\_acute\_o} = max\left(\sum_{t=0}^{1h} C_{fictive\_r,o}(t).\Delta t\right)$$

Equation 7

With $C_{fictive\_r,o}$ *(t)* the fictive concentration in *[µg.m*$^{-3}$*] of* the room *r* where the occupant *o* is at time step *t*, and Δt the time step of simulation.

$E_{PM2.5\_acute}$: maximum of the cumulative occupant exposure over 1hour

For occupants *o* in the building:

$$E_{PM2.5\_acute\_o} = max\left(\sum_{t=0}^{1h} C_{PM2.5\_r,o}(t).\Delta t\right)$$

Equation 8

With $C_{PM2.5\_r,o}$ *(t)* the $PM_{2.5}$ concentration in *[µg.m*$^{-3}$*] of* the room *r* where the occupant *o* is at time step *t*, and Δt the time step of simulation.

ACH: Average building ACH due to ventilation

Energy losses due to ACH ventilation (voluntary)

Calculation ventilation heat loss for the time when heating (or mechanical cooling) system is in operation.

From (Abadie et al. 2017)[6]:

$$Q_{heat\_loss} = C_{p_m}.q_m.\left(1 - \varepsilon_{heat_{ex}}\right).(T_{in} - T_{ex})\ [kJ]$$

Equation 9

With q_m the total exhaust mass airflows in *[kg.s*$^{-1}$*]*, C_{pm} the thermal mass capacity of air (we used 1 $kJ.kg^{-1}.°C^{-1}$), $\varepsilon_{heat_{ex}}$ the heat exchanger efficiency. We can use for example a constant theoretical efficiency rate of 0.8 for ventilation with

[6] Abadie, M. Wargocki, P. Rode, C. Rojas, G. Kolarik, J. Laverge, J. Cony, L. Qin, M. et Blondeau, P. (2017). Indoor Air Quality Design and Control in Low-energy Residential Building Subtask 1: Defining the metrics. IEA Annex 68

heat recovery and 0 with no heat recovery and this value can be adjusted depending on the systems design. T_{in} the zone temperature where the air is extracted, and T_{ex} the external temperature *[°C]*.

Optionally, it is also possible to provide results as total energy consumption for particular simulated cases including heating/ cooling consumption.

Fan electric consumption over the simulation period (voluntary)

According to ASHRAE Standard 90.1 :

$$P_{fan}(t) = P_{fan} \,.\, P_{nom}$$

Equation 10

$$P_{nom} = Qmax\ .SFP$$

Equation 11

$$P_{fan} = 0.0013 + 0.1470\ .\ PLR_{fan} + 0.9506\ .\ PLR_{fan}^{2} - 0.0998.\ PLR_{fan}^{3}$$

Equation 12

$$PLR_{fan} = Q(t)\ /\ Qmax$$

Equation 13

With P_{nom} the nominal power of the fan, Qmax the maximal design aiflow, SFP the specific fan power and Q(t) the current total exhaust (or supply) airflow.

Exposure to a pollutant emitted only in toilets (odours) (voluntary)

For occupants *o* in the building:

$$E_{odour\_o} = \sum_{t=0}^{d} C_{odour\_r,o}(t).\Delta t$$

Equation 14

With $C_{odour\_r,o}$ *(t)* the fictive pollutant representing odours concentration in *[µg.m⁻³] of* the room *r* where the occupant *o* is at time step *t*, *d* the total duration of the simulation, and Δt the time step of simulation.

30 day average RH on a thermal bridge (voluntary)

The **30 day average relative humidity on a typical thermal bridge** of a well designed and constructed building should be smaller than 80% RH:

$$30\ day\ average\ RH_{si} < 80\%$$

$$RH_{si} = \frac{P_w}{P_{w,sat}(\theta_{si})}$$

Equation 15

With

RH_{si} The local relative humidity on the thermal bridge

P_w The room vapor pressure

$P_{w,sat}(\theta_{si})$ The local saturation vapor pressure

θ_{si} The surface temperature on the cold-bridge

The surface temperature on the cold-bridge **could be a direct output of a BES model. Another approach is the use of the** temperature factor (f_h) to estimate the surface temperature on the cold-bridge.

A typical thermal bridge of a well-designed and well-constructed building should have a relatively high temperature factor (f_h). This means that the surface temperature lies closer to the indoor air temperature then the outdoor air temperature in steady-state conditions.

This factor can be country specific, depending on local legislation. For Belgium, a minimum temperature factor of 0.7 is required.

$$f_h = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e}$$

Equation 16

With

f_h The dimensionless temperature factor of a cold bridge

θ_{si} The surface temperature on the cold-bridge

θ_e The exterior temperature

θ_i The interior temperature

With equation 14 and 15. For each timestep, the RH_{si} can be calculated.

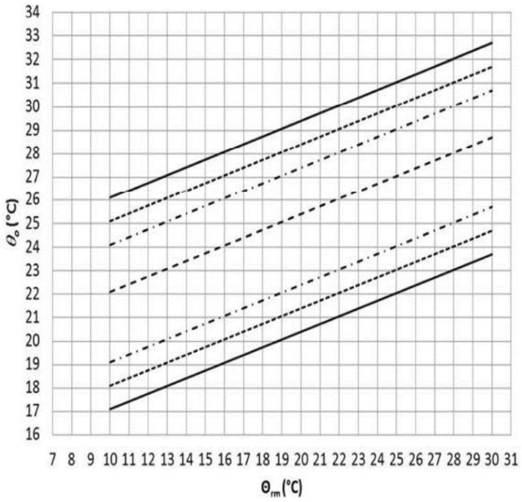
The **running 30-day average** of this output should not exceed 80%. Be careful to also include the analysis for data going past the full year (e.g. 15/dec to 15/Jan)

Thermal comfort indicator (voluntary)

The percentage of time when the thermal comfort ranges for indoor environmental category II (IEQ_{II}) according to EN 16798-1:2019 and CEN/TR 16798-2:2019 are exceeded during the simulation period. For yearly simulations the exceedance during maximum 6% time is considered acceptable.

The thermal comfort ranges are defined differently for buildings with and without mechanical cooling.

Buildings without mechanical cooling - Adaptive thermal comfort model according to EN 16798-1:2019, Annex B, section B.2.2



Key

θ_o = indoor operative temperature, °C

θ_{rm} = running mean outdoor temperature °C

Cat. III upper limit

Cat. II upper limit

Cat. I upper limit

Comfort temperature

Cat. I lower limit

Cat. II lower limit

Cat. III lower limit

Figure 1 – Default design values for the indoor operative temperature for buildings without mechanical cooling as a function of the exponentially-weighted running mean of the outdoor temperature (Figure B.1 from EN 16798-1:2019)

See also additional explanation in CEN/TR 16798-2:2019 section 6.3.2.

The following approximate Formula (1) can be used where records of daily mean external temperature are available:

$$\Theta_{rm} = \frac{(\Theta_{ed-1} + 0,8\Theta_{ed-2} + 0,6\Theta_{ed-3} + 0,5\Theta_{ed-4} + 0,4\Theta_{ed-5} + 0,3\Theta_{ed-6} + 0,2\Theta_{ed-7})}{3,8} \quad (1)$$

$\Theta_{ed\text{-}i}$ = daily mean outdoor air temperature for the *i-th* previous day

In buildings with mechanical cooling, the thermal comfort range is determined using PMV/PPD model – see EN 16798-1:2019 section B.2.1

In the case that the simulation tool does not calculate thermal comfort indices directly, they can be calculated using the CBE Thermal Comfort Tool (https://comfort.cbe.berkeley.edu/; Tartarini, F., Schiavon, S., Cheung, T., Hoyt, T., 2020. CBE Thermal Comfort Tool : online tool for thermal comfort calculations and visualizations. SoftwareX 12, 100563. https://doi.org/10.1016/j.softx.2020.100563)

8.3. Appendix 3 - Results of the survey on inspection. January 2025

Results of the survey among Annex 86 participants regarding inspection of ventilation systems in residential buildings conducted in January 2025.

A.1.Questions

Question 1: To your knowledge, is there a protocol for ventilation inspection for residential buildings in your country?

- ☐ Yes - regulatory
- ☐ Yes - voluntary label
- ☐ Yes - other
- ☐ No

Question 2: If yes, do they include a part specific to smart ventilation?

- ◯ Yes
- ◯ No

Question 3: If yes, what is the name of the protocol text, and what part of this text concerns smart ventilation? *(example for France: Protocol ventilation RE2020, p 44-45)*

Question 4: What is checked or measured for smart ventilation systems? *(example for France: for humidity DCV, pressure measurement at each ATD)*

Question 5: Regarding your feedback and expertise:

- What should we pay attention to if we want to implement an inspection for smart ventilation?

- How should traditional inspection schemes for ventilation be adapted for smart ventilation?

- What would be the technical specifications for smart ventilation?

A.2.Answers

A.2.1.Respondents

Seven answers were obtained, from the following countries: UK, Austria, India, Belgium, Netherland (two answers) and Denmark. Five respondents belonged to an University (from UK, Austria, India, Belgium), and the other respondents (from Netherlands and France) belonged respectively to a consultancy firm, a company selling ventilation systems and a technical center.

A.2.1.Answer to question 1

Yes - regulatory	No
Yes - regulatory	No

No	No
Yes - voluntary label	No
Yes - regulatory	Yes
Yes - other	No
Yes - voluntary label	No

A.2.2.Answer to question 3

Country	Answer to question 3
UK (University)	Building Standards technical handbook 2017: domestic buildings Section 3.14 Ventilation Mandatory Standard
Netherland (consultancy firm)	
India (University)	Typically, for mechanical ventilation, the rated fan flow is used to determine the airflow rates in the room (along with air change rates). For natural ventilation, there is no protocol followed either.
Austria (University)	Passive House certification (measurement and adjustment of all airflow in- / outlets and balance)
Belgium (University)	Residential: Ministrial decrees in the three Belgian regions, example for Brussels (others are identical): https://document.environnement.brussels/opac_css/elecfile/Annexe1-2023-determination_des_facteurs_de_reduction_pour_ventil_a_la_demande_PER.pdf Recognised systems are included in the EPBD product database www.epbd.be (details can be found in paper presented by A. Janssens at AIVC-conference Dublin 2024. Non-residential: Ministerial decrees in the three Belgian regions, example for Brussels (others are identical) :https://environnement.brussels/sites/default/files/user_files/amb20150506_method_peb2014_annex5_fr.pdf
Denmark (University)	
Netherlands (company selling ventilation systems)	
France (technical centre)	Protocol ventilation RE2020, p 44-45

A.2.3.Answer to question 4

Country	Answer to question 4
UK (University)	
Netherland (consultancy firm)	The ventilation systems (whether smart or not) have to comply with the ventilation rate requirements from the Dutch building code. In most cases this means the ventilation system will be set to the highest manual setting prior to conducting ventilation measurements. The ventilation rate in practice (under smart operation) does not have to be verified according to national law. If we investigate buildings with smart ventilation systems, we often make use of a combination of continuous (CO_2 & RV) measurements in combination with an assessment of the maximum available ventilation rates.
India (University)	Not Applicable.
Austria (University)	
Belgium (University)	The EPB reporter (energy auditor) declares the performances of ventilation systems in newly constructed or deeply renovated buildings after completion of construction works based on as-built data, as needs to be done for other inputs of the energy performance calculation. For smart ventilation systems (in fact demand controlled systems) the value of f_reduc is checked, and whether the applied system is a system recognised by the authorities in the EPBD Product database. If performances don't comply with energy performance or ventilation requirements, the builder has to pay a fine. In Flanders, as in all ventilation systems, the nominal mechanical ventilation flow rates need to be measured by a competent person, and are used as input in the energy performance report of the EPB reporter, details see https://www.vlaanderen.be/epb-pedia/technieken/ventilatie/kwaliteitskader-ventilatie In case of smart systems the reporter also checks the brand of the system and visually inspects if the system is correctly used.
Denmark (University)	In Denmark there exists "The nationwide VENT scheme", which offers maintenance services, which are carried out by certified companies. Technicians from VENT certified companies are specialists with high professional knowledge acquired through further education and by passing so-called the VENT exam. The webpage is here: https://vent.dk/ The scheme includes so called VENT-Basis and VENT+ Energy Check. The scheme's guidelines are available here: https://vent.dk/kunde/. VENT-Basis and VENT+ Energy Check (focus on operation and energy optimization) are conducted according to a fixed checklist, ensuring that all relevant parts of the ventilation system are measured and reviewed.
Netherlands (company selling ventilation systems)	In NL, smart ventilation are dealt with in 'gelijkwaardigheidsverklaringen', this is industry association oriented info.
France (technical centre)	For ventilation system unidirectional regulating with humidity, pressure measurement for extract air terminals

A.2.4.Answer to question 5

Country	Answer to question 5
UK (University)	
Netherland (consultancy firm)	It's important to first verify the design principle of the smart system: is it expected to guarantee sufficient indoor air quality? This can be verified by looking at the locations and specifications of the sensors used for indoor air quality monitoring. E.g. if a dwelling has CO2-controlled ventilation which is controlled by one sensor in the living room, sufficient ventilation in de the bedroom is not guaranteed. Next, it would be best to make use of continuous monitoring when conducting an inspection of spaces with smart ventilation. Technical specifications for smart ventilation should address sensor location, applicable control variables (CO2 & RH, not VOC), sensor accuracy (for instance RESET), calibration of sensors, impact of smart ventilation strategies on total ventilation rate calculation etc.
India (University)	Measuring the pressure drop across the fan and its power consumption can provide valuable feedback. These measurements, combined with the rated flow and power consumption, help estimate the airflow through the fan. Additionally, we have used CO2 measurements (and occupancy sensors, if available) to calculate air exchange rates after the occupancy period, providing insights into the ventilation rates of mechanical or HVAC systems.
Austria (University)	Correct installation and accuracy of sensing devices used for demand control, typically CO2 sensors. Air flow distribution in dwelling and overall balance should be checked at most likely air flow setting. Most likely the CO2 concentration is low during commissioning, and then distribution and balance measurements are done with low airflows only. Since system curve is not linear, the adjustments should be done for nominal/most likely conditions.
Belgium (University)	In order to create an incentive for smart ventilation, it should be taken into account in regulatory requirements, such as energy performance regulations.
Denmark (University)	Regarding the smart ventilation - I mean that the inspection schemes should include not only control of the basic functionality, but also control of the correctness of the control algorithms. This would however require long-term data collection.
Netherlands (company selling ventilation systems)	Inspection of standard ventilation units is complicated enough, and not always done. So inspection of smart ventilation systems is one step ahead, and too complicated for now.
France (technical centre)	Calibration of the pollutants sensors

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