ANNEX **86**

EBC

Energy in Building and
Communities Programme

D3 - Methods and tools for the rating of IAQ management strategies

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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 (*)

Table of content

1. Executive Summary

This deliverable is an integrated report bringing together the most important methods and tools developed in SubTasks 1-5 of Annex 86 in one document. It provides a short introduction and essential background information regarding the key findings of the subtasks. For more in depth information on each of these findings, references to further reading are included where appropriate. The references included in this document are also available as a stand-alone literature list in deliverable D.1 and through AIVC.

Indoor air quality (IAQ) has a direct impact on human health, yet most building standards still regulate ventilation without explicitly considering objectives, principles, criteria and indicators for the performance of this intervention in the IAQ. This report brings together the work of Annex 86 to address this gap, developing and applying new ways to assess the health, performance, and economic consequences of exposure to indoor air contaminants.

A first achievement is the use of Disability-Adjusted Life Years (DALYs) to measure the health burden of exposure. This approach allows contaminants to be compared on a common scale and prioritised according to the harm they cause. Particulate matter and formaldehyde emerge as dominant contributors. This methodology is outlined in chapter 2 of this report and now underpins the world's first accepted harm-based compliance pathway in ASHRAE Standard 62.2, marking a major step forward for health-focused standards.

The Annex also explored how IAQ management strategies, including but not limited to ventilation, can be assessed across multiple criteria, including IAQ, energy, cost, resilience, and robustness. Chapter 2 continues with discussions of these methods and their application. Simulations showed the trade-offs between system types, and how performance changes under both typical and high-pollution conditions. A resilience framework was developed to evaluate how systems respond to shocks such as outdoor pollution episodes, indoor source peaks, and power outages. These methods make it possible to judge not only average performance, but also reliability under stress. Economic analysis revealed the scale of socio-economic costs linked to poor IAQ. Productivity loss from Sick Building Syndrome accounts for the largest share, while chronic disease burdens are driven largely by particulate matter. Case studies show that measures such as low-emission materials, filtered ventilation, and higher airflow rates can significantly reduce these costs. Each of these examples demonstrates that, with careful selection of the appropriate criteria and indicators, performance-based assessment provides a framework to more effectively achieve the desired objectives .

As the implementation of performance-based approaches heavily relies on simulations, a second achievement is the development of 2 datasets listing available literature on sources and typical exposures/concentrations. The datasets are complemented with easy-to-use methods to check the distribution of these crucial simulation inputs, providing modelers the tools to perform uncertainty and sensitivity analysis and test the robustness of their results. The data schemas on which the datasets are created allow for the integration of both small-scale studies and large scale IoT based data collection campaigns explored in SubTask 2. The methods underpinning these datasets are discussed in chapter 3, accompanied by an example of their application for formaldehyde. This shows a remarkable agreement between the top-down and bottom-up approaches provided through both datasets. The datasets themselves, the algorithms to process the data and their access is discussed in deliverable D.2. Participants in the annex actively host open databases such as Pandora and the Global IAQ Database, perpetuating this work.

A third achievement is the proof of concept of using new, custom designed materials as active componentes of an IAQ management strategy. Chapter 4 outlines the potential of smart materials, indetifies Metal Oxide Frameworks (MOFs) as a particularly promising category of materials for this particular application and reports on the development of set of particular MOFs for the absorption of VOCs in indoor environments. It then shows that these materials outperform the traditional sorbants by up to an order of magnitude and can be tuned to provide additional benefits such as easy regeneration. Finally, models are presented that allow to simulate the performance of these materials and include them into a performance-based design of an IAQ management strategy. IEA-EBC Annex 92 is dedicated to the innovation of Heating, Cooling and IAQ control in residential buildings through smart materials.

Chapter 5 presents the achievements of SubTask 4 of the Annex, providing an overview of the implementation of performance-based approaches to assess the potential of smart ventilation. The results of a literature review, a common simulation exercise and an investigation report consistently show the importance of continually verifying the performance of the IAQ management strategies to achieve the stated objectives over the entire lifetime of the systems. Regulatory frameworks must be designed to provide appropriate criteria, indicators and verifiers as well as a support structure for all stakeholders involved for each stage of the life cycle of the technologies. Participants in the annex are implementing this approach to defining IAQ indicators through their activity in the relevant CEN and ISO technical committees (CEN TC 156 WG 25 and ISO TC 205/163 JWG 4).

Taken together, these achievements provide a toolkit for designers and decision-makers looking to implement a performance-based approach to IAQ management.

2. Metrics and development of an IAQ management strategy rating method

Editor: Benjamin Jones

2.1. Introduction

Authors: Benjamin Jones and Pawel Wargocki

The aim of Subtask 1 was to develop general rating methods for the benchmarking of the performance of IAQ management systems in residential buildings.

The primary performance indicator is occupant health, but it was also important to consider other factors, such as resilience and economic factors.

Common metrics for assessing air quality in buildings are based on guidelines and standards that regulate concentrations by stating threshold concentrations that should not be exceeded over a period of time. There is disagreement on the magnitude of these thresholds, perhaps because methods for determining them do not relate the magnitude of any exceedance to specific health outcomes. Accordingly, there is a need to develop health-centred IAQ metrics that can quantify the burden of disease using current epidemiological and toxicological evidence of population morbidity and mortality.

Much of the work described herein uses the disability adjusted life year (DALY) as a metric of harm. It was developed in the 1990s and is the sum of the years of life lost, and the time lived with a disability, attributable to some cause (Homedes, 1996).

$$DALY = Years\ of\ Life\ Lost + Years\ of\ Life\ with\ Disability \qquad (2.1)$$

The DALY has been used to quantify the harm caused by air pollution in global burden of disease studies (Cohen *et al.*2017). DALYs can be summed for different disease outcomes, and for different hazards. Therefore, the harm from any number of contaminants can be summed to obtain the total harm they cause.

This chapter outlines the work carried out by the subtask. It identifies six key indoor air contaminants that account for the majority of harm: $PM_{2.5}$, PM_{10}, NO_2, formaldehyde (HCHO), radon (Rn), and ozone (O_3). It presents a health-centred framework for assessing exposure. It introduces the Dynamic DALY method to capture temporal variations in exposure and harm and proposes a performance-based methodology for ranking ventilation systems under uncertainty. A multi-criteria decision-making approach is used to balance IAQ and energy performance, and a new resilience metric is developed to assess the capacity of buildings to maintain acceptable air quality during disruptions. Finally, it estimates the economic burden of poor IAQ, highlighting the dominant role of productivity losses from sick building syndrome. The findings support the case for smart, health-focused, and robust ventilation design in residential buildings.

This chapter presents a set of complementary methods for assessing the harm caused by indoor air contaminants and the performance of ventilation systems.

Section 2.2 introduces the use of Disability-Adjusted Life Years (DALYs) as a metric to quantify population harm from exposure to indoor pollutants. DALYs make it possible to compare contaminants and prioritise those that cause the greatest health burden. Importantly, this work now underpins the first accepted harm-based compliance pathway in ASHRAE Standard 62.2, marking a major step in embedding health outcomes into ventilation standards.

Section 2.3 identifies prevalent contaminants in homes and quantified their contributions to population harm. Particulate matter and formaldehyde are shown to dominate the estimated DALYs.

Section 2.4 presents a framework for evaluating ventilation systems using multiple criteria: IAQ, energy, cost, resilience, and robustness. Building simulations illustrated how different systems perform under low- and high-pollution scenarios.

Multi-criteria aggregation enable comparison across indicators, and a robustness analysis shows which systems maintain performance under uncertain conditions.

Section 2.5 develops a resilience framework, focusing on how systems respond to short-term shocks. Indicators of absorptivity, recovery, and shock impact are combined into a resilience score. Case studies demonstrate how different ventilation strategies compare under CO_2 peaks, PM episodes, and power outages.

Section 2.6 adds an economic perspective by estimating the costs of injury. Productivity loss due to SBS accounted for the largest share of costs, while DALY-related costs were dominated by particulate matter. The analysis also shows that mitigation measures such as low-emission materials, filtered ventilation, and higher airflow rates can substantially reduce costs.

The reported methods provide a basis for health-based performance benchmarking of IAQ management strategies. By using disability-adjusted life years (DALYs) to quantify harm, they allow contaminants to be prioritised according to their contribution to disease burden. This supports a shift away from threshold-based guidelines toward evidence-based targets that reflect actual health outcomes. The dynamic DALY method adds temporal and spatial resolution to this approach, enabling the design of smart ventilation systems that reduce exposure when and where it matters most.

Together, these methods provide a toolkit for understanding and reducing harm from indoor air contaminants. DALYs quantify the health burden, system evaluation links design choices to IAQ and energy trade-offs, resilience indicators capture performance under shocks, and cost analysis translates harm into economic terms. Applied jointly, they allow comparisons across contaminants, systems, and mitigation measures, and provide a stronger evidence base for decisions on IAQ.

Together, these methods support a transition toward ventilation and IAQ standards that explicitly protect health.

The work also supports decision-making in practice. A robust, multi-criteria assessment framework is introduced to evaluate IAQ systems under uncertainty, balancing health protection, energy use, and resilience. The resilience metric captures a building's capacity to absorb and recover from pollution events, while the economic assessment quantifies the cost of inaction—dominated by productivity losses linked to sick building syndrome. Together, these methods allow health-centred design to be integrated into building codes, performance standards, and practical ventilation design.

Future work should extend these methods to cover a wider range of contaminants, building types, and occupant behaviours. Stronger links between resilience indicators and DALY-based health outcomes would improve consistency across approaches. More detailed economic analyses are also needed to reflect differences in context, valuation, and uncertainty. Finally, case studies that integrate all four methods in parallel would help demonstrate their combined value. Building on the success of ASHRAE 62.2, future standards should embed harm-based metrics more systematically, ensuring that ventilation and IAQ requirements are explicitly tied to reductions in health burden.

References

Cohen, A. J. et al. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. The Lancet, 389(10082), 1907-1918.

Homedes, N. (1996). The disability-adjusted life year definition, measurement and potential use. Tech. rept. The World Bank.

2.2. DALYs as a measure of population harm from exposure to indoor air contaminants

Author: Giobertti Morantes

Common metrics for assessing air quality in buildings are based on guidelines and standards that regulate concentrations by stating threshold concentrations that should not be exceeded over a period of time. There is disagreement between regulator authorities on the magnitude of these thresholds, perhaps, because methods for determining them do not relate the magnitude of any exceedance to specific health outcomes (Jones et al. 2025). Accordingly, there is a need to develop health-centred IAQ metrics that can quantify the burden of disease using current

epidemiological and toxicological evidence of population morbidity and mortality. The DALY is used as an air quality metric because it can be used to quantify and rank the burden of household air contaminants.

This work is now a contributed report to the Air Infiltration and Ventilation Centre (IEA Annex 5) (Morantes, 2025).

2.2.1. Indoor Air Quality and Health

IAQ directly affects public health. People spend most of their time indoors, particularly in their homes, where they are exposed to a mixture of airborne contaminants, including volatile organic compounds (VOCs), particulate matter (PM), biological agents like mold, and radiological hazards such as radon. Exposure to these contaminants has been linked to adverse health outcomes.

While the evidence linking indoor exposures to health outcomes is extensive, quantifying the overall health burden remains challenging. Several metrics are available for this purpose. One is the disability-adjusted life year (DALY), which aggregates the years of life lost due to premature death and those lived with disability. Another, the quality-adjusted life year (QALY), is more commonly used in health economics to evaluate medical interventions, weighting life expectancy by perceived health quality. In this work, we adopt the DALY framework because it is well established in environmental health assessments, including the Global Burden of Disease project, and is better suited to quantifying the impact of environmental exposures across populations.

This section examines the connection between IAQ and health, focusing on contaminants found in residential environments. It assesses how these contaminants contribute to health outcomes, evaluate current methods for measuring their impact, and discuss implications for policies aimed at improving air quality indoors.

2.2.2. Prevalent Contaminants in Homes

Evaluating IAQ in residential settings requires a comprehensive understanding of prevalent airborne contaminants. Our analysis (Morantes et al. 2024; Morantes, 2025) drew from 145 unique references and 827 data sets to determine representative concentrations of 44 airborne contaminants commonly found in homes. These data, collected between 2000 and 2020, cover 31 countries and grouped regions, with most datasets originating from high-income, industrialized nations, primarily the United States, China, Canada, and the United Kingdom.

The most abundant contaminants in dwellings by mass include ethanol, PM_{10}, formaldehyde (HCHO), $PM_{2.5}$, and nitrogen dioxide (NO_2), reflecting typical exposures in residential environments. Median concentrations for ethanol, PM_{10}, and formaldehyde were 110 µg/m³, 62 µg/m³, and 28 µg/m³, respectively, indicative of common household activities such as cooking, smoking, and the use of combustion-based heating and lighting. These findings align closely with previous literature reviews from countries in the Global North, which share similar industrial profiles and IAQ challenges.

The distribution of contaminant concentrations mirrors the variety of activities in residential settings. For example, the high levels of ethanol and formaldehyde are linked to off-gassing from household products and building materials, while PM_{10} and $PM_{2.5}$ are primarily associated with combustion-related activities. Nitrogen dioxide, an outdoor contaminant, infiltrates indoor spaces and contributes to overall exposure, particularly in urban areas.

2.2.3. A Metric of Harm: The Harm Intensity

A metric was designed to establish the relationship between the concentration of a contaminant and its associated physical or psychological harm. The harm intensity (HI) is measured in DALYs per unit concentration (e.g., DALYs per microgram per cubic meter per person per year), offering a standardized way to assess the health risks of various contaminants. This metric makes it possible to normalize the individual harm caused by indoor air contaminants based on exposure levels.

The Harm Intensity is derived from both toxicological and epidemiological data. Toxicological studies quantify the harmful effects of contaminants on organisms, often using the effective dose (ED50) to measure the response. This data is integrated with population metrics, such as breathing rates and damage factors, to calculate the HI. Epidemiological studies, on the other hand, provide real-world insights by linking disease incidence rates with exposure concentrations through concentration-response functions. These approaches are rooted in life-cycle impact assessment methodologies. For acrolein, benzene, formaldehyde, ozone, and radon, both toxicological and epidemiological data are available. The integration of these approaches captures a broader range of health effects by combining specific disease risks identified through toxicology with those from epidemiology.

PM$_{2.5}$ has the highest HI, with PM$_{10}$ and chromium also showing elevated values due to their toxicological profiles and links to all-cause mortality. However, HI alone is not sufficient to assess overall harm, as it represents harm per concentration unit. To fully understand health risks, both HI and the actual concentration of contaminants must be considered. A contaminant with a high HI at low concentrations may pose a greater risk than one with a low HI at high concentrations.

Table 2.1: Representative concentrations, HIs, and Harm of Contaminants of Concern

Pollutant	Representative Concentration (µg/m^3 or Bq/m^3)	Harm Intensity (DALYs/µg.m^{-3}/10^5 people/year)	Harm (DALYs/10^5 people/year)
PM$_{2.5}$	26	60	1600
PM$_{10-2.5}$	35	3.8	130
NO$_2$	22	5.7	120
HCHO	28	4.3	120
Rn	78	0.44	34
O$_3$	7.3	1.3	10

2.2.4. Harm from Residential Indoor Air Contaminants

The Harm from airborne contaminants is calculated by multiplying the concentration of each contaminant by its Harm Intensity (HI). By summing these individual harms, the cumulative health impact of multiple contaminants can be assessed, providing a comprehensive view of IAQ. Our analysis estimates chronic harm, expressed in Disability-Adjusted Life Years (DALYs) per 100,000 person-years, for 45 indoor air contaminants. Among them, PM$_{2.5}$ and PM$_{10-2.5}$, nitrogen dioxide, formaldehyde, radon, and ozone contribute the most to the total burden, with PM$_{2.5}$ leading at 1600 DALYs; see Table 2.1. PM$_{10-2.5}$ refers to the coarse fraction of particulate matter, derived by subtracting PM$_{2.5}$ from PM$_{10}$, and is required because PM$_{10}$ measurements include both fine and coarse particles. These six contaminants account for 99.5% of the total harm. They are outlined as the Contaminants of Concern (CoCs) in residential environments.

PM$_{2.5}$ and PM$_{10-2.5}$, known for their ability to penetrate deep into the lungs, are linked to cardiovascular and respiratory diseases. Formaldehyde, common in newer buildings, poses significant risks due to off-gassing from materials, while nitrogen dioxide, an outdoor contaminant that infiltrates indoor spaces, worsens respiratory conditions like asthma. Together, these contaminants highlight the pressing need for targeted IAQ management to mitigate their impact on public health.

2.2.5. Ventilation for Health

A harm budget provides a quantitative framework for managing IAQ in health terms. It defines the maximum allowable health burden, measured in DALYs, that is considered acceptable for a given space or population.

The harm budget is estimated by multiplying the threshold concentrations of CoCs, prescribed by relevant by ventilation standards or authorities, with their corresponding harm intensities. Summing all harms for CoCs gives the total potential harm associated with maintain indoor concentrations at those thresholds. This value represents the maximum allowable harm within the space under compliant conditions.

Once established, the harm budget can be used as a benchmark. If the calculated harm exceeds those associated with other common risks, such as transport or lifestyle-related exposures, this suggests that current thresholds may be too lenient. Conversely, if the harm is substantially lower, the thresholds may be considered suitably protective.

Compliance with a harm budget does not require prescriptive concentration limits for each contaminant. Any combination of exposure levels across CoCs that keeps the total harm below the defined budget satisfies the health-based requirement. This flexibility allows designers and regulators to prioritise measures where they deliver the greatest health benefit, without being constrained by fixed pollutant-by-pollutant limits.

This approach links ventilation performance directly to health outcomes by grounding air quality targets in population health metrics. It enables IAQ standards, such as those under ANSI/ASHRAE 62.2, to move beyond prescriptive ventilation rates and adopt health-based performance criteria. The harm budget can be adapted across different building types and environments, providing a consistent and quantitative basis for defining and comparing acceptable IAQ across contexts.
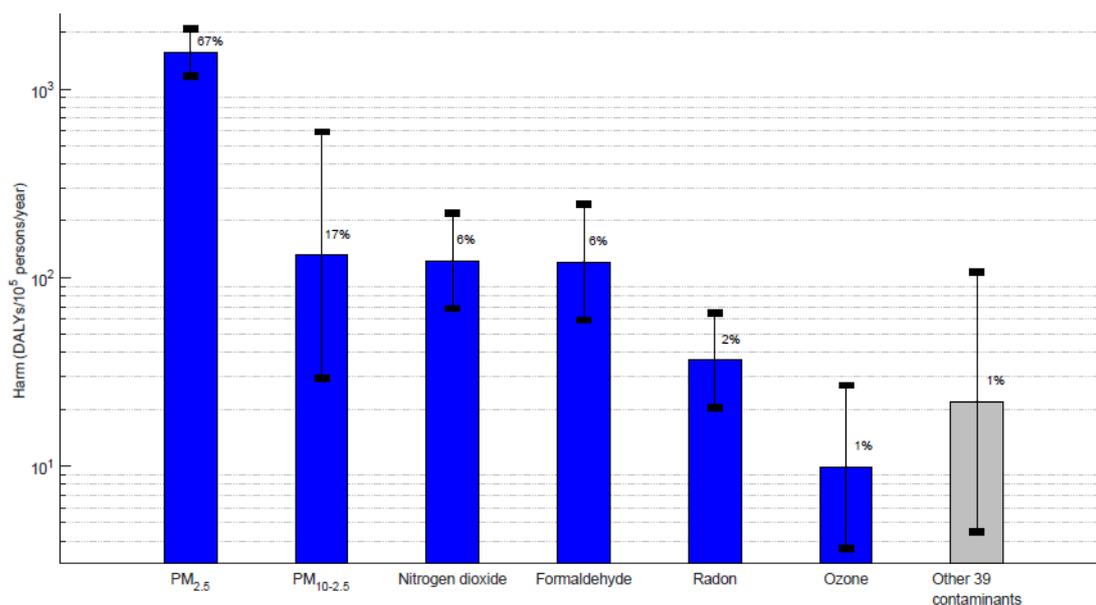
Figure 2.1: Harm caused by CoCs in houses in the Global North. Median (bar) and GSD (error bar). Percentage contribution for total harm

References and further reading

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Morantes, G. 2025. Quantifying population harm from indoor air contaminants in dwellings. AIVC Contributed Report 22. https://www.aivc.org/sites/default/files/CR22.pdf

Jones, B, Morantes, G, Molina, C, Sherman, M, McGrath, JA. 2025. Harm from indoor air contaminants: protection by exposure limit values. International Journal of Ventilation, 1–11. https://doi.org/10.1080/14733315.2025.2513855

2.3. Dynamic DALYs as a measure of time varying contribution to harm caused by indoor air contaminants

Author: Klaas De Jonge

Different rooms can easily have large differences in contaminant concentration that vary in time and space due to differences in activities, materials used, furniture present, humidity and temperatures, weather conditions, and ventilation system design and controls. People, therefore, are exposed to different contaminant concentrations in the indoor air in different indoor spaces.

To investigate the time periods and spaces where the most harm occurs it is possible to apply the Dynamic DALY methodology (De Jonge & Laverge, 2022).
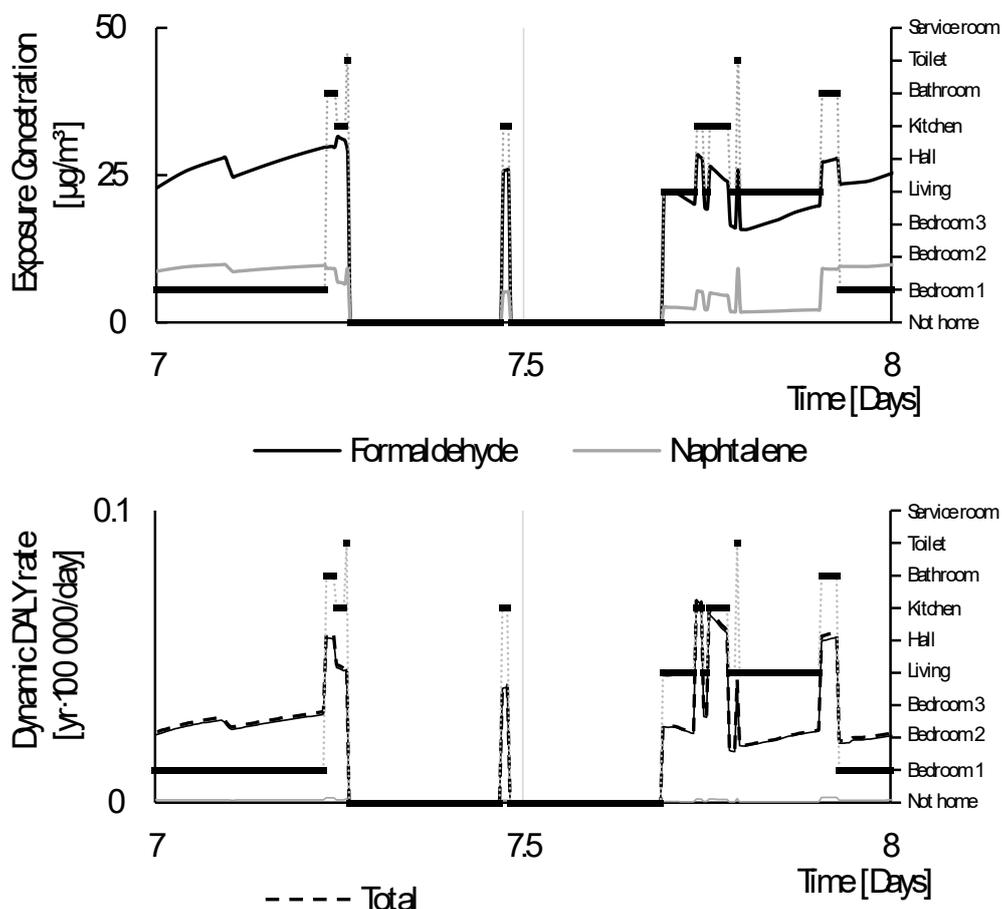
Figure 2.2: (Top) Simulated exposure of a working adult to Formaldehyde and Naphthalene with an indication in a range of locations over seven days. (Bottom) Corresponding Dynamic DALY rate for Formaldehyde and Naphthalene as well as the sum of these two. The harm from Naphthalene is minimal when compared to the harm from Formaldehyde exposure (De Jonge, Laverge - 2022)

2.3.1.   Dynamic DALYs

Dynamic DALYs calculate chronic harm from indoor air contaminant exposure. They also show when and where the largest harm contributions occur. The method uses statistical epidemiological and toxicological data. It can't predict individual harm accurately. However, it works for representative occupants and exposure conditions of a larger population subset. For this reason, dynamic DALYs are best expressed as DALYs lost per 100,000 people.

The method builds on Logue et al.'s (2012) approach. However, Logue's method needs the mean exposure concentration as input. This makes it less suitable for high-resolution, time-resolved exposure data from simulation software or detailed measurements.

Figure 2.2 illustrates the dynamic DALY concept through a simulated case of a working adult exposed to formaldehyde and naphthalene over seven days, showing how both exposure and resulting harm vary across time and location. The upper panel presents the time-varying indoor concentrations across a range of locations, while the lower panel shows the corresponding dynamic DALY rates for each contaminant and their combined effect. The results demonstrate that the harm from naphthalene is minimal compared with that from formaldehyde, highlighting how dynamic DALYs can distinguish which pollutants and exposure events contribute most to total harm.

2.3.2. Dynamic ID Method

The dynamic ID method calculates the intake rate, IR(t), as the product of the time-resolved exposure concentration profile, $C_{exp}(t)$, and the time-resolved breathing rate, $\dot{V}_{br}(t)$.

The intake rate is then multiplied by pre-defined carcinogenic and non-carcinogenic mass-intake DALY factors, $\frac{\partial DALY}{\partial M_C}_{cancer}$ and $\frac{\partial DALY}{\partial M_C}_{non-cancer}$, respectively. For carcinogenic health effects, an Age-Dependent Adjustment Factor (ADAF), is added that accounts for age-based vulnerability. The result is $\frac{DALYs}{time}$, a function of DALYs gained per unit of time. Integrating this gives $DALYs(t)$, the accumulated DALYs for the investigated period.

$$DALYs(t) = \int_{t_0}^{t} \frac{DALYs}{time} \tag{2.2}$$

$$\frac{DALYs}{time} = \left(population \times IR(t) \times ADAF \cdot \frac{\partial DALY}{\partial M_C}_{cancer} \right) + \left(population \times IR(t) \times \frac{\partial DALY}{\partial M_C}_{non-c} \right) \tag{2.3}$$

$$IR(t) = \dot{V}_{br}(t) \cdot C_{exp}(t) \tag{2.4}$$

The main reference for this method is Huijbregts et al. (2005), which can be updated in the future with the new parameter values developed by Morantes et al., and described in Section 2,2.

2.3.3. Dynamic IND Method

The dynamic IND method is calculated for each relevant disease linked to an exposure to a specific indoor air contaminant. First, it determines the time-resolved disease incidence rate, $\frac{INC}{time}$. This uses a concentration-response function (C-R function) from epidemiological studies.

The C-R function incorporates the time-resolved exposure concentration profile, $C_{exp}(t)$. Typically, a non-linear C-R function is used. It's defined by the baseline health outcome per second, $y_{0,s}$ and the coefficient of concentration change, β. Multiplying by the investigated population size, *population*, and integrating gives the cumulative disease incidence over time, $INC(t)$. Multiplying this incidence by the incidence-based DALY factor, $\partial DALY/\partial INC$, also gives the accumulated DALYs during the period, $DALYs(t)$.

$$DALYs(t) = \left(\frac{\partial DALY}{\partial INC} \right) \cdot INC(t) \tag{2.5}$$

$$INC(t) = \int_{t_0}^{t} \left(\frac{INC}{time} \right) \cdot pop \tag{2.6}$$

$$\frac{INC}{time} = -y_{0,s} \cdot \left(e^{-\beta \cdot C_{exp}(t)} - 1 \right) \tag{2.7}$$

Figure 2.3 shows the cumulative DALYs for a person exposed to formaldehyde over a week when the ventilation system is either continuous or smart. The smart ventilation system moderates the airflow rate over time in response to a range of stimuli and so in this case the formaldehyde concentration and the harm are higher.

2.3.4.   Advantages of Dynamic DALYs

The new approach helps IAQ and ventilation engineers and researchers better understand and optimize IAQ management solutions. It quantifies how changes in strategy affect expected harm. This allows energy-saving smart ventilation while limiting harm.

Dynamic DALYs visualize harmful trends. Figure 2.4 shows an example using the same Belgian case-study. The cumulative harm function (y-axis) for a full year (x-axis) reveals the summer months (in the middle of the year) cause more harm than the winter months (at the beginning and end of the year). This is shown by the gradients of the dashed lines, which are marginally higher during the middle of the year. This case-study shows higher energy-saving potential is higher during the winter months where the energy gradients are higher.
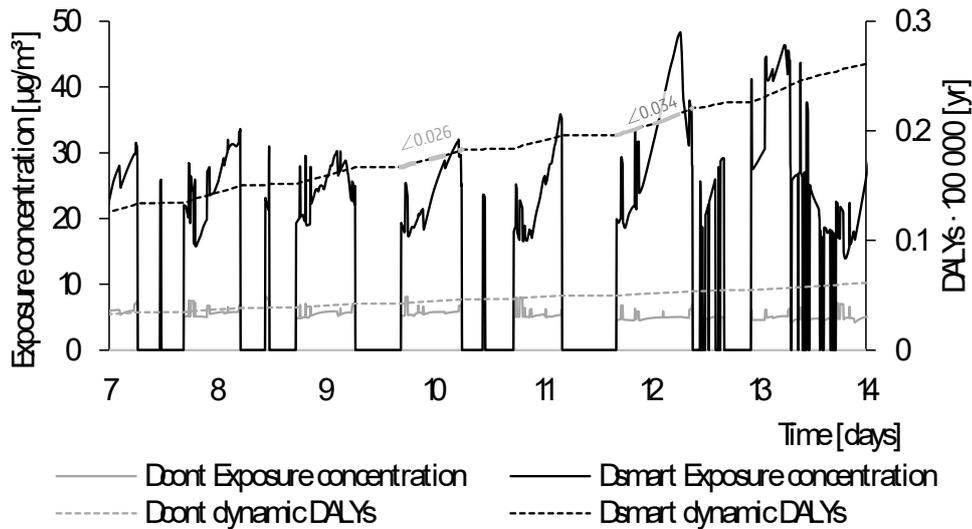
Figure 2.3: Exposure concentration profile of a working adult to formaldehyde over one week (solid lines) and the related dynamic DALYs (dotted lines) for a continuous ventilation system, Dcont, and a smart ventilation system, Dsmart (De Jonge, Laverge - 2022)
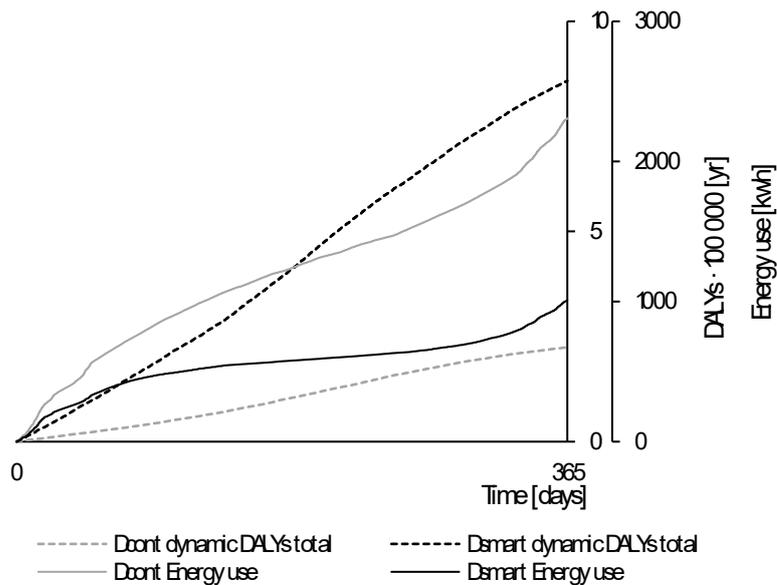
Figure 2.4: Cumulative total dynamic DALYs (dotted lines) and building energy use (solid lines). Dcont (grey) are the results for a continuous airflow system. Dsmart (black) are the results for a smart, demand-controlled ventilation system (De Jonge, Laverge - 2022)

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2.4. Methods of assessing systems and making decisions to reduce harm

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Reducing harm from indoor air contaminants requires careful selection and operation of ventilation systems. This section presents a method for assessing the performance of residential ventilation systems under a range of conditions. The aim is to support design and policy decisions that prioritise health, while recognising the need to balance energy, cost, and operational resilience.

The approach does not calculate DALYs directly but contributes to harm reduction by identifying system designs that are most effective at reducing indoor concentrations of contaminants known to affect health—such as $PM_{2.5}$ formaldehyde, and CO_2. These outputs can be used in further health impact assessments, including DALY-based metrics introduced earlier in this report.

This method evaluates ventilation systems across five criteria:

1. Inputs scenarios definitions,
2. Building modeling and simulation,
3. Output performance calculation,
4. Multi-criteria aggregation,
5. Robust design score calculation and ranking.

Each criterion is assessed through building simulations, which are run across different cases and input scenarios. The analysis includes both "typical" and "high-pollution" outdoor conditions, and considers uncertainty in occupant behaviour and indoor sources. Particular attention is paid to smart ventilation systems, which adjust operation based on real-time signals.

The results provide a structured basis for comparing systems and guiding ventilation design choices. Subsequent sections describe how performance is assessed for each criterion and how these assessments support decisions to reduce harm.

2.4.1. Input scenario definitions

Ventilation systems are evaluated using a performance-based approach that compares how well each system meets the five criteria defined above. This avoids reliance on single-threshold values and instead focuses on relative performance across a range of conditions. The analysis supports multi-criteria decision-making, where trade-offs between health, energy, cost, and system stability must be considered.

For each system, a set of building simulations is carried out under two representative outdoor conditions—low and high pollution—to reflect variation in external air quality. Key internal parameters such as occupant activity, indoor emissions, and ventilation rates are also varied. The result is a matrix of system responses that can be compared across cases and indicators.

System performance is evaluated on a normalised scale from 0 to 1, where 1 represents the best-performing system for a given criterion within each case. This enables side-by-side comparison of systems using multi-criteria analysis (MCA). The approach supports both visual and quantitative ranking of design options, allowing decision-makers to prioritise health or other goals depending on context.

To assess robustness, a limited set of input parameters is systematically varied. These include indoor pollutant emissions, moisture loads, and airflow capacity. Table 2.2 lists the values used to define "low," "reference," and "high" input conditions. Although this simplified approach does not represent the full uncertainty space, it is sufficient to identify systems whose performance is more stable across realistic variations.

The following sections explain how IAQ, energy, resilience, cost, and robustness are quantified, and how the results inform design choices that are more likely to reduce harm.

Table 2.2: Summary of input variables. Parameters varied to reflect uncertainty in occupant emissions, indoor sources, and system operation. Each parameter is evaluated at three levels (Low, Reference, High) to test system stability under realistic variation

Inputs	Description	Units	Low	Reference	High
Bio-eff	Occupant CO_2 and H_2O emissions	*dimensionless*	0	0.333	1
Acti-H$_2$O	Moisture emissions from activities	*dimensionless*	0.7	1	1.3
Acti-PM$_{2.5}$	$PM_{2.5}$ emissions from cooking	mg h^{-1}	1.26	1.91	2.55
Furn-HCHO	Formaldehyde emissions from furniture	µg m^{-2} h^{-1}	4.5	12	23.6
Q-exh	Exhaust airflow multiplier	*dimensionless*	0.7	1	1.3
Q-max	Maximum airflow (boost mode) multiplier	*dimensionless*	0.7	1	1.3

2.4.2. Building modelling and simulation

Each ventilation system was evaluated using a multizone model in CONTAM (NIST). The model represents a typical low-energy dwelling with defined rooms and airflow paths. It simulates transport and removal of key contaminants: $PM_{2.5}$, formaldehyde (HCHO), CO_2, and indoor moisture. Outdoor concentrations drive infiltration of PM and HCHO. Occupancy schedules drive CO_2 and moisture generation.

Design options. Five system configurations were implemented as the design options (Dopt) in CONTAM:

1. **MEV-CAV:** mechanical extract, constant airflow;
2. **MVHR-CAV:** balanced mechanical ventilation with heat recovery, constant airflow;
3. **MEV-RH:** mechanical extract with humidity-controlled airflow;
4. **MVHR-RB:** balanced system with heat recovery and room-level CO_2 and humidity control with reactive boost;
5. **MEV-RB:** mechanical extract with room-level CO_2 and humidity control, adapted from MVHR-RB.

Inputs and scenarios. Source strengths and operational parameters were varied to reflect realistic uncertainty in occupant behaviour, indoor sources, and system operation. Table 4.1 defines the three levels used for the robustness runs: Low, Reference, and High. Parameters include occupant CO_2 and moisture generation (Bio-eff), activity-related moisture (Acti-H$_2$O), cooking $PM_{2.5}$ (Acti-PM$_{2.5}$), formaldehyde from furniture (Furn-HCHO), total exhaust flow multiplier (Q-exh), and maximum boost airflow multiplier (Q-max). These values span typical ranges drawn from Annex 86 sources and are applied consistently across systems.

Two outdoor conditions are modelled to reflect variation in ambient air quality: a low-pollution case and a high-pollution case. Together with the input levels above, they generate a matrix of runs that captures the spread in IAQ and energy outcomes for each system. In addition results from a larger, previously developed sensitivity study, covering 500 combinations of input parameters, were used to confirm that the simpler three-scenario approach produces consistent rankings of system performance.

Outputs computed by the model. For each run the model reports time series and aggregates for:

- Cumulative exposure indicators for CO_2, HCHO, and $PM_{2.5}$ (e.g. InCO$_2$ above 1000 ppm; InHCHO; InPM$_{2.5}$);
- Humidity exceedance metrics (InRH$_{70}$ and time outside 30–70% RH);
- Energy indicator for ventilation heat losses (IEwh), derived from exhaust mass flow, indoor–outdoor temperature difference, and an assumed heat-recovery efficiency where applicable. A constant efficiency of 0.8 is used for MVHR and 0 for systems without heat recovery. Fan energy can be added where needed. These indicators are defined in Table 4.2 and prior studies.

Link to harm. This section does not calculate DALYs. Instead, it provides the exposure and energy outputs that feed the performance aggregation in Sections 4.3–4.5. Exposure indicators for $PM_{2.5}$ and HCHO, in particular, map directly to contaminants with established health burdens in the DALY framework discussed earlier. This maintains a clear line of sight from system design choices to harm reduction at population level.

Reuse of prior simulations. To check efficiency against fidelity, rankings from the three reference scenarios (Low, Reference, High) are compared with rankings obtained from the 500-scenario sensitivity set. The simplified approach reproduces the broader ranking with acceptable agreement, which supports its use at the design stage when time and data are limited.

2.4.3. Outputs and performance evaluation

The CONTAM simulations generate a set of indicators that describe IAQ, humidity, and energy use for each system and scenario. These indicators are reported as annual averages and percentiles to reflect both chronic and episodic exposure potential.

The main outputs are:

- **$InCO_2$:** cumulative exposure above 1000 ppm;
- **InHCHO:** cumulative exposure to formaldehyde;
- **$InPM_{2.5}$:** cumulative exposure to $PM_{2.5}$;
- **$InRH_{70}$:** time with relative humidity above 70%;
- **$InRH_{30-70\%}$:** time outside the recommended comfort band;
- **IEwh:** energy indicator for ventilation heat losses, accounting for airflows and an assumed 80% heat-recovery efficiency in MVHR systems.

These indicators are labelled using the prefix "In–" to denote cumulative indoor exposure. They are summarised in Table 2.3, which also lists outputs, their units used, and the assessment targets (AT) used for comparison. The AT values are reference values, not simulation results; for example, 1000 d(ppm.h) is used as the cumulative CO_2 exposure target, while for humidity the ATs specify the maximum acceptable percentage of time above 70% or outside the 30-70% band.

Table 2.3: Summary of outputs. Indicators used in the evaluation, with descriptions and associated units. The symbol "d" denotes that the indicator is expressed as a daily cumulative value (e.g. ppm·h per day or µg·m⁻³·h per day), which allows exposure magnitudes to be compared consistently across contaminants.

Outputs	Description	Assessment Targets
$InCO_2$	Maximum cumulative CO_2 exposure over 1000 ppm	1000 .d (ppm.h)
InHCHO	Maximum cumulative HCHO exposure among all the occupants	9.d (µg.m⁻³.h)
$InPM_{25}$	Maximum cumulative $PM_{2.5}$ exposure among all the occupants	10.d (µg.m⁻³.h)
$InRH_{70}$	Maximum percentage of time with RH > 70% among all the rooms	18%; 10.8%;1.8%
$InRH_{30\_70}$	Maximum percentage of occupant time spent with RH outside the range [30-70%]	14.4%
IEwh	Heat losses from total exhaust airflows	-

To enable comparison, each output is transformed into a normalised score between 0 and 1, where 1 represents the best-performing system and 0 the worst within the same case. MCA weight sets are in Table 4.3. This approach removes the effect of absolute units and allows side-by-side evaluation of systems across multiple indicators.

Four systems are compared:

1. **MEV-CAV:** central mechanical extract, constant airflow;
2. **MEV-DCV:** mechanical extract, demand-controlled;
3. **MEV-HR:** extract with heat recovery;
4. **MVHR-rb:** balanced mechanical ventilation with heat recovery and a reactive boost mode (smart ventilation).

Results are presented for two outdoor conditions: a low-pollution case and a high-pollution case. In the low-pollution case, IAQ differences between systems are limited, with MEV-HR and MVHR-rb performing slightly better due to higher air change rates and heat recovery. In the high-pollution case, differences are more pronounced: MVHR-rb consistently maintains lower indoor concentrations of $PM_{2.5}$ and formaldehyde through its adaptive control, although this comes at higher energy use.

These results demonstrate the importance of evaluating systems under varying outdoor conditions. A system that performs well under typical conditions may not be the most protective in more challenging scenarios. Smart ventilation approaches, in particular, show value in balancing IAQ gains against higher energy demand.

2.4.4. Multi-criteria aggregation

The indicators presented above describe individual aspects of system performance, but design and policy decisions require an integrated view across multiple criteria. To provide this, results are combined using a multi-criteria aggregation (MCA) approach.

In this method, the outputs for each criterion are first normalised on a 0–1 scale, where 1 represents the best-performing system and 0 the worst within the same case. The normalised values are then combined to provide an overall comparison. Different aggregation methods can be used depending on the decision context:

- Simple ranking, where systems are ordered by the number of times they achieve the best score;
- Averaging, where scores are combined without weights to reflect balanced performance;
- Weighted aggregation, where greater emphasis is placed on selected criteria, such as IAQ or energy.

This allows flexibility: policymakers may choose to prioritise health outcomes, while building designers may balance IAQ against energy or cost. The approach also makes transparent how different priorities affect system rankings.

Case study results show that under low outdoor pollution, the differences between systems are modest, with several options performing acceptably. Under high outdoor pollution, however, adaptive systems such as MVHR-rb perform better overall, particularly when IAQ is given higher weight. This highlights the value of smart ventilation in contexts where outdoor conditions vary significantly.

While MCA does not provide a direct measure of harm, it creates a structured basis for selecting systems that are most likely to reduce population exposure when considered alongside DALY-based metrics introduced earlier in this report.

2.4.5. Robustness calculation and ranking

Robustness reflects the stability of system performance when uncertain inputs vary. To assess this, the input parameters listed in Table 4.1 were varied at three levels (low, reference, high) and the resulting system scores recalculated. These parameters represent occupant emissions, indoor sources, and airflow capacities, all of which can influence IAQ and energy performance.

For each combination of input values, the multi-criteria aggregation (MCA) described in Section 2.4.4 was applied. The proportion of cases in which each system achieved the highest ranking was then calculated. This provides a simple but informative measure of robustness: systems that remain near the top of the ranking across many input combinations are considered more robust.

To test the efficiency of this simplified approach, results were compared with those from a more extensive 500-scenario sensitivity analysis. The agreement between the two methods was high, confirming that the three-level approach provides a reliable picture of relative robustness while being feasible for design-stage assessments.

The analysis shows that systems with adaptive controls, such as MVHR-rb and MEV-rb, are more robust, consistently maintaining good IAQ and energy performance despite input variation. By contrast, fixed-flow systems (MEV-CAV) are more sensitive to changes in emissions and occupancy, and their rankings fluctuate more widely.

Considering robustness alongside IAQ, energy, cost, and resilience provides a fuller picture of system performance. It helps identify ventilation strategies that are not only effective under reference conditions but also more likely to reduce harm reliably under the uncertainties of real buildings and occupant behaviour.

Table 2.4: Weight distribution for IMC calculation. Weighting schemes applied in the multi-criteria aggregation (MCA). IMC_IAQ-E assigns equal weight to all indicators, while IMC_IAQ-E* applies higher weights to IAQ indicators ($PM_{2.5}$, HCHO) and to energy (IEwh). Weights are given to two significant figures and are normalised in the aggregation

Distribution	Weight ω_i					
For I_{MC} calculation	$InCO_2$	$InRH_{70}$	$InRH_{30\_70}$	$InPM_{25}$	InHCHO	IEwh
I_{MC_IAQ-E}	0.16	0.16	0.16	0.16	0.16	0.16
I_{MC_IAQ-E*}	0.071	0.071	0.071	0.143	0.143	0.5

2.4.6. Example of performance results

To illustrate the method, Figure 2.5 presents the integrated design scores for the six ventilation systems tested. These scores are calculated using the MCA approach described in Section 2.4.4, with weights given in Table 2.4. They are not normalised, so the absolute score values and their differences provide a direct basis for comparison.
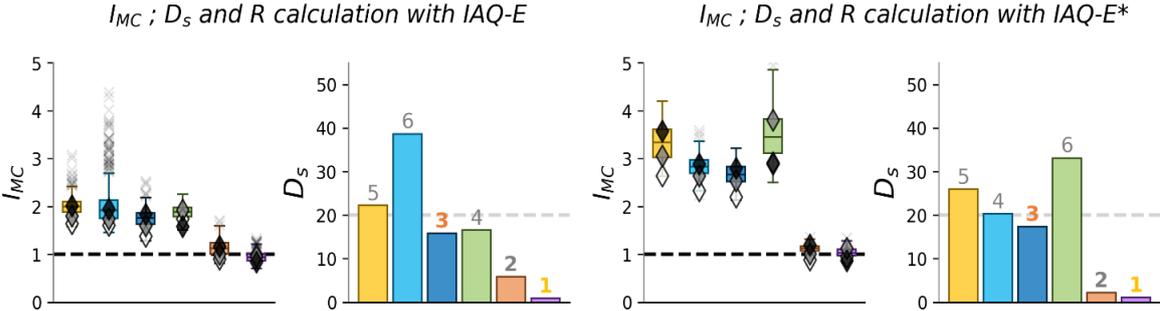
Figure 2.5: Design Score results for the 6 ventilation systems tested (Poirier 2023a)
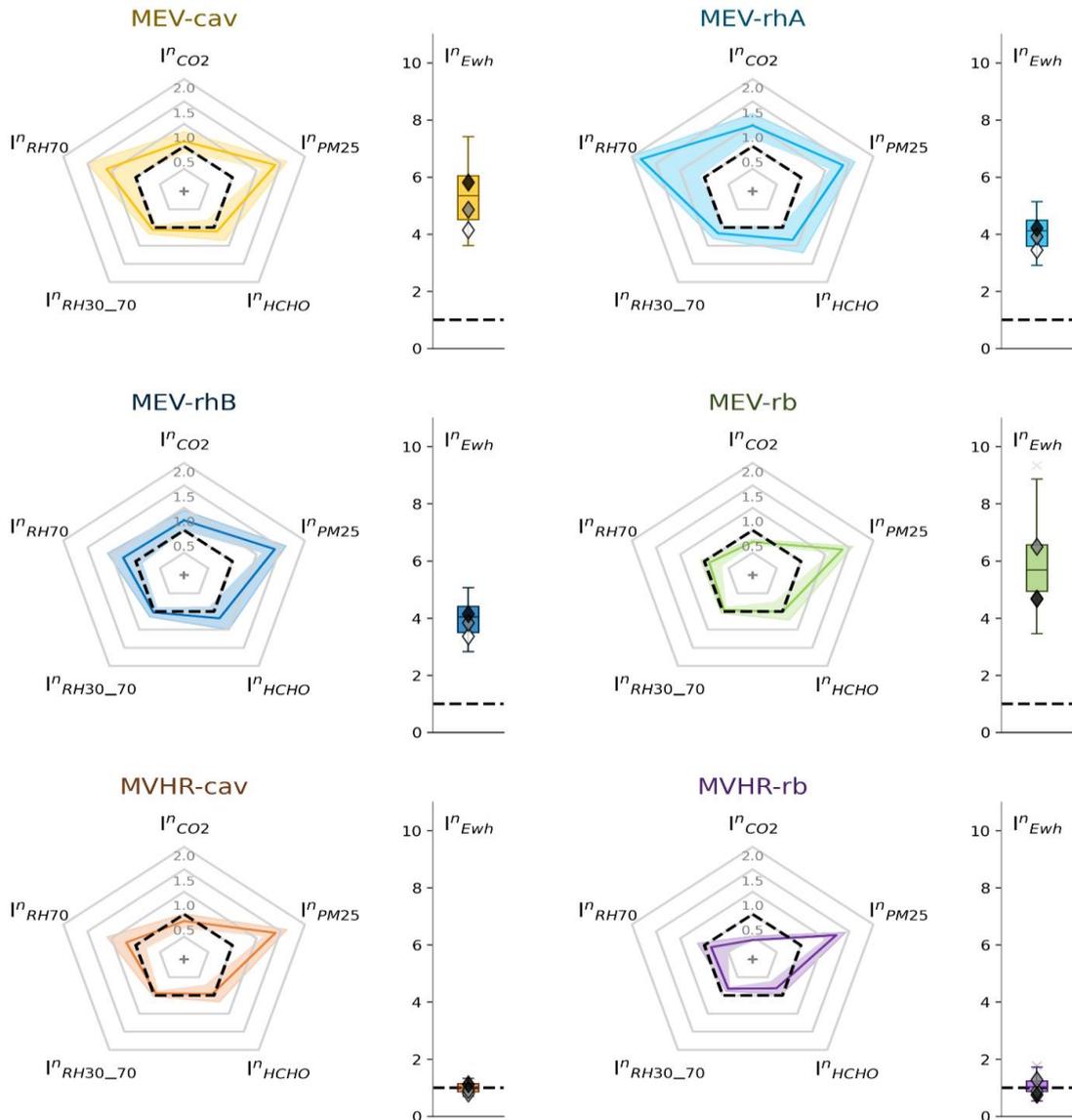
Figure 2.6: Example of results by Ventilation System (Poirier 2023a)

Figure 2.6 illustrates how the results can be presented in a form suitable for a design-support or decision-making tool. IAQ performance is shown using a combined radar graph and boxplot, with the median indicated by a solid line and the interquartile range (Q1–Q3) shown as a shaded background. Ventilation heat losses (IEwh) are displayed as a boxplot, and the bottom panel presents the integrated design scores (IMC) for the two weighting schemes defined in Table 2.4.

This format highlights both central tendencies and variability in system performance, making it easier to identify trade-offs. For example, adaptive systems such as MVHR-rb maintain better IAQ across pollutants, but with higher energy use. Constant-flow systems are more stable in energy terms, but less protective during high-pollution conditions.

Under the low-pollution case, all systems achieve relatively high IAQ scores. Energy use becomes the main differentiator: demand-controlled and heat recovery systems (MEV-DCV, MEV-HR) perform better than constant-flow systems (MEV-CAV).

Under the high-pollution case, IAQ differences between systems are much more pronounced. The MVHR-rb system maintains the lowest indoor concentrations of $PM_{2.5}$ and HCHO due to its reactive boost function, though this results in higher energy use. In contrast, constant-flow systems are less effective in maintaining IAQ when outdoor pollutant loads increase.

These examples demonstrate how the method highlights trade-offs between criteria. A system that appears adequate under typical conditions may not be the most protective during pollution episodes. By combining IAQ, energy, cost, resilience, and robustness into a consistent framework, the method enables informed comparisons and supports decisions that are more likely to reduce harm.

Taken together, the approach presented in this section provides a practical framework for evaluating residential ventilation systems under realistic conditions of variability and uncertainty. By combining indicators of IAQ, energy, cost, resilience, and robustness, and by illustrating how results can be presented in decision-support tools, the method helps identify ventilation strategies that are more likely to deliver consistent health benefits. While not a substitute for DALY calculations, it creates a clear pathway from system design choices to population-level harm reduction.

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2.5. Resilience as a measure of a building's capacity to limit the harm cause by indoor air contaminants

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Resilience performance in building design has emerged as a critical consideration in the face of increasing uncertainties or 'shocks' posed by natural disasters, climate change & excessive pollution events. To evaluate and optimize building design decisions, holistic performance metrics are needed. This work defines a novel quantitative assessment framework of ventilation resilience which output is the resilience score (**RS**) metric. The **RS** integrates all ventilation resilience performance aspects and building-relevant contaminants into one representative metric.

2.5.1. Resilience Assessment Framework

Step 1 consists of inflicting a "shock" that causes a rise in the concentrations of prominent contaminants in the built environment. In **Step 2**, the concentration of contaminants are extracted from the building zones. In **Step 3**, the normalized indices of the three aspects of ventilation resilience are calculated. In **Step 4**, the calculated indices are visualized on a spider chart for the different building-relevant contaminants. To calculate one single **RS** representative of the building and accounting simultaneously for all the contaminants, the weighted sum of the individual **RS** for the contaminants is computed (**Step 5 to 7**). The evolution of the resilience with increasing shock degree can be analyzed.

Resilience aspect 1: Absorptivity: The period Δt_{abs} between $C_p(t)$ crossing the threshold reference value (TRV) for contaminant *p* until it reaches the maximum concentration (Fig.2.7). The **normalized absorptivity effectiveness index** was defined below as:

$$\varepsilon_{abs} = \frac{\Delta t_{abs}}{occupied\ period}$$

(2.8)

ε_{abs} varies between 0 (i.e., worst case scenario, the system absorbs the shock quickly) and 1 (i.e., best case scenario, the system takes considerable amount of time to fully absorb the shock).

Resilience aspect 2: Recovery: The period Δt_{rec} between the shock end time or when an intervention strategy became effective such that $C_p(t)$ decreased significantly from its peak C_{max} to reach the TRV or lower (Fig.2.7). The **normalized recovery effectiveness index** was defined below as:

$$\varepsilon_{rec} = 1 - \frac{\Delta t_{rec}}{occupied\ period}$$

(2.9)

ε_{rec} varies between 0 (i.e., worst case scenario, the system recovers slowly throughout the occupied period) and 1 (i.e., best case scenario, the system recovers almost instantaneously).

Resilience aspect 3: Shock impact: The impact of the shock is the unmet ventilation $ppm.hours$ above the TRV (Fig.2.7). The shock **impact** was expressed via the **normalized resilience effectiveness index** below:

$$\varepsilon_{res} = \frac{ppm.hours_{ref} - ppm.hours_{system\ under\ shock}}{ppm.hours_{ref} - ppm.hours_{system\ normal\ operation}}$$

(2.10)

Where $ppm.hours_{ref}$ is the ppm.hours of a worst case scenario without ventilation. ε_{res} varies between 1 (i.e., lowest **impact** and best resilience) and 0 (i.e., biggest **impact** and worst resilience).

The resilience score (RS) metric: The total resilience score (**RS**) of a building is a normalized indicator that aggregates resilience across all contaminants of concern. At the contaminant level, the resilience score of each contaminant (RS_i) is calculated by combining the absorptivity, recovery and shock impact ($\varepsilon_{abs}, \varepsilon_{rec}, \varepsilon_{res}$), which together describe how the system responds to a disturbance. These three components can be visualized as the sides of a triangle, where the enclosed area represents the contaminant-specific resilience. The total building-level **RS** is then obtained by weighting and summing the individual RS_i values across contaminants, as shown in equation (2.11):

$$\mathbf{RS} = \frac{5}{13}\left\{ RS_{CO_2} + \underbrace{\sum_{i=1}^{\#HAPs} \omega_i RS_i}_{RS_{HAPs}} \right\}$$
$$where \ \sum \omega_i = 1$$

(2.11)

In Equation (2.11), the factor 5/13 reflects the weighting of absorptivity within the overall resilience score. The denominator (13) corresponds to the total number of possible indicator points across all components, while the numerator (5) reflects the maximum attainable score for absorptivity.

The total **RS** splits the building contaminants between CO_2 and hazardous air contaminants (HAPs) (e.g., particles, volatile organic compounds (VOCs), etc.) due to their different impacts on health and building designers' understanding of them. The weights associated with each HAP are calculated based on combined quantitative approach based on an exposure risk assessment and a qualitative approach based on hazard classification.
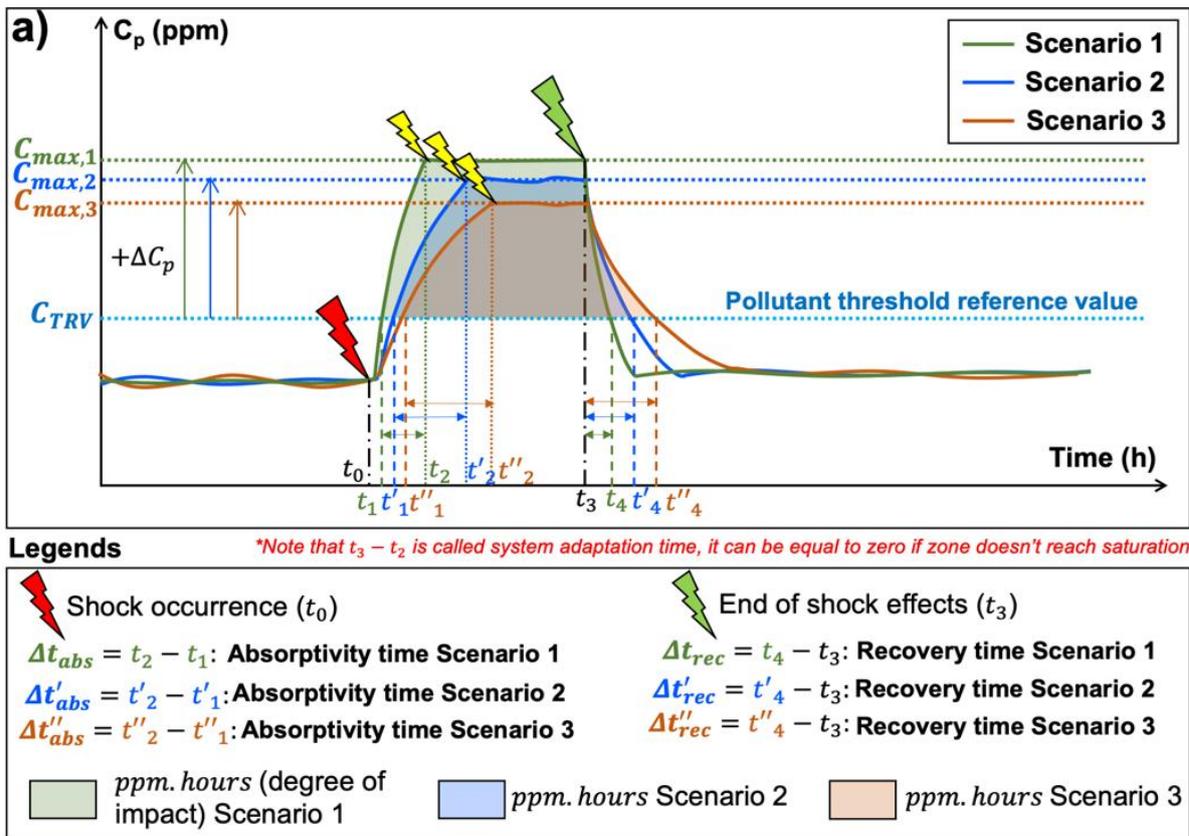
Figure 2.7: Illustration of IAQ resilience aspects

While the resilience score is calculated independently of the DALY-based metrics introduced earlier in this report, both approaches share the same conceptual aim of quantifying harm from indoor exposures. The DALY framework captures the long-term health burden from chronic exposure, whereas the resilience framework evaluates how systems perform during short-term events such as pollution episodes or indoor source peaks. A potential future development would be to link resilience indicators to acute health outcomes and express these in terms of DALYs, thereby providing a consistent health-based metric across both chronic and episodic exposures. This work, however, lies beyond the current scope of the Annex.

2.5.2.   Demonstration: Educational Case Study

The resilience framework is illustrated through a simple case study comparing two ventilation strategies: a constant air volume (CAV) system and a demand-controlled ventilation (DCV) system. The systems are evaluated in a typical residential setting under two representative "shock" scenarios. The first is an outdoor PM2.5 episode, modelled as a 5-day period with elevated concentrations (75 µg/m³). The second is an indoor CO_2 event, modelled as a 3-hour period

with ten occupants in a single room. The resilience indicators described in Section 2.5.1 (absorptivity, recovery, shock impact) are then applied to assess how each system responds to these disturbances.

Figure 2.8 illustrates illustrates the evolution of the **RS** with increasing degree of shock (doS) for the three ventilation systems: CAV, DCV & DCV without filters (**Step 7**).In addition to the two contaminant-based scenarios described above ($PM_{2.5}$ and CO_2), the figure also includes a mechanical shock case, represented by a power outage. This example shows how the same framework can be applied to non-contaminant disturbances that affect system operation.

Initial analysis showed that the **RS** decreased quickly following a linear trend until a certain value of doS, defined as the relative deviation of an exposure indicator from its baseline during the event, where it either plateaued or continued its decrease at a slower pace. For example, in a power outage scenario, where ventilation is interrupted and then restored, the framework showed that 64% of IAQ performance was recovered within 2.8 hours. In this case, the **RS** decreased more slowly, following concave parabolic trend. This change in pace reflects the fact that, once much of the system's resilience capacity has been exceeded, further increases in shock severity cause proportionally smaller reductions in the RS.

When comparing the three systems, CAV and DCV ended up having the same RS. This occurs because, in the CO_2 event, both CAV and DCV responded in the same way: their absorptivity, recovery, and shock impact indicators for CO_2 were identical. As a result, their resilience score for CO_2 (RS_{CO_2}) converged to the same value. For harmful indoor air contaminants (RS_{HAPs}), the values between systems also evened out. The pollutant weighting applied in the analysis gave slighting higher importance to particulate matter, which would normally favor the DCV system since is performance marginally better for PM removal. However, CAV had a lower recovery efficiency for VOCs ($\varepsilon_{rec,VOCs}$), which carried a higher weight in this case, balancing out the results and leading to similar values of RS_{HAPs} overall. Beyond 2.8 hours of power outage, DCV without filters had a 13% lower **RS** than the other systems, due to the effect of particulate matter and its high weighting.
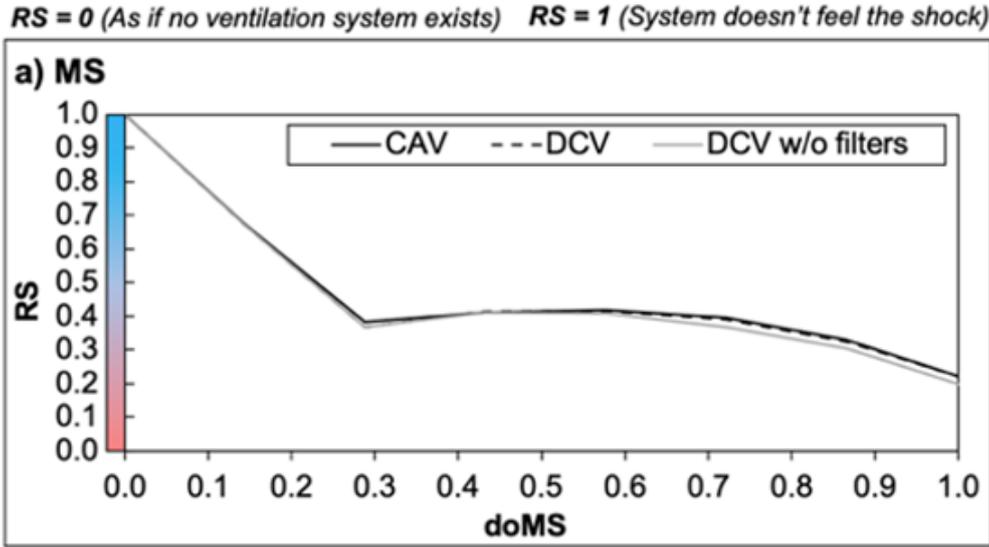
Figure 2.8: Evolution of the total **RS** for CAV, DCV, and DCV with no filters for a power outage shock with increasing degree of shock (doS)

This case study demonstrates how the resilience framework can distinguish system responses under different shocks, highlighting where performance converges and where design choices such as filtration or control strategy make a critical difference.

The resilience framework provides a complementary perspective to the DALY-based and multi-criteria approaches described in earlier sections. Each method addresses a distinct dimension of IAQ management. The DALY approach quantifies the long-term health burden of chronic exposures, identifying which contaminants cause the greatest harm. The multi-criteria analysis compares ventilation systems under typical conditions, integrating IAQ, energy, costs, and robustness to reveal trade-offs in design choices. The resilience framework extends this by examining system behaviour during short-term shocks and recovery events, conditions that real buildings often experience. Together, these three approaches form a coherent set of methods for evaluating ventilation systems, linking to chronic health

impacts, steady-state performance, and dynamic response into a single framework. This combination supports both design and policy decisions that protect health not only in normal operation but also during episodic or disruptive events.

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2.6.　　Economic costs of harm caused by indoor air contaminants

Author: Louis Cony

Indoor air contaminants contribute to chronic (long-term) diseases like lung cancer and leukemia. They also cause acute (short-term) issues like headaches and respiratory discomfort. These reduce concentration and productivity, especially in office workers. Assessing indoor pollution costs is crucial.

This work proposed a method to calculate economic costs for individuals or populations. It uses DALY costs for chronic effects. This accounts for healthcare expenses, years of life lived at lower quality than normal, and productivity losses associated with each contaminant. Acute effects are included in Sick Building Syndrome (SBS) costs.

2.6.1.　Chronic effects with dynamic DALY cost

Environments with elevated contaminant concentrations can cause sickness or severe diseases. Assessing health-related costs is necessary. This requires an estimation of health impacts first.

One approach counts the DALYs lost due to contaminant exposure. DALYs measure the number of healthy years lost. Logue et al. (2012) proposed two methods to calculate dose-response functions for many chemical species. De Jonge and Laverge (2022) adjusted the DALY approach to use real time exposures (instead of annual average concentration), which is discussed in Section 2.

We are aiming to define a cost that can be applied at the scale of an individual person or a building, so that each ventilation strategy can be studied independently. In this approach, total cost induced for 1 DALY/person of a contaminant i is the sum of concerned medical cost ($H\ cost_i$), productivity loss (P_{loss}) as well as life cost ($LY\ cost$). In a previous socio-economical study, life year (LY) cost was estimated around 115 000€ per year per person. Average national productivity (P_{cost}) is estimated around 145 000 € per year per person (ANSES, 2014). When applied individually to a specific building, P_{cost} should be recalculated, based on average employees productivity inside building.

Concerning the productivity cost due to DALY, we consider that the proportion of productivity loss is equal to the life quality loss. Authors are aware that this may induce a bias because some diseases may have a low-quality life lost and yet induce a working stop.

Medical costs vary from one contaminant to another as the diseases induced are also different, therefore, a cost per DALY must be determined for each contaminant. Average medical cost per DALY is proposed for studied contaminants (INCA, 2007) in Table 2.5. For contaminants whose medical cost could not be found, authors arbitrarily selected a cost of 30,000€ (Average of all costs). Considering PMs contribution to total DALY in results section (92%), unknown medical costs have almost neglectable impact on total cost.

Table 2.5: Medical cost induced by contaminant (€/year)

Contaminant	Medical cost (€)
Benzene	46 000

Trichloroethylene	70 971
Radon	25 526
PM	10 402
CO	1 085

2.6.2. Short-term effects with SBS cost

Although there is already a productivity loss integrated in the DALY calculation, it is important to also integrate a global productivity loss. Productivity loss associated to DALY cost is due to severe chronic diseases. Nevertheless, a bad environment can cause concentration disturbance and productivity loss without leading to severe diseases. For one person that may suffer severe disease, there is a proportion of other employees who feel uncomfortable and suffer temporary acute effects.

Two indices are often used in this context. The Indoor Air Pollution Index (IAPI) combines concentrations of several key indoor pollutants into a single score of air quality, while the Indoor Environment Index (IEI) extends this approach to include other aspects of the indoor environment, such as thermal, acoustic, and visual comfort. In IAQ applications, only the air quality component of the IEI is usually calculated.

When having an in situ inquiry it is possible to ask the Percentage of Occupants Presenting at least 1 (SBS) symptom in a persistent way (from 1 to 3 days a week) during the last 4 weeks (POPS) or at least 2 symptoms (POPS2). A correlation was proposed (Kirchner et al., 2007) between POPS and IAPI (Sufuoglu and Moschandreas, 2013) index as well as another one between POPS2 and IEI (Moschandreas and Sufuoglu, 2004). This correlation is adapted in equations 6.1 and 6.2.

$$Mean\ IAPI = 0.25 \times Mean\ POPS - 14.3 \tag{2.12}$$

$$Mean\ IEI = 0.30 \times Mean\ POPS2 - 14.6 \tag{2.13}$$

Productivity loss (P_{loss}) is derived from published studies linking IAQ and sick building syndrome (SBS) symptoms to reductions in work performance. In this framework, the value for POPS2 is taken directly from the literature, while the value for POPS is assumed to be half of this, reflecting the lower severity of symptoms. In line with published studies, the productivity loss for POPS2 is taken as 2% of working performance, while POPS is assumed to be half of this value (1%). Therefore, cost due to SBS can be estimated as

$$SBS_{cost} = P_{cost} \times \left[(P_{loss} \times POPS2) + \left(\frac{P_{loss}}{2} \times (POPS - POPS2) \right) \right] \tag{2.14}$$

By reusing equations (6.1) and (6.2), we can write

$$SBS_{cost} = P_{cost} \times P_{loss} \left(\frac{IEI + 14.6}{0.60} + \frac{IAPI + 14.3}{0.5} \right) \times \frac{2}{5} \tag{2.15}$$

As POPS and POSPS2 describe persisting symptoms as occurring from 1 to 3 times a week, a coefficient of 2/5 was added to account for Productivity loss and consider it occurs 2 days in working week of 5 days. As IEI is dependent of IAPI

$$IEI = \frac{IAPI + IDI}{2} \tag{2.16}$$

Here, IDI denotes the composite IAQ predictor used to estimate the prevalence of SBS symptoms. Practically, IDI is derived from the pollutant-based indices already introduced (IAPI/IEI) and provides a single, scaled variable that feeds

the empirical relationships to POPS (percentage of occupants with ≥1 persistent SBS symptom) and POPS2 (≥2 symptoms), as adapted in Equations 6.1 and 6.2.

Now finally, SBS cost is finally calculated as:

$$SBS_{cost} = P_{cost} \times P_{loss}(0.83 + 2.83IAPI + 0.83IDI) \times \frac{2}{5} \qquad (2.17)$$

Productivity decrease due to SBS in office buildings is assumed to be 6% for POPS2 and 3% for POPS, which is in agreement with findings of Wargocky et al. (2000).

2.6.3. Numerical Modelling

A model based on a coupling process (type98) between CONTAM and TRNSYS was created to generate realistic pollution data. Demand balanced ventilation is implemented in all rooms except for corridors and toilets, which have constant balanced ventilation systems.

The contaminants considered include CO, CO_2, Acetaldehyde, Acrolein, Benzene, Formaldehyde, Styrene, Tetrachloroethylene, Toluene, Trichloroethylene, xylene, and Particulate Matters (PMs). The PMs are separated into 20 size bins according to aerodynamic diameter, which is consistent with the exposure-response functions used in the cost calculations.

Table 2.6: Simulation configuration

Parameter	Possible value	Unit
Ventilation flow rate	5;22;56	m^3/h/person
Indoor sources	Low; High	Stat percentile
Outdoor pollution	Low; High	measured pollution
Filtration	Yes/No	

The model was configured to study 3 parameters, ventilation flow rate, level of indoor emission sources[1], level of outdoor pollution[2], presence or absence of filtration. For the purpose of the study, a total of 24 configurations were applied. These configurations are combinations of the possibilities listed in table 2.6. The simulations are run for the entire year.

The cost estimates are presented for three ventilation scenarios, expressed as outdoor air supply rates of 5, 22, and 56 m^3/h per person. Figure 2.9 shows the SBS- and DALY-related costs at the lowest rate (5 m^3/h per person). Costs are highest under this scenario because pollutant concentrations are greatest, leading to both higher prevalence of SBS symptoms and greater long-term health burdens.

Figure 2.10 presents results for the intermediate case (22 m^3/h per person). Here, both SBS and DALY costs are reduced compared with Figure 2.9, reflecting the benefits of increased ventilation in diluting indoor pollutants. While the distribution of costs across categories remains similar, the overall magnitude is lower.

Figure 2.11 shows results for the highest ventilation rate (56 m³/h per person). In this case, pollutant concentrations and associated health costs are lowest, with SBS and DALY values substantially reduced compared with the 5 and 22 m^3/h cases. However, this improvement comes with higher energy demand for conditioning outdoor air, which is not included in the cost estimates here but is relevant for practical implementation.

Finally, Figure 2.12 compares cost differences across the three ventilation scenarios. The plot highlights the substantial reduction in both SBS and DALY costs when moving from 5 to 22 m^3/h per person, and the further, though smaller, reduction achieved at 56 m^3/h per person. These results illustrate the strong influence of ventilation rate on the economic costs of harm caused by indoor air contaminants.

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[1] Low/High emission match P25/P75 level of statistical data from PANDORA indoor emission database.

[2] Low/High outdoor pollution match lowest and highest outdoor pollution year (from 2013 to 2019) for the same location.

Overall, the results demonstrate that increasing ventilation reduces the combined health and productivity costs of poor IAQ. The largest relative benefit is observed when moving from very low (5 m³/h per person) to moderate ventilation (22 m³/h per person), while further increases to high ventilation (56 m³/h per person) yield diminishing returns.
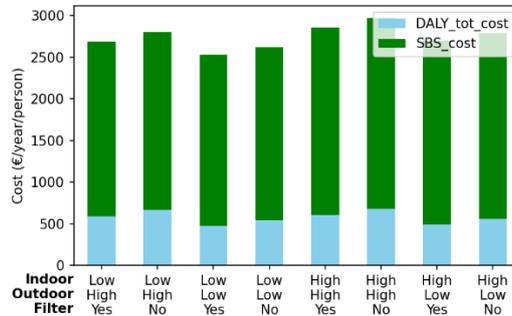
Figure 2.9: SBS and DALYs costs for 5m³/h/person
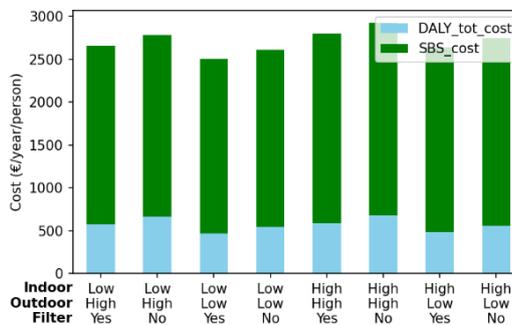
Figure 2.10: SBS and DALYs costs for 22m³/h/person
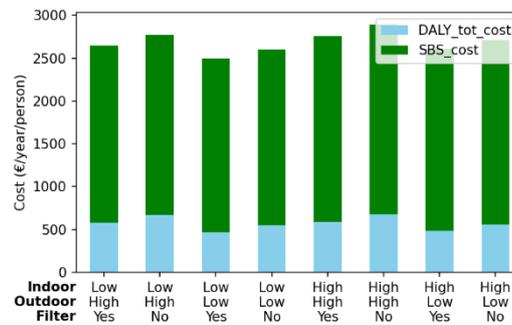
Figure 2.11: SBS and DALYs costs for 56m3/h/person
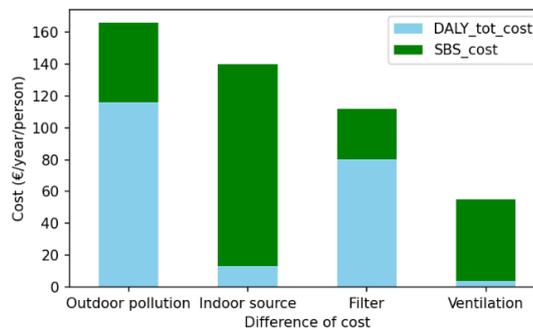
Figure 2.12: SBS and DALY cost differences by source

2.6.4. Summary

In this study, total average socio-economic cost attributed to poor IAQ in an office environment is estimated to be 2.711€/year/person. The major share of this cost (2.141 €/year/person or 79%) was associated with the daily reversible loss of productivity due to sick building syndrome (SBS). The remaining costs (570 €/year/person or 21%) were linked to chronic health outcomes, including loss of life quality, medical costs and productivity loss. Within this category, particulate matter (PM) account for around 92% of the DALY-related costs, reflecting the dominant role of outdoor air pollution in driving indoor exposures.

Mitigation measures can reduce these costs. In this case, the use of low-emission materials lowered the estimated costs by 141 €/year/person (-5%), filtered balanced ventilation by 111 €/year/person (-4%), and increased flow rates by 55 €/year/person (-2%). If all three of these measures are combined, the reduction reaches 305 €/year/person (-11%). Based on the total estimates, the implied economic valuation is around 265.250 €.

These results are specific to the office scenario modelled and depend on assumptions about SBS prevalence, productivity loss, pollutant selection, and DALY valuation. These results are based on available data on exposure-effect relationships. Although designing empirical validation studies is not straight forward, this is identified as a major focus for further research. The results should therefore be interpreted as indicative rather than universal values. Nonetheless, they underline the substantial socio-economic burden associated with poor IAQ in office buildings, which is likely to be underestimated when SBS is not included.

More broadly, this analysis complements the approaches presented in earlier sections of the report. The DALY framework (Section 2) quantifies population health burdens, the multi-criteria system assessment (Section 4) evaluates how design choices affect exposure and harm, and the resilience framework (Section 5) considers performance under shocks. By adding an economic perspective, this section highlights the financial implications of harm from indoor air contaminants. Taken together, these approaches provide a more comprehensive evidence base for prioritising IAQ improvements in building design and operation.

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3. Source characterization and typical exposure in residential buildings

Editors: Gabriel Rojas and Marc Abadie

3.1.   Introduction

The activities of Subtask 2 aimed to characterize indoor pollutant sources and the resulting concentrations in residential buildings. Section 3.2 documents the structure, content and user-interface of the comprehensive PANDORA database and summarizes the underlying emission rate measurement studies and the expansion of the database as part of the subtask 2 activities. An exemplary application of the PANDORA database, and its data analysis results, shows how the formaldehyde emission rate in a children's room can be easily estimated, e.g. for IAQ modelling. Selecting more recent database entries, a floor-area specific formaldehyde emission rate of around 30 µg/(m²h) was determined for new construction.

Section 3.3 describes the standardized data processing workflow developed within this subtask to extract pollutant concentrations from measurement data of >1000 homes collected during past IAQ studies across multiple countries. The creation of an openly accessible IAQ database repository, along with associated analytical tools, ensures that this research can remain an evolving resource for the scientific community. The meta-analysis of CO_2 concentration confirms and quantifies that bedrooms are clearly the most under ventilated rooms in residential setting, with mean CO_2 concentration well above 1000 ppm during the night if not mechanically ventilated. Formaldehyde concentrations were significantly lower in mechanically ventilated homes with values around 25 µg/m³. However, mechanically ventilated homes exhibited higher $PM_{2.5}$ concentration compared to the other ventilation types with high variability, in particular in the kitchen. The formaldehyde emission rates derived from these measurements match well with the bottom-up calculation approach from section 2 (applying most recent database entries).

The output of the activities of Subtask 2 of IEA EBC Annex 86 enables the characterization of pollutant sources and typically encountered pollutant concentrations in residential buildings. Section 3.2.2 documents the PANDORA database containing a rich dataset for emission rate measurements (mostly laboratory) for a multitude of pollutants and sources. It can be used to estimate and model the pollutant emission in residential homes in a bottom-up approach. The output of section 3.3 allows a top-down approach using empirical data of pollutant concentrations and ventilation rates in homes. But how well do those fit together?

Addresses this question for formaldehyde emissions by combining the results from the two activities (documented in sections 3.2 and 3.3) one can model and/or characterize indoor air pollutant exposure in residential buildings applying a bottom-up and a top-down approach. The bottom-up example for formaldehyde emissions presented in section 2, exhibited a great variance in the results depending on how emitting products are selected from the database. The floor-area specific formaldehyde emission rate after 28 days varied from around 1000 µg/(m²h) down to 70 µg/(m²h) reflecting the interquartile range of approach 2 (based on statistical analysis). In contrast, approach 1 (plausible selection of more recent database entries) resulted in around 28.5 µg/(m²h).

The top-down approach used one of the studies contained in the IAQ database repository, which had investigated 123 new single-family homes in Austria with and without mechanical ventilation. Within this subtask the median floor-area specific formaldehyde emission rate in bedrooms was estimated to around 29 µg/(m²h) and 24 µg/(m²h) about three and 15 months after occupants moved in, respectively.

Remarkably, the bottom-up approach and the empirical top-down approach agree unbelievably well. However, one needs to acknowledge the uncertainties and assumptions (many of them rather arbitrary) that result in a great variance of the results. Accounting that 1) the bottom-approach will generally tend to overestimation, 2) that the statistical analysis of the emission source database may also include outdated products, and 3) that those emission rates generally reflect the emission rate in rather new product state (around 30 days in the presented example) one can conditionally recommend to use the lower quartile when estimating emission rates in a bottom-up approach, as done in approach 2 in section 3.2. Naturally, this may not be generalizable to other pollutants.

Future work may focus on integrating additional data sources, refining analytical methodologies, and incorporating data from emerging technologies such as IoT-based air quality sensors to allow a comprehensive evaluation of indoor air quality and its health and comfort related impacts on building occupants.

3.2. Source Characterization

Indoor air quality (IAQ) models require diverse input data, including envelope leakage information, weather conditions, ventilation system characteristics, contaminant source emission rates, sink removal rates, occupant schedules, and air cleaner removal rates. Howard-Reed and Polidoro (2006) highlighted that while much of this data is available in the literature, it is rarely compiled into a readily accessible source. They concluded that to streamline the IAQ modeling process and enable the assessment of data quality and completeness, there is an urgent need for well-designed databases of measured contaminant modeling data. This led to the creation in 2009 of the PANDORA (a com**P**il**A**tion of i**ND**o**OR A**ir pollutant emissions) database (Abadie and Blondeau, 2011), which systematically compiles available data on the emission rates (ER) of both gaseous and particulate pollutants, providing valuable information for IAQ modelers until 2014. The primary goal of participants in Annex 86 Subtask 2 was to discover and gather new input data necessary for IAQ modelers to accurately characterize indoor sources of pollutants. The first section outlines the methodology used to identify, implement, and analyze emission rates of pollutants from indoor sources. The second section details the PANDORA database, including its underlying data and instructions on utilizing it to assess IAQ modeling tools' emission rates.

3.2.1. Literature review on emission rates of indoor pollutant sources

Scientific research on ER initially focused on indoor emissions from heating and cooking appliances —such as domestic gas-fired ranges, gas-fired stoves, gas-fired unvented space heaters, kerosene-fired unvented space heaters, conventional and catalytic woodstoves in the early 1980's. This category now represents 12% of the references collected. In the 1990's, several studies were interested in electrical equipment encountered in offices (printers, photocopiers, computers, etc.) as sources of indoor pollutants. In 1997, Bluyssen *et al.* outlined the principles for assessing VOC emissions from building materials, specifically focusing on a procedure to evaluate solid flooring materials through emission factor determination. That was the start of different projects regarding the emissions of construction and decorative materials (21% of the references implemented in PANDORA). As a result, multiple emission databases were developed, including the European SOPHIE (Oliveira Fernandes, 2001), the Californian one for construction materials for school buildings (Alevantis, 2003), the Canadian MEDB-IAQ (Won and Shaw, 2004) and, more recently, the European BUMA (Barrero, 2009). Interest in emissions from cleaning products and air fresheners (11% of the references) and from furniture (7%) also began in the early 2000's (Zhu *et al.*, 2001; Oliveira Fernandes, 2001). In parallel, various studies focused on emissions from office electrical equipment (14% of the references). The study of Klepeis *et al.* (2003) on environmental tobacco smoke (ETS) from cigars and cigarettes can be considered the first data on sources related to the occupants and their activities. This category has grown significantly and now accounts for 30% of the total references. The last category of sources (*whole room or building,* with 5% of the references) appears more recently. It treats the indoor spaces as a single emission source.

The following sections summarize the papers whose data have been integrated into PANDORA. The literature is organized according to the database structure, which is based on seven source categories. For a deeper understanding of the methods and sources employed in the measurement of pollutant emission rates, summary tables are presented in Appendix 1 providing additional information like the studied sources, the experimental chamber dimensions, the environmental conditions and fresh air supply rate, the duration of the measurement, the selected pollutant along with the measurement system employed, and the kind of emission rate data that is provided by the authors.

3.2.1.1 Construction and Decorative Materials

Bluyssen et al. (1997) developed a procedure to assess VOC emissions from building materials, focusing on solid flooring through emission factor determination and modeling indoor VOC concentrations. Oliveira Fernandes (2001) emphasized the need for low-emission materials, reporting VOC and formaldehyde emissions from various building materials. Alevantis (2003) compared VOC emissions from standard and sustainable materials, with rubber-based flooring showing higher emissions. Afshari et al. (2003) studied VOC emissions from paint, highlighting the role of film thickness. Won and Shaw (2004) created a database covering 60 building materials, aiding in the selection of low-emission products. Berrios et al. (2005) found that office materials like carpets emitted fewer VOCs than electronic devices. Bartekova et al. (2006) tested OSB and coatings, concluding they met low-emission standards. The BUMA project (Barrero, 2009) developed an emissions database for over 400 construction materials. Plaisance et al. (2014) found significant variability in carbonyl emissions from 23 materials. Maupetit (2014) noted that additive models, i.e.

adding individual source emission rates, overestimate the total emissions from sources located in a room. Kozicki et al. (2018) assessed VOC emissions from waterproofing materials, stressing the importance of ventilation. Kozicki and Guzik (2021) analyzed adhesives, finding variations in emissions depending on the material composition. Caudron et al. (2022) observed increased emissions from bio-based materials at higher humidity. Jung et al. (2022) proposed formaldehyde emission models, and de Kort et al. (2023) evaluated emissions from various board materials, emphasizing the differences between bio-based and synthetic options.

3.2.1.2   Furniture

Oliveira Fernandes (2001) summarized VOC emissions from indoor sources in the SOPHIE database, highlighting tests on cushions using small chambers under controlled conditions (23 ± 1 °C, 45 ± 5% RH) and measuring VOCs and formaldehyde emissions. Berrios et al. (2005) analyzed emissions from passive (e.g., desks, chairs) and active (e.g., printers, PCs) sources in office settings, finding negligible TVOC emissions from furniture. Roux (2012) measured VOCs and aldehydes emitted from 21 nursery furniture pieces and 38 individual components, noting generally low emission levels with variable results depending on whether the item was a complete piece of furniture or separate components. Yan et al. (2019) studied a foot stool and bedside table, finding VOC emissions peaked within 1–2 hours and identified health risks from xylene exposure. Zheng et al. (2024) examined emissions during daycare activities, especially from mattresses, under different conditions, revealing critical health risks for young occupants, with emission patterns influenced by product type and age.

3.2.1.3   Cleaning Products and Air Fresheners

Cleaning products and air fresheners are significant contributors to indoor air pollution, emitting VOCs and fine particulate matter ($PM_{2.5}$) that can react with ozone to form harmful secondary pollutants, such as formaldehyde and SOAs (Zhu et al., 2001; Singer et al., 2006). Terpenes like limonene and α-pinene, often present in scented products, are particularly reactive, with ozone exacerbating pollutant formation (Liu et al., 2004; Nicolas et al., 2013). Zhu et al. (2001) identified 2-butoxyethanol as a key VOC in cleaning products, while Singer et al. (2006) demonstrated that dilution reduces VOC emissions. Afshari et al. (2005) and Géhin et al. (2008) highlighted significant spikes in ultrafine particles during cleaning, especially in the 5–40 nm range. Nicolas et al. (2018) emphasized the variability in emissions from commercial and homemade products, while Zheng et al. (2024) showed how brand, temperature, and humidity influence emission profiles. Critical mitigation strategies include proper ventilation, diluted usage, and avoiding ozone-generating devices.

3.2.1.4   Occupants and Occupant Activities

Klepeis et al. (2003) developed a model to estimate particle emission factors from indoor sources, applied to environmental tobacco smoke. He et al. (2004) measured $PM_{2.5}$ emission rates for residential activities in Brisbane, linking elevated concentrations to specific behaviors. Lee and Wang (2004) studied air pollutant emissions from incense burning in a controlled chamber, showing incense as a significant source of indoor pollution. Moser et al. (2005) investigated exhaled VOCs, finding differences between smokers and non-smokers using PTR-MS. Afshari et al. (2005) measured particle emissions from various indoor sources, including cigarettes and candles, in a chamber experiment. Wallace (2006) reported particle concentrations from different cooking types, revealing varying particle mass releases. Health Canada (2006) analyzed tobacco emissions, comparing domestic and imported cigarettes. Zai et al. (2006) used emission models to quantify candle smoke particles across different burning modes. Yeung et al. (2008) explored cooking-related particle emissions, estimating emission rates for Chinese and Western cooking styles. Evans et al. (2008) examined fume production from frying, noting significant differences among homes. Kurosawa et al. (2008) investigated VOCs from TVs and shoes, identifying high emissions of certain VOCs. Gehin et al. (2008) measured particle emissions from residential activities, finding ultrafine particles from cooking and cleaning. Pagels et al. (2009) studied candle emissions, reporting higher mass rates during sooting. Riess et al. (2010) assessed VOCs in exhaled breath during exercise. Derbez and Solal (2014) quantified emissions from school supplies and cleaning products. Tang et al. (2016) quantified VOC emissions from humans, revealing a significant contribution to indoor VOC levels. Persily and de Jonge (2017) provided data on human CO_2 generation, critical for ventilation assessments. Nicolas et al. (2017) investigated incense and candle emissions, finding that incense produced higher levels of pollutants. O'Leary et al. (2019) studied cooking emissions in Dutch homes, noting significant reductions when operating the cooker hoods. Zhao et al. (2021) quantified indoor source emissions in 40 German homes, highlighting candles as major contributors. Wang et al. (2022) measured human VOC emissions under controlled conditions, finding enhanced emissions in the presence of ozone. Zheng et al. (2024) evaluated VOC emissions from daycare center activities, with a health risk assessment.

3.2.1.5   Heating and Cooking Appliances

Several studies have focused on pollutant emissions from heating and cooking appliances in residential settings. Traynor et al. (1982) quantified emissions from gas-fired ranges, demonstrating the effectiveness of an indoor air quality

model in predicting pollutant levels. Similarly, Girman et al. (1982) evaluated emissions from gas-fired stoves and unvented space heaters, highlighting the risks associated with these appliances, particularly in poorly ventilated spaces. Borrazzo et al. (1987) used mass-balance models to study CO and NO_2 emissions in energy-efficient homes, emphasizing the role of air exchange in pollutant levels. Cácares, Soto, and Lissi (1989) measured emissions from gas and kerosene heaters, noting that predicted values often exceeded air quality standards. McCrillis and Burnet (1990) measured the PAH emission rates of Naphthalene, Pyrene and Benzo(a)pyrene from residential wood burning in woodstoves (conventional and catalytic) over a range of burn rates, wood types and altitude. Tissari et al. (2008) compared combustion conditions in wood stoves, finding that smoldering combustion significantly increased emissions of CO, VOCs, and particulate matter. These studies collectively stress the importance of proper ventilation and appliance maintenance to reduce indoor air pollution from heating and cooking appliances sources.

3.2.1.6 Electrical Equipment

Numerous studies have examined emissions from office equipment and electronic appliances, highlighting their contributions to indoor air pollution. Hetes et al. (1995) reported that emissions from materials (e.g., casings, inks) and operational processes increase hydrocarbon, ozone, and particulate concentrations, prioritizing dry-process photocopiers for exposure prevention. Black (1999) and Brown (1999) quantified emissions of VOCs, ozone, and PM_{10} from printers, photocopiers, and computers, finding laser printers emitted significantly higher VOC and ozone levels than inkjet printers. Lam and Lee (2000) confirmed this disparity by identifying higher TVOC and ozone emissions from laser printers. Wensing (2002) and Nakagawa et al. (2003) noted a decay over time in VOC emissions from electronics but consistent emissions during operation. Funaki et al. (2003) demonstrated that devices like portable PCs and photo journals significantly contribute to VOC and aldehyde levels. Berrios et al. (2005) linked active sources (e.g., computers, printers) to elevated TVOC levels. He et al. (2007) emphasized the impact of printer types on ultrafine particle (UFP) emissions. Finally, Gehin et al. (2008) highlighted fine and UFP emissions from residential activities, with negligible emissions from printers.

3.2.1.7 Whole room or building

Studies on emission rates from heating and cooking appliances in residential buildings have provided valuable insights into indoor air quality. Offermann et al. (2009) found that homes with mechanical ventilation systems often failed to meet required standards for formaldehyde, with higher-than-expected emission rates, especially in the winter months. Blondel and Plaisance (2011) measured formaldehyde emission rates from indoor materials in student residences and found that emission rates varied, with higher emissions from specific materials like beds. Chan et al. (2020) provided detailed data on multiple contaminants in California homes, including $PM_{2.5}$, CO, NO_2, and formaldehyde, capturing time-varying concentrations of these pollutants and highlighting the importance of accurate emission rate measurements for assessing indoor air quality. Zhou et al. (2022) focused on formaldehyde emissions, using a regression model to estimate emission rates across various homes, emphasizing that mechanical ventilation and air leakage could significantly affect emissions.

3.2.2. Pandora Database

3.2.2.1 Structure

Since its creation in 2009, the database structure has not changed. Figure 3.1 presents the main tables of data and the connections between them. Its main structure is based on four levels (Abadie and Blondeau 2011):

- **category**: the database structure starts with 8 main categories of indoor sources (Construction and Decorative Materials, Furniture, Cleaning Products and Air Fresheners, Occupants and Occupant Activities, Heating and Cooking Appliances, Electrical Equipment, and Whole room or building).
- **global_type (or sub-category)**: the first sub-category refines the description of the indoor sources. For example, for "Occupants and occupant activities" category, different sources are found, such as body, breathing, cooking, painting, smoking, etc.
- **type (or source)**: one last level is used to give additional information on the type of source (e.g. frying meat with oil on an electric stove, frying fish on an electric stove, cooking fish in an electric oven) but also on the experimental protocol (duration, environmental conditions, airflow rates, quantity of products, etc.), location (residential, school, office, hospital, etc.), country of origin, and reference of the original study.
- **contaminant:** the definition of the indoor pollutants generated by the source; their emission rates are given at this last level.

This four-level structure has been chosen to facilitate navigation into the data. However, additional information about the sources or the experimental conditions of the emission rate measurement may be needed. Additional fields are provided in both **type** and **contaminant** categories for comments to be added. Therefore, the PANDORA database

includes the main pollutants of indoor environments and provides additional information such as the pollutant common names, synonyms, CAS numbers, etc.
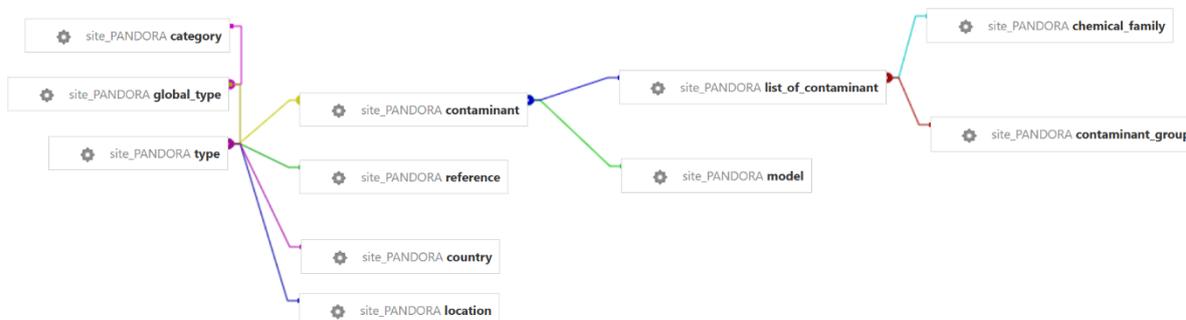
Figure 3.1: PANDORA's structure overview

Table 3.1: Pollutant emission models used in the PANDORA database

#	Description	Equation[1]
01	Gas - Steady-State - Emission Rate (µg/unit)	$S = a$
02	Gas - Steady-State - Emission Rate (mg/h)	$S = a$
03	Gas - Steady-State - Emission Rate (mg/m^2.h)	$S = a$
04	Gas - Steady-State - Emission Rate (mg/g)	$S = a$
05	Gas - Steady-State - Emission Rate (µg/(h.person))	$S = a$
06	Gas - Steady-State - Discrete Emission Data Model - Temp/RH (µg/h)	$S(T, RH) = a_i \; at \; T_i \; and \; RH_i$
07	Gas - Steady-State - Discrete Emission Data Model - Temp/RH (µg/(h.m²))	$S(T, RH) = a_i \; at \; T_i \; and \; RH_i$
08	Gas - Steady-State - Metabolism dependant (µg/(h.person)) [2]	$S(BMR, M) = 3197 \times BMR \times M$
09	Gas - Steady-State - T/RH - House (mg/(h.m²floor)) [3]	$S(T, RH) = H \times C_s \times \dfrac{\left(1 + A \times (T - 25)\right)\left(1 + B \times (RH - 25)\right)}{\dfrac{1}{a_t} + \dfrac{1}{k \times L}}$
10	Gas - Transient - Discrete Emission Data Model (µg/h)	$S(t) = a_i \; at \; t = t_i$
11	Gas - Transient - Discrete Emission Data Model (µg/m^2.h)	$S(t) = a_i \; at \; t = t_i$
12	Gas - Transient - Discrete Emission Data Model (µg/(h.unit))	$S(t) = a_i \; at \; t = t_i$
13	Gas - Transient - Discrete Emission Data Model (µg/(h.g))	$S(t) = a_i \; at \; t = t_i$
14	Gas - Transient - Peak Model (mg/m^2.h)	$S(t) = a_1 \, e^{-0.5\left(\frac{ln\frac{t}{t_p}}{a_2}\right)^2}$
15	Gas - Transient - Power Law Model (mg/m^2.h)	$S(t) = a_1 \times t_p^{-a_2} \; if \; t \leq t_p$ $S(t) = a_1 \times t^{-a_2} \; if \; t > t_p$

#	Description	Equation[1]
16	Gas - Transient - Single Exponential Decay Model (µg/h)	$S(t) = a_1\, e^{-a_2 t}$
17	Gas - Transient - Double Exponential Decay Model (mg/(h.m²)))	$S(t) = a_1\, e^{-a_2 t} + a_3\, e^{-a_4 t}$
18	Gas - Transient - Single Exponential Growth Model (µg/h)	$S(t) = a_1 + a_2(1 - e^{-a_3 t})$
19	Gas - Transient - Steps (mg/h)	$S(t) = a_i \; if \; t(i-1) < t < t(i), t(0) = 0$
20	Particles - Steady-State - [dpmin; dpmax] (#/min)	$S(t) = a$
21	Particles - Steady-State - [dpmin; dpmax] (µg/unit)	$S(t) = a$
22	Particles - Steady-State - [dpmin; dpmax] (mg/min)	$S(t) = a$
23	Particles - Steady-State - Log-Normal Distribution (#/min)	$S(t) = \sum S_i \int \dfrac{1}{d_p(2\pi)^{0.5}lnGSD_i} e^{-\frac{(lnd_p - lnGMD_i)^2}{2(lnGSD_i)^2}} dd_p$
24	Particles - Steady-State - Log-Normal Distribution (mg/min)	$S(t) = \sum S_i \int \dfrac{1}{d_p(2\pi)^{0.5}lnGSD_i} e^{-\frac{(lnd_p - lnGMD_i)^2}{2(lnGSD_i)^2}} dd_p$
25	Particles - Transient - Steps (mg/h)	$S(t) = a_i \; if \; t(i-1) < t < t(i), t(0) = 0$

[1] S: Emission rate (unit depends on model); a: mean, min, max, median and/or standard deviation (unit depends on model); t: time (h); a_i: constants (unit depends on model); t_p: time constant (h); d_p: particle diameter (µm); GSD: Geometric Mean Diameter (µm); GSD: Geometric Standard Deviation (-).

[2] BMR: Basal Metabolic Rate (MJ/d); M: metabolic rate (met).

[3] H: ceiling height (m); A, B, and C_{st}: fitted parameters; L: effective emitting material loading rate in the house (m²/m³); a_t: average air exchange rate for 1h (/h); k: mass transfer constant (m/s).

One important table is the list of models used to describe the indoor pollutant emission rates of a source. **Table 3.1** presents the 25 models (or ways to express emission rates) included in the database accounting for the pollutant (gas or particles), the temporal dependency (steady-state or transient) and the emission rate unit. For example, VOC data for Construction and Decorative Materials are surface-specific emission rates and are usually expressed for different periods of time (model #11) while those for Occupants and Occupants' Activities can be found relative to a use (per unit, mass of product or energy) or directly integrated as mass per time. For particles, emission rates are expressed as mass or number per time. To limit the number of models, additional calculations have been made from the original data when sufficient information was provided by the authors.

Additional libraries are updated with the integration of new data such as the **list_of_contaminants (or groups)** that provides the pollutant group (particles, VOCs, SVOCs, etc.), usual name and CAS number, the **country** library to store the geographical origin of the data, the **location** library to specify where the source is usually found (residential building, school, nursery, etc.) and the **reference** library to keep track of the scientific paper or report from where the data have been extracted.

3.2.2.2 Individual data

The following graphs present the nature of the data implemented in PANDORA: almost 10,000 emission rates (ER) from literature have been integrated so far. The first studies presenting ER of indoor pollutant have been published in 1982 and concerned emissions from Construction and Decorative Materials (Figure 3.2). 2003 is a pivotal year with the publication of several reports from American and European projects on materials' emission of VOCs. Studies reporting emission rates from Cleaning Products, Air Fresheners and Occupants' Activities have been published since 2013.

Currently, about 65% of the ER implemented in the database are related to the Construction and Decorative Materials, 16% to Cleaning Products and 12% to Occupants and Occupants' Activities.

Figure 3.2: Number of data implemented according to the category of indoor sources (left) and country (right).

A total of about 3,000 indoor pollutants is found in the database linked to at least one ER. Figure 3.3 shows that formaldehyde is currently the most cited pollutant with 336 ER, followed by TVOC (311), particle matter (173) and benzene (150).
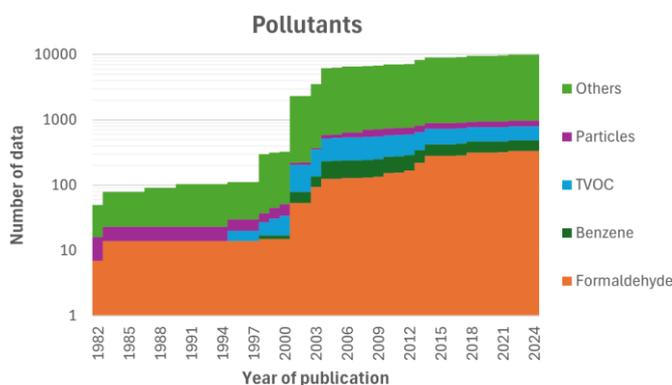
Figure 3.3: Number of data implemented according to the indoor pollutants.

Particle matters are expressed in terms of $PM_{2.5}$, PM_{10} or by size intervals. The main sources available in PANDORA are Occupants' Activities and Heating and Cooking Appliances (Figure 3.4). Formaldehyde emissions have been investigated in literature for all categories of sources, for Construction and Decorative Materials, Cleaning Products and Air Fresheners and Occupants' Activities. Most of the ERs for benzene come from Construction and Decorative Materials and Occupants' Activities. TVOCs have been mainly investigated for Construction and Decorative Materials and Electrical Equipment (mostly printers and photocopiers).
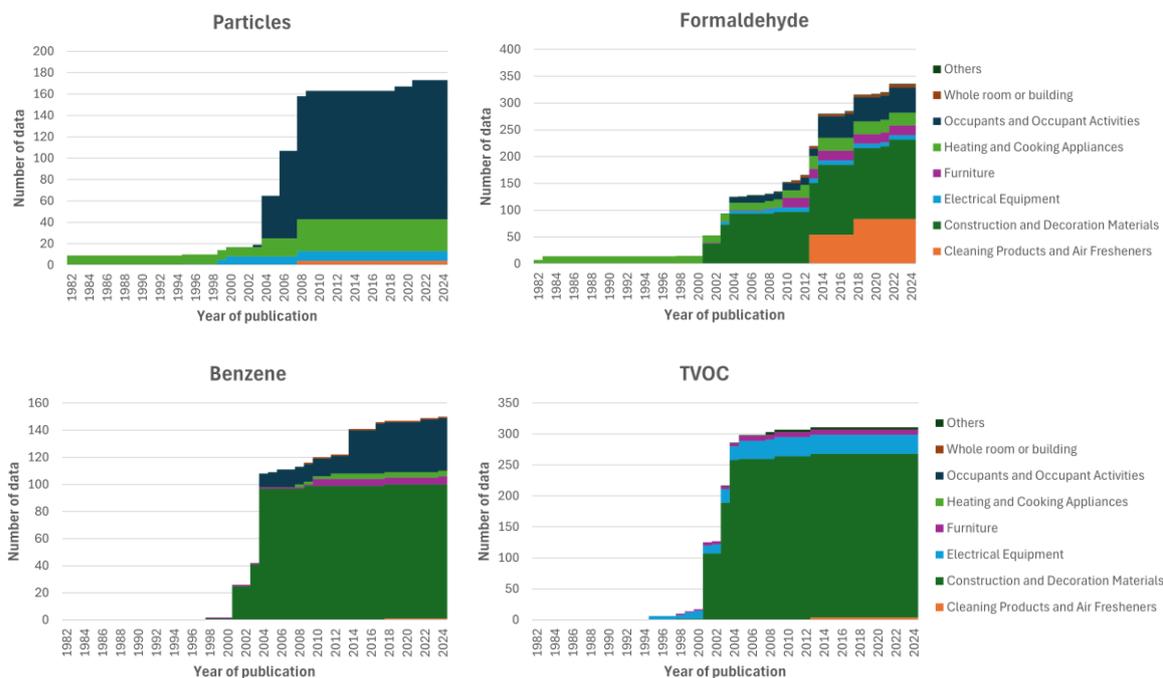
Figure 3.4: Number of data implemented according to the category of indoor sources for Particles, Formaldehyde, Benzene and TVOC.

Most of the data (62%) implemented in the database comes from peer-reviewed scientific journals such as Indoor Air Journal, Atmospheric Environment and Environmental Science and Technology. Reports from research projects account for 25% of the data including Construction and Decorative Materials data from the historical databases (SOPHIE, MEDB-IAQ or BUMA) or more recent projects on Occupants' Activities and Cleaning Products. The rest of the data comes from international conference papers such as Indoor Air and Healthy Buildings conferences.

All the data are accessible from the database homepage (https://db-pandora.univ-lr.fr/). Data can be searched by the source of pollutants defined by **category**, **sub-category,** and **source** and/or by the pollutant of interest via its **group** and **name** or **CAS number** (Figure 3.5). Results are shown in the lower part of the webpage as tags (Figure 3.6). By clicking on the selected tag, information about the source, reference paper (on the left side) and emission rate/model (on the right side) are then displayed (Figure 3.7).

Figure 3.5: Filtering the data in the PANDORA database.

Figure 3.6: Results display.
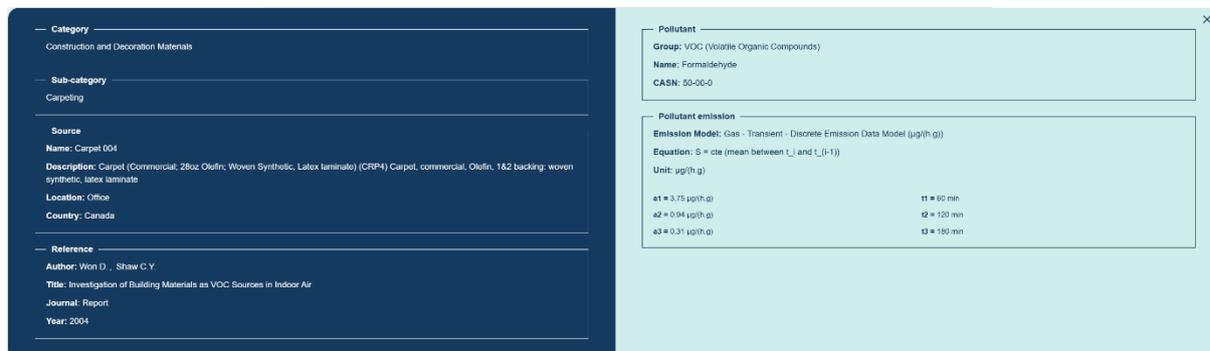
Figure 3.7: Information about the emission rate of the selected pollutant and source.

3.2.2.3 Data analysis

Finding or selecting individual data in the database can be challenging due to the wide range of options. To provide more practical information for IAQ modelers, a dedicated companion website has been created to offer statistical analyses of certain data groups, enabling more informed decision-making. The website can be accessed through the "Data Analysis" page of the PANDORA database by clicking on the link labeled "PANDORA Statistical Analysis."

The analysis focused on four target pollutants: PM$_{2.5}$, formaldehyde, benzene, and TVOC. For each indoor pollutant, the data were compiled based on their primary indoor sources, namely Construction and Decorative Materials, Furniture, and Occupants and Occupants' Activities (including cleaning products). While most of the results on the webpage are straightforward compilations, the Construction and Decorative Materials category offers a more detailed analysis due to the large volume of data (65%) available in the database. Note that the results are displayed in figures, and the associated statistics (mean, standard deviation, min., P25, median, P75, and max.) can be downloaded for external use.

Construction and Decorative Materials

The analysis results for Construction and Decorative Materials data for formaldehyde from flooring materials are presented in Figure 3.8. The first chart shows ERs at 3 days, 28 days, and 365 days, while the second splits these results based on the year of data publication.
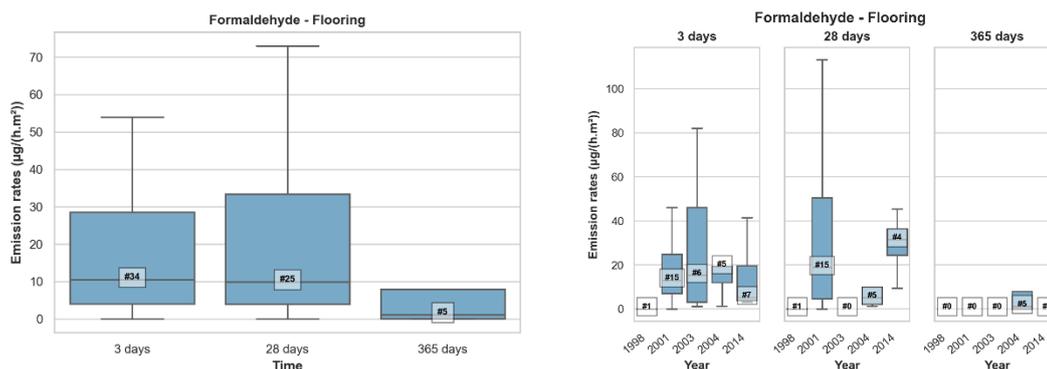
Figure 3.8: Statistics of ERs of formaldehyde for flooring after 3, 28, and 365 days (left: all data; right: separated by the year of publication).

As previously noted, data are expressed in different formats. In the case of Construction and Decorative Materials, five modeling approaches have been used to calculate the statistics at three time points: 3 days, 28 days, and 365 days. The methodology for each model is as follows:

- Model #03: References provide an emission value for t = 3 days and t = 28 days only. Note that the data availability is limited, and the age of materials is often unknown or not reported.

- Models #14, #15, and #17: Calculations are performed for each time point. These equations are typically based on data from periods under 30 days (sometimes extending to 60 days). Calculations for t = 365 days are extrapolated and should be interpreted with caution.
- Model #11:
  - For t = 3 days: The closest available time point less than or equal to 3 days is used.
  - For t = 28 days: The closest available time point less than or equal to 30 days is used (to account for the abundance of data at t = 30 days instead of t = 28 days).
  - For t = 365 days: The closest available time point greater than 6 months is used (currently, no data for this duration is available in PANDORA).

In the previous results, sources were still separated by sub-categories, these are: Carpeting, Acoustical Materials, Finishes, Flooring, Furnishing Materials, Installation Materials, Interior Panels, Structural Materials, Insulation Materials, Wall Covering and Openings. In that way, IAQ modelers must select the emission rates corresponding to the materials composing the floor, ceiling, and vertical walls of the indoor environment they need to model. To facilitate the process of calculating a global emission rate that accounts for all those building parts, we calculate an ultimate aggregated data called meta-data that is related to the geometrical surface area i.e. the sum of the floor, ceiling and vertical walls surface areas (Figure 3.9). However, currently, the database does not include a specific field to distinguish whether the material is used for the floor, vertical walls, or ceiling. As a result, all materials are equally applied to each surface type with the same probability. In this way, there is no dependency on the building or room dimensions. Therefore, the meta-data statistics are derived from a single statistical value (mean or maximal) of each material category (Acoustical Materials, Carpeting, etc.) previously calculated and the number of available data points. The methodology employed here is based on the rules of the French LCA database INIES (INIES, 2022) to calculate default values when specific values are not available:

- If only one value is available, then the resulting value is multiplied by two.
- If two values are available, the resulting value is the maximal value of the two available values multiplied by 1.3.
- If there are more than two available values, the resulting value is the mean value multiplied by 1.3.

When available, the French Label color-scale for VOC emissions from construction and decorative materials (French Decree April 19th, 2011) is displayed for emissions at 28 days. The color code used to categorize the emissions is: green (A+ = low emission), light green (A), yellow (B), and red (C = high emission). The following reference room dimensions and air change rate are 4.0 × 3.0 × 2.5 m³ and 0.5 vol/h of clean air. The present calculations considered that the material is applied to all internal surfaces (ALL, 59 m²), only the Floor or Ceiling (F/C, 12 m²) and only vertical walls (VERT, 35 m²).
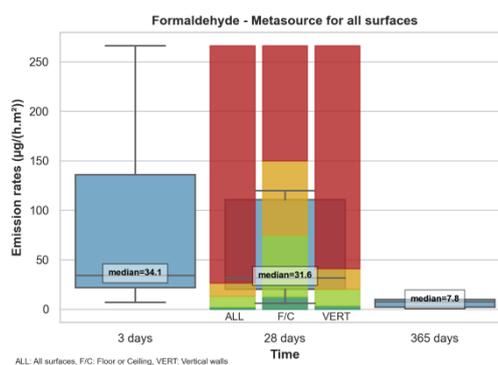
Figure 3.9: Meta-data statistics of ERs of formaldehyde after 3, 28 and 365 days (French label color-scale is displayed for comparison).

Other sources

Since the number of available data points is insufficient to calculate statistics, all emission rates for other sources of formaldehyde, benzene, and TVOC (furniture and occupants and their activities), as well as particles expressed as PM$_{2.5}$ (occupants and their activities), are provided on the Data Analysis webpage and can be downloaded as a *.txt* file. Figure 3.10 presents how the information is displayed for formaldehyde as an example.
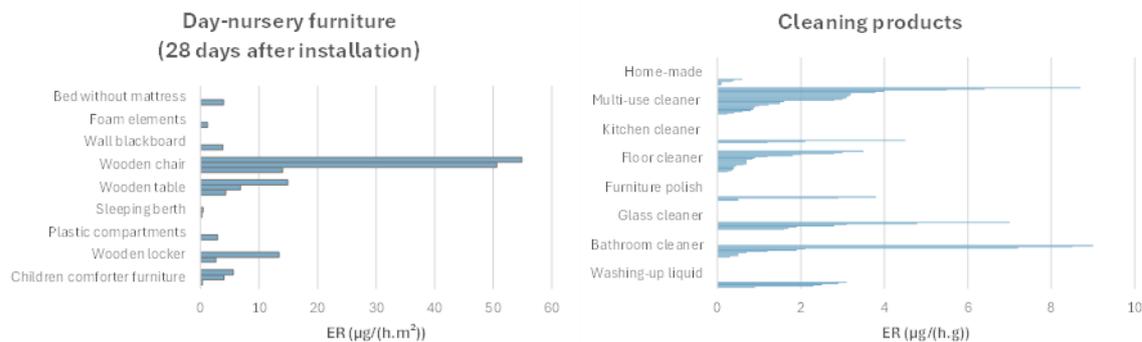
Figure 3.10: Data available for formaldehyde for day-nursery furniture (left) and cleaning products (right).

3.2.2.4 Use of PANDORA (Example case)

This section provides a calculation example of the emission rates for a children's room using PANDORA's data. Note that:

- In this example, we will focus on formaldehyde emissions only.
- Only ER after 28 days are considered here.
- To calculate the ER for the whole room, the sum of ER for all individual sources considered in this example has been done.

As noted by Maupetit (2014), additive models that sum emissions of all sources located in a room tend to overestimate total emission. As a result, the methodology applied here can be considered conservative.

Description of the room

The children's room dimensions are 4 m × 3 m × 2.5 m = 30 m³. A carpet covers the floor while the vertical walls and ceiling are painted. The pollutant emission-free window area is 2 m². The following furniture is considered: one bed with its mattress, a wooden chair, a wooden table, a wooden locker, two plastic compartments, and a blackboard. Because of the presence of furniture, the emitting surface area of the floor is reduced by 2.5 m². Also, the emitting surface area of the vertical walls is reduced by 6 m² because of the presence of the locker and hanging artworks and pictures. Cleaning of the furniture surfaces is supposed to be done daily.

Table 3.2. Surface areas contributing to formaldehyde emissions from the walls, furniture, and cleaning activity.

	Surface area of formaldehyde emission (m²)
Floor, vertical walls and ceiling	
Carpet	9.5
Finishes	64.0
Furniture	
Bed without mattress	4.5
Foam elements	2.4
Wooden chair	1.5
Wooden table	0.7
Wooden locker	6.2
Plastic compartment (2)	3.7
Blackboard	0.3
Cleaning activity	
Multi-use cleaner	5.0

Evaluation of the ER for the whole room

There are three approaches to evaluate the emission rate of formaldehyde for the whole room using data from PANDORA (https://db-pandora.univ-lr.fr/): (1) **Individual source selection** using the database search tool and selecting the most appropriate ones, (2) **Using ranges from Annex86**, that reported a statistical analysis of PANDORA's data, or (3) the **"Metasource" approach**, that merges altogether ER from all sources of the "Construction and Decoration Materials" category into a single estimate.

- **Approach 1**: selecting individual sources from the database

Selecting individual sources from the database search tool is the usual way of finding input data for IAQ simulations. As presented in Figure 3.5, the data can be filtered by source and pollutant. Sources are filtered according to the database structure i.e. *Category*, *Sub-Category*, and *Source*. Pollutants can be found easily by first filtering by Pollutant Group, then by the name or CAS number (in the present case, formaldehyde or 50-00-0). It is recommended that the search fields be cleaned up by hitting the "reset filter" button between searches. **Table 3.3** presents the selected sources with their ER. A column titled "Motivation" has been added to document why a specific ER entry was chosen for this example.

Table 3.3. Selection of inputs from the database – Approach 1.

	Category	Sub-category	# of results	Selected Source	Motivation	ER (µg/(h.m²))
Floor, vertical walls and ceiling						
Carpet	Construction and Decoration Materials	Carpeting	9	Carpet	Most recent data (2014)	1.9
Finishes	Construction and Decoration Materials	Finishes	8	Acrylic paint 1	Most recent data (2014) - random choice between two sources	3.9
Furniture						
Bed without mattress	Furniture	Day-nursery furniture	17	Bed without mattress (G06482B)	Only one data	3.9
Foam elements	Furniture	Day-nursery furniture	17	Foam elements (MBR 13 A)	Only one data	1.2
Wooden chair	Furniture	Day-nursery furniture	17	Wooden chair (10/2701R/5-1)	Lowest ER out of three data	14
Wooden table	Furniture	Day-nursery furniture	17	Wooden table (10/2701R/8-1)	Lowest ER out of three data	4.3
Wooden locker	Furniture	Day-nursery furniture	17	Wooden locker (MBR-05 A)	Lowest ER out of two data	2.6
Plastic compartment (2)	Furniture	Day-nursery furniture	17	Tidying up furniture with plastic compartments (MBR-17 A)	Only one data	2.9
Blackboard	Furniture	Day-nursery furniture	17	Wall blackboard (MBR 01 A)	Only one data	3.8
Cleaning activity						
Multi-use cleaner	Cleaning Products and Air Fresheners	Cleaning Products	86	Multi-purpose bleach-less cleaner – spray (PEPS21 #2)	Recent data and bleach-less	6.0[*]

[*] ER has been calculated as the average over 2 hours from the data 4.0 µg/(h.g) between 0h-1h and 0.8 µg/(h.g) between 1h-2h after application. The mass of product applied is given in the information regarding the experimental methodology (2.5 g/m²).

The ER for the whole room is calculated by adding the products of each source's ER and its emitted surface area, weighted by the emission duration (over 24h for all, except for the multi-use cleaner that is supposed to emit for 2 hours). The total ER for this room is **342 µg/h**. Figure 3.11 compares the importance of the different sources where it can be observed that the *Finishes* element is responsible for the majority (73%) of the emission of formaldehyde, and 20% comes from the furniture.
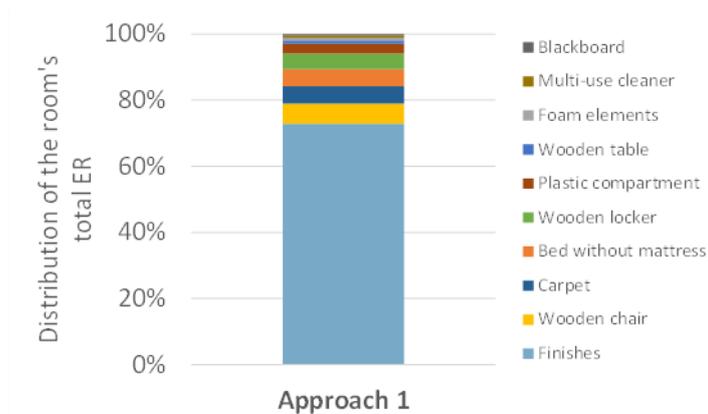
Figure 3.11: Importance of the different sources based on a total ER of 342 µg/h – Approach 1.

- **Approach 2**: using the results of the statistical analysis

The companion website of PANDORA is accessible via the "Data Analysis" menu by clicking on "**PANDORA Statistical Analysis**" link. For formaldehyde, statistical data are available for Carpeting and Finishes at different times and split according to the year of publication of the reference papers as presented in Figure 3.12 and Figure 3.13 via the Formaldehyde/Construction and Decoration Materials/Data section. Tabulated values corresponding to these Figures can be downloaded via the "Download data" subsection ("Formaldehyde Emission rates per types for all materials" link). Data for the Furniture and Cleaning products, displayed in Figure 3.10, can be downloaded by clicking on "Formaldehyde Emission rates per type for all Furniture" and "Formaldehyde Emission rates per type for all other Sources" located in the "Furniture" and "Other Sources (Occupants, etc.)" sub-sections, respectively.
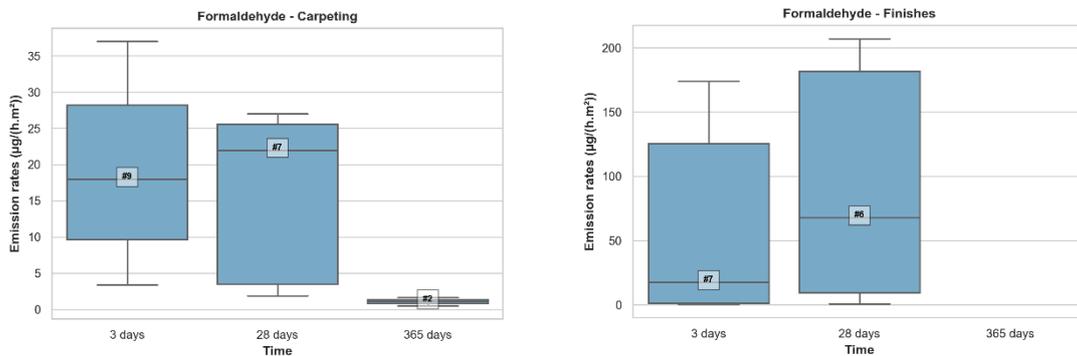
Figure 3.12: Statistics of ER of formaldehyde for carpeting and finishes after 3, 28 and 365 days – Approach 2.
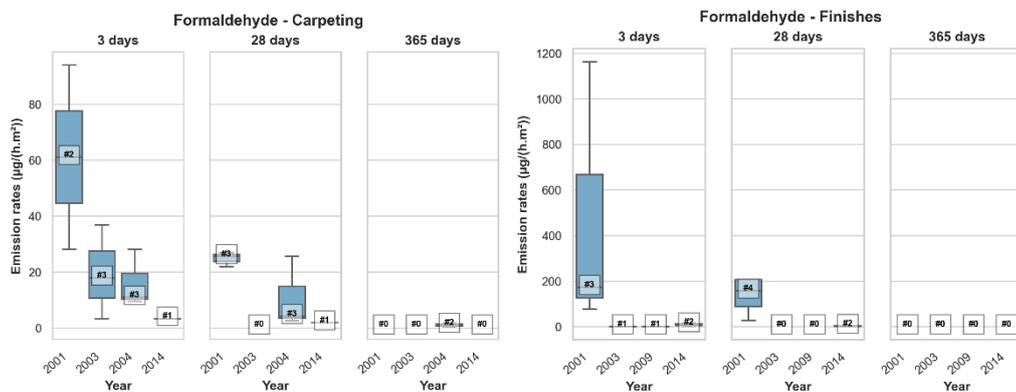
Figure 3.13: Statistics of ER of formaldehyde for carpeting and finishes after 3, 28 and 365 days, split by years – Approach 2.

To compare the sources' strengths, an identical treatment was applied to calculate their ER in µg/h. This was done by multiplying each source's statistics by its emitted surface area and weighted by the time of emission per day. Figure 3.14 (left) presents the resulting ER for all formaldehyde sources. As the first approach, Finishes are the dominant contributor. For the two wall-related sources, a wide range of possible values, with high maximal ones, can be observed. This originates from the oldest data (2001), as shown in Figure 3.13; more recent data present lower ER. The right graph of Figure 3.14 compares the results for the two approaches. To the sum of individual ERs in the second approach, we consider all statistical measures (maximum, P75, P50, etc.) individually as if the user would have chosen one of those values to calculate the resulting ER for the whole room. Because of the arbitrary choices (or "Motivation") taken in approach 1 (a single value from more recent data), its ER is in the lowest ER region of approach 2.
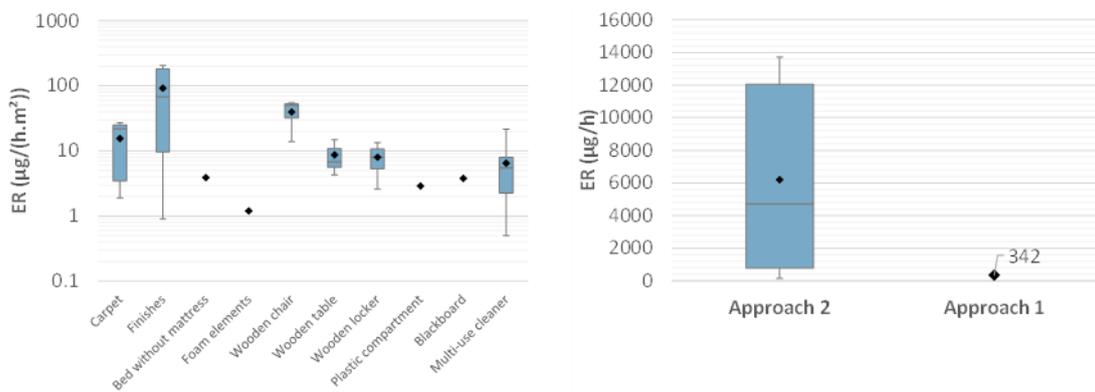
Figure 3.14: Statistics of ER for all sources (left) and for the room (right) – Approach 2.

- **Approach 3**: using the Metasource data

The Metasource data merged the ERs of all available Construction and Decoration Materials into one fictive emission source (see section 0). The tabulated data can be downloaded by clicking on "Formaldehyde Meta emission rates" located in the "Meta-data" subsection of the "Construction and Decoration Materials" section for formaldehyde. Figure 3.15 compares the emission rates obtained with the three approaches. Compared to the second approach, the range of variation of the data using approach 3 is slightly narrower but still shows high differences between the extreme values.
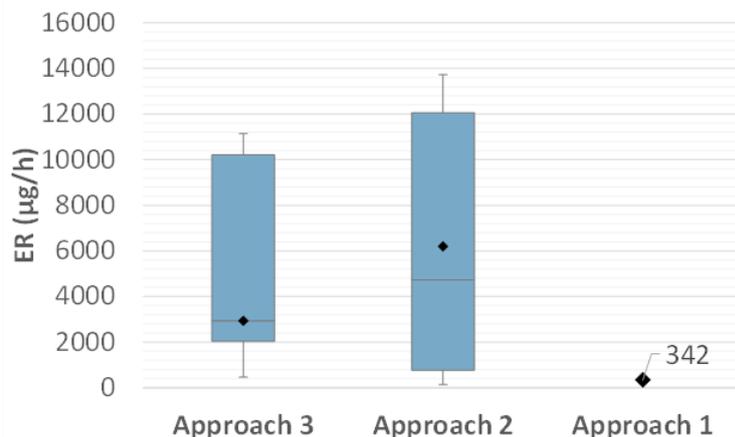
Figure 3.15: Comparison of the three approaches in terms of ERs for the whole room.

Figure 3.16 shows the *equilibrium concentration, also known as steady-state concentration,* of formaldehyde using the three different methods. Equilibrium concentration refers to the level reached over time with constant ER and air exchange, calculated as the emission rate divided by the airflow rate. In this case, an airflow rate of 15 m³/h, equivalent to 0.5 air changes per hour (ACH), was selected, a common value found in bedrooms. Considering that values of formaldehyde found indoors are often lower than 100 µg/m³, one should consider the lower values from approaches 2 and 3 to be representative. Even for formaldehyde, which has the largest number of emission values recorded, the data is still insufficient to statistically represent the wide variability of real-world sources and sources' strengths. As a result, the reported emission rates are likely to overestimate actual averages.

Based on our expertise in using this data for IAQ modeling within the framework of Annex86, we recommend using P25 emission rate statistics (rather than means or medians) to achieve reliable average concentration levels using mass balance calculations in indoor environments. This conclusion only stands for formaldehyde; additional analyses would be necessary to extend this recommendation to other pollutants.
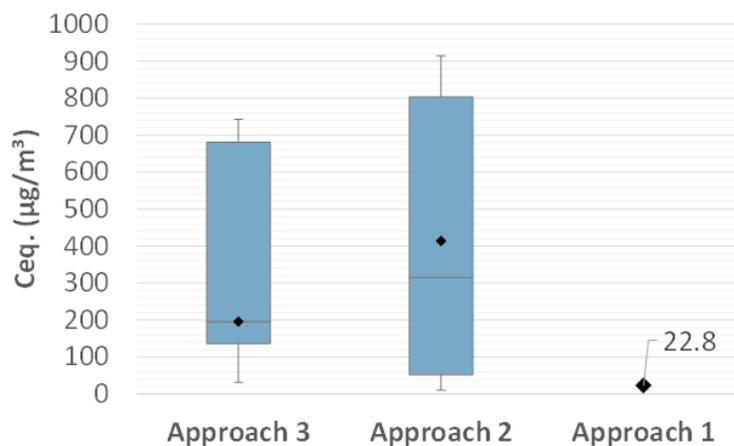
Figure 3.16: Comparison of the three in terms of equilibrium concentration.

3.3. Typical exposure / typical concentration

The research conducted within Subtask 2 (ST2) of IEA EBC Annex 86 aims to enhance the understanding of indoor pollutant exposure levels in residential buildings. To achieve this, ST2 systematically analyzed data from field measurements collected in residential homes with the objective to support the estimation of typical pollutant concentrations in residential environments. Rather than compiling a static and finite collection of "typical pollutants" and their respective concentrations, the project has focused on developing a dynamic and adaptable workflow, coupled with a comprehensive database repository hosted on Zenodo. This approach ensures that the dataset remains an evolving resource that can be updated and expanded as new data and analytical methods become available. This report includes a summary of the indoor pollutant concentrations derived from many different IAQ measurement studies. However, the workflow and database have been designed as "living objects" that can continue to grow and develop beyond the formal conclusion of this Annex 86 project. With the increasing availability of IAQ measurement data, the analyses can be re-executed to incorporate additional data points. Moreover, the analytical algorithms can be extended with new functionalities, e.g. for benchmarking individual studies against a representative aggregate of other studies. It also provides a good foundation for further big data analysis procedures, e.g. for processing IAQ data gathered from IoT devices.

The following section 3.3.1 presents the "registry" that has been created within this subtask to collect all IAQ studies known to the ST2 participants that could potentially serve as data sources for the stated objective. It also summarizes the studies that were effectively used to produce the IAQ data repositories presented in section 3.3.2. Section 3.3.2 presents the workflow that was developed and implemented within an R package to generate the IAQ data repository. The results obtained from analyzing the generated IAQ data within a meta-analysis is summarized in section 3.3.4.

3.3.1. Summary list of relevant IAQ measurements

Table 3.4 summarizes IAQ studies identified within this subtask to have potentially relevant IAQ measurement data from field studies in residential homes. The full table (called "registry" within the project consortium) with more detailed information about the investigated buildings, their ventilation provisions, and the conducted measurements is available in the following Zenodo repository: https://doi.org/10.5281/zenodo.15399188.

Table 3.4: Summary table of registry of IAQ measurement studies in residential homes. The studies analyzed within ST2 are marked in bold letters. Win: Window ventilation, Nat: Naturalventilation (designed), Mech: Mechanical ventilation, MVHR: balanced ventilation with heat recovery, MEV: mechanical extract ventilation.

Country / Region or City	Project Name/Acronym (Institution)	Reference/Contact	Sample Size	Building Type	Ventilation Type
AUS / Melbourne	Indoor air project (CSIRO)	Galbally et al. (2011)	40	various	
AUS / Melbourne	- (Monash University)	Kang et al. (2021)	12	MFH	MVHR
AUT	**Lueftung 3.0 (IBO)**	**Wallner et al. (2014)**	**120**	**SFH**	**MVHR, Win**
AUT / Innsbruck	**Sinfonia (UIBK)**	**Bliem (2021)**	**200**	**MFH**	**MVHR, Win**
AUT / Innsbruck	**Lodenareal (UIBK)**	**Rojas et al. (2015)**	**24**	**MFH**	**MVHR, Win**
BEL	Clean Air, Low Energy (VITO)	Stranger et al. (2012)	51	SFH, MFH	various
BEL	Renovair (UGENT)	Jelle Laverge		SFH, MFH	various
BEL	My Healthy Home (UGENT)	Jelle Laverge		SFH, MFH	various
BEL	- (Renson)	De Maré et al. (2019)	350	SFH, MFH	MEV
CHE	Mesqualair (EPFL, HEIA)	Shen Yang et al. (2020)	650	SFH	various
CHE	**Buren (Zehnder)**	**Bart Cremers**	**4**	**MFH**	**Win, MVHR**
CHL	Fondecyt Iniciación (UC)	Constanza Molina	32		
CHL	RENAM (UC)	Constanza Molina	284	SFH, MFH	Nat, Win
DEU / Berlin, Leipzig	- (TROPOS)	Zhao et al. (2022)	40	various	various
DEU / Erfurt	INGA (GSF)	Schneider et al. (1999)	20		Nat
DNK / Copenhagen	CISBO (DTU)	Bekö et al. (2013)	58	various	various
DNK / Odense	**IECH (DTU)**	**Bekö et al. (2019)**	**500**	**various**	**various**
ESP / Madrid	**CISC (IETCC)**	**Sonia Garcia**	**12**	**MFH, AB**	**Nat, Win**
ESP / Pampl., Sevil.	**ClimateReady (UNAV)**	**Aurora Monge-Barrio**	**23**	**MFH**	**various**
FRA	- (CETIAT)	Laure Mouradian, Benoit Golaz	4	various	Mech
FRA	**ALLO (ULR)**	**Marc Abadie**	**6**		**Hyb**
FRA / French Alps	Kanama (Cerema)	Gaelle Guyot	1	SFH	MVHR
GBR	**AMR (STRATH)**	**Sharpe et al. (2020)**	**21**	**TH, AB**	**Nat, Mech**
GBR / Scotland	dMEV (STRATH)	Sharpe et al. (2019)	41	various	MEV
GBR / Scotland	**VentStd (STRATH)**	**Sharpe et al. (2023)**	**16**	**various**	**MEV, MVHR**
IRL	**ALIVE (UGA)**	**James McGrath, I. Alhindawi**	**9**	**SFH**	**Nat**
IRL	**ARDEN (UGA)**	**Coggins et al. (2022)**	**26**	**SFH**	**Win, Mech**
IRL	**VALIDate (MU)**	**James McGrath**	**87**	**SFH, TH, AB**	**various**
ITA / Bari	- (ARPA)	De Gennaro et al. (2015)	6		
ITA	- (UNIFE)	Pietrograpde et al. (2021)	2		various
ITA / Lodi	- (UNIMI)	Cattaneo et al. (2011)	60		
MEX / Mexico City	- (GSA)	Moreno-Rangel et al. (2018)	1	AB	Hyb

MEX, USA, GBR	**- (GSA)**	**Moreno-Rangel (2019)**	**7**	**various**	**Hyb, MVHR**
NLD	Care facilities (TUe)	Kulve et al. (2017)	7		Mech
NLD	**PH renovation (TU/e)**	**Marcel Loomans**	**10**	**TH**	**MVHR**
NOR / Trondheim	**ZEN (NTNU)**	**Alonso et al. (2021)**	**21**	**various**	**various**
PRT / Porto	- (PUV)	Ricardo Almeida, Eva Barreira	3	various	various
SGP	- (NTU)	Zhou et al. (2013)	5	MFH	various
SVK / Samorin	Renovation (SUT)	Földvary et al. (2017)	94	MFH, AB	Nat
SWE	Swedish housing stock (IVL)	Langer and Bekö (2013)	305	various	various
SWE / Falun	- (Renson)	Ivan Pollet	1	SFH	MEV
SWE	Swedish passive house (IVL)	Langer et al. (2014)	41	SFH, TH	MVHR
USA	Particle Penetration (UT Austin)	Stephens and Siegel (2012)	19		Nat, Mech
USA / California	**HENGH (LBNL)**	**Singer et al. (2020)**	**70**	**SFH**	**MEV (mostly)**
USA / California	**LIA (LBNL)**	**Zhao et al. (2020)**	**23**	**MFH**	**MEV**
USA / California	High Perf. Homes (LBNL)	Less et al. (2015)	24		various
USA / California	Apt. Retrofits (LBNL)	Noris et al. (2013)	16		Mech, Hyb
USA / McAllen	- (GSA)	Moreno-Rangel et al. (2020)	13	SFH	Nat
USA / Washington	Weather influence (WSU)	Huangfu et al. (2019)	1		Mech
USA / Washington	Wildfires (WSU)	Kirk et al. (2017)	2		Mech

Within the scope of ST2 activities, the consortium had access to a significant subset of the listed studies. Short textual summaries of their objectives, methods, and results are provided in Appendix 2. To ensure a comparable and joint analysis a standardized analysis was developed.

3.3.2. Description of standardized analysis

3.3.2.1 Overall concept

To allow a meta-analysis of different IAQ measurements around the world, a standardized data structure and analysis methods was developed. The method should be able to accommodate different kinds of data sources e.g. measurements from short-term vs. long-term campaigns, with different measurement sampling rates using different measurement devices, etc. and allow a combined assessment.

This could be accomplished by centrally collecting the original time series data from the different studies and processing those data sets in a standardized way jointly. Alternatively, the datasets can be processed in a decentralized manner, i.e. staying with the data owners. In this approach the standardized analysis method is applied by the research institution that collected the data and only the output of the statistical analysis, enriched with relevant meta information is collected centrally for further analysis, e.g. meta-analysis, benchmarking, etc. This latter approach was chosen mainly for two reasons:

- **Data protection:** Since the time series data can contain a wealth of time resolved information with respect to home occupancy, occupant activities, etc., potential data protection issues can be avoided. Since the introduction of the General Data Protection Regulation [GDPR, 2016] in the European Union, some uncertainties among research institutions have arisen on how GDPR-conform data handling of IAQ data should look like. Consequently, very restrictive consent declaration forms were drafted and used in IAQ field studies, limiting the processing of the original data to the research institution performing the measurements. Therefore, the chosen approach avoids the need to hand out the original time series data to a third-party data processing team, and only highly aggregated (monthly) and anonymized/ pseudonymized data is collected centrally.
- **Scalability and continuity:** To allow a continuous integration of additional data from new or other IAQ studies extending or updating this meta-analysis, the aggregated datasets from the statistical analysis (and its respective meta information) can be stored and processed easier in a data repository if they have a standardized format and a notably reduced size compared to the original time series data sets.

3.3.2.2 Analysis procedure

The following analysis procedure was applied to the measurement data of each IAQ study provided by participants of ST2. Therein, the statistics for each study, home, room and pollutant (relevant measured variable) are calculated. To allow a distinct assessment of a certain time of year or time of day, the statistics are also calculated for each month of the year, for daytime (07:00 – 23:00) and nighttime (23:00 – 07:00) hours. This results in a data structure as depicted in Figure 3.17, where the statistical analysis is performed for each branch of the structure, when data is available for that branch. Relevant meta information can be collected on four distinct levels of the data structure, i.e. on study, home, room and pollutant level. More information on the collected meta data can be found in Table A3.1 in Appendix 3.
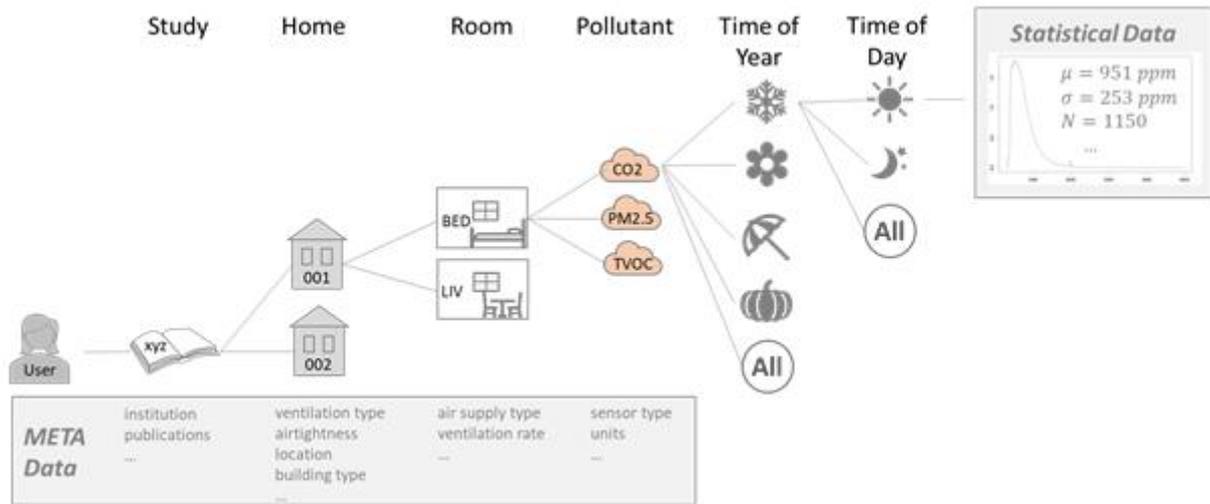
Figure 3.17: Data structure for the standardized data analysis procedure developed within ST2 of IEA EBC Annex 86

The procedure is geared towards the processing of time series data gathered during IAQ measurement studies, e.g. CO_2 or $PM_{2.5}$ concentrations measured over several days, weeks or years. However, the data structure can be (and was also) used to accommodate single-value measurements, stemming from e.g. active or passive sampling techniques for VOC measurements.

For time series data the following statistical measures are derived for each branch of this data structure:

- arithmetic mean
- standard deviation
- percentiles from 0 to 100% in 1%-steps, plus 0.5%, 2.5%, 97.5% and 99.5% resulting in 105 percentile values (note that median and lower and upper quantile are also included)

Additionally, the following data quality indicators are calculated:

- start and end date
- statistics on sampling interval: mean, median, min, max, lower and upper quantile
- total number of data points and number of invalid data points (non-numeric entries)
- estimated number of data points assuming an uninterrupted measurement from start and end date with a sampling interval equal to the observed median sampling interval
- percentage of data points exceeding a lower or upper plausibility threshold (see below)

During calculation, the following cleaning and selection steps are performed to each branch. (The procedure assumes that the measured raw data has been cleaned and/or corrected from faulty measurements, e.g. sensor failures, CO_2 sensor drifts, cross-sensitivities, etc.)

- Invalid non-numeric entries or data gaps are marked as NA and excluded from further analysis
- If the number of valid data points, i.e. total (N) minus invalid (NA) data points, is equal to or greater than 30, all statistical measures and data quality indicators as described above are calculated.

- If the number of valid data points is lower than 30, but at least two, the data quality indicators and the percentiles are calculated. However, the mean and standard deviation are set as NA, as their explanatory power would be small.
- If there is only one data point, the sampling interval statistics as well as the estimated number of data points will be set to NA.

In addition to this data cleaning procedure, values are checked for plausibility. For each possible indoor pollutant (measured variable) a plausible range is defined, see Table A3.2 in Appendix 3. Unrealistic low or high values are identified, and the user (of the executing script) is warned and the respective amount of exceedance (% of data points below or above threshold) is provided as a data quality metric in the analysis results (e.g. 1.5 % of measured CO_2 concentration < 350 ppm).

The results of the statistical analysis and its respective data quality indicators are provided for each segregation branch, which is represented by a single line in the output file (see Figure 3.18. E.g., if an IAQ study measured CO_2, T and RH in bedroom and living room for 6 consecutive months, the results are summarized in 126 lines, i.e. 2 rooms x 3 variables/pollutants x 7 (6 months + entire period) x 3 (daytime, nighttime and 24-hour-day).

user	study	home	room	year	month	tod	variable	quality_lower	quality_upper	quality_start	quality_end	interval_Min	interval_Q1	interval_Median	interval_Mean	interval_Q3	interval_Max	Nestim	N	NAs	Mean	Sd	p00	p00.5	p01
0010	NL_ML	H0100	BED2	2012	11	all	CO2	0	0	28-11-2012	30-11-2012	58	180	180	155.6	180	180	1440	1191	1	518.9146	92.66	368.4967	370.6336	372.9723
0010	NL_ML	H0100	BED2	2012	11	all	RH	0.08	0	28-11-2012	30-11-2012	58	180	180	155.6	180	180	1440	1191	0	39.7517	3.3566	0	34.73	34.825
0010	NL_ML	H0100	BED2	2012	11	all	T	0	0	28-11-2012	30-11-2012	58	180	180	155.6	180	180	1440	1191	0	19.8708	0.4882	4.69	19.39	19.39

Figure 3.18: Example of three data points giving the results of the statistical analysis of the time series for the month of November, for CO_2, temperature (T) and relative humidity (RH). Time of day (tod) is "all", i.e. 0-24h. Note that the remaining columns with all the percentiles are not shown here.

3.3.2.3   Implementation in R

The analysis procedure described above was implemented in R, a programming language for statistical computing and data visualization. For easier usability, distribution, and maintenance it has been made available as an R package (https://github.com/IEA-EBC-Annex86/annex). Prior to launching the analysis functions, the user has to import the measurement data as proper R data frames. The user must also assign the pollutant names, unit of measurements, as well as a home and room identifier to each column of the data frame within an external configuration file or within a configuration variable.

After importing the time series datasets and configuration file, a set of processing functions have been developed to perform the standardized analysis in a few steps, as shown in Figure 3.19.
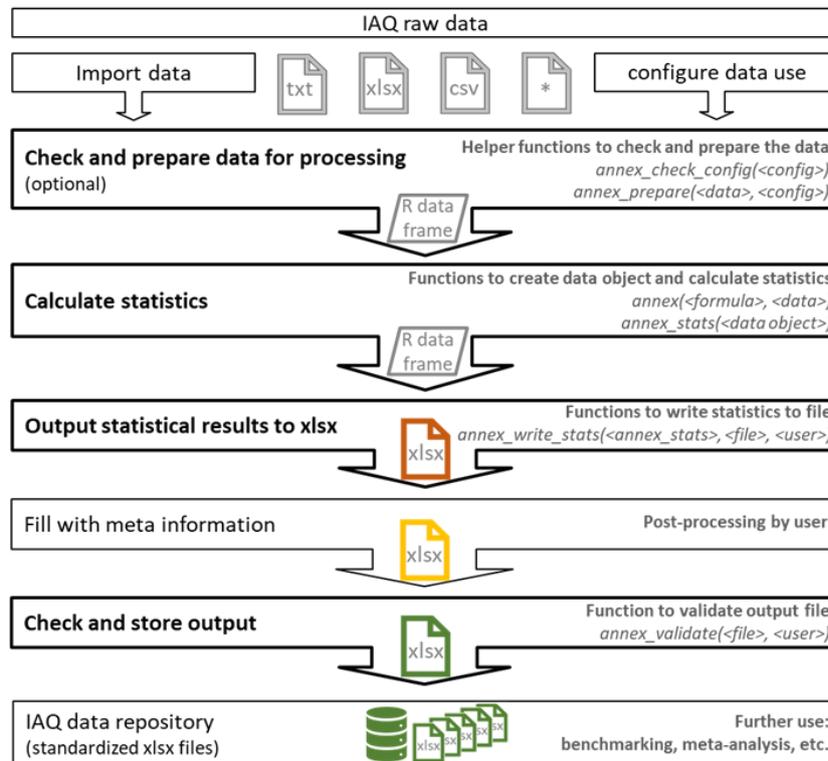
Figure 3.19: Schematic representation of the developed workflow of the standardized data analysis process for IAQ measurement data. For the steps drawn with bold frames, easy to use functions have been programmed and made available in the R package "annex".

The analysis functions will take care of proper unit conversions and account for time zones and/or time changeovers when calculating the statistics and data quality indicators as described above.

Table A3.2 (in Appendix 3) shows the pollutants (and other variables) that have been defined and can be processed currently with these R analysis functions. It also shows the allowable units (where unit conversion has been defined) and lower and upper bound values used for the calculation of data quality indicators. The documentation includes a detailed description of the functions and tutorials for different data sources (https://iea-ebc-annex86.github.io/annex/). An exemplary application for benchmarking is also illustrated in deliverable 4 of this project. Additionally, several instructional videos have been recorded for each step of this process, see Installation (update) and Documentation (4 min), Importing (reading) data (11 min), Prepare data for analysis (12 min), Calculating statistics (9 min), Write/save results (12min), Validate output file, entering meta data (13min).

3.3.2.4 Providing meta information

The analysis functions implemented in R and described above output the results in a standardized Excel file containing the statistical results in one sheet and four additional sheets to provide relevant meta information. The meta information that can be provided is structured according to the four levels "study", "home", "room" and "variable" and contains fields such as:

- **Study:** contact, institution, publications, links, additional information.
- **Home:** country, city, ventilation type, ventilation rate on home level, airtightness, type of building, energy standard, year of construction or renovation, size of home, type of occupants, further comments, etc.
- **Room:** type of fresh air supply, ventilation rate, method of ventilation rate determination, type and number of occupancy, further comments, etc.
- **Variable:** additional information on the measured variable, unit, measurement device, further comments.

Not all studies will have enough information available to fill all those fields. Therefore, most fields are considered optional and only an informative note will be printed when the validation function is applied. The only mandatory fields for each home are country and the ventilation type. If ambiguous measurement variables, such as "VOC, "TVOC", "PMOther" or "Other" have been processed, then the field "additional information" for these variables must be filled out

too. For comparability and compatibility reasons, some of the meta information fields allow only a defined set of answers (in form of a dropdown list). For example, ventilation type must be selected from one of the following four categories:

- Window airing (not designed): homes which are only ventilated via occupant operated windows (besides natural in-/exfiltration), often also referred to as purged ventilation,
- Natural ventilation (designed): homes which have been designed for natural ventilation with dedicated shafts, openings, automated window control, etc.,
- Hybrid/mixed mode ventilation: homes which apply natural and mechanical ventilation including homes with intermittent, occupant driven fans,
- Mechanical ventilation: homes with continuous mechanical ventilation, e.g. mechanical extract ventilation (MEV), or balanced mechanical ventilation with heat recovery (MVHR).

3.3.3. Data repository and open source repository (Git)

3.3.3.1 IAQ database repository

A key component of ST2's research efforts was the compilation and processing of measurement data contributed by ST2 participants from 11 countries. These data were analyzed to derive the statistical distributions of pollutant concentrations using the presented standardized data processing and analysis workflow (implemented in a newly developed R package). The output consists of structured datasets presented in Excel format, categorized by country and study name. The design of the data structure ensures that it can function as a rudimentary database or be easily imported into more sophisticated, dedicated database systems.

The compiled dataset encompasses measurement data from 21 independent IAQ studies, representing a total of 1,173 residential homes and 3,268 distinct measurement locations. The dataset includes 44 different IAQ parameters, which provide a comprehensive assessment of indoor air quality. These parameters include, but are not limited to:

- Carbon dioxide (CO_2)
- Relative humidity (RH)
- Temperature (T)
- Particulate matter (PM_1, $PM_{2.5}$, PM_{10})
- Formaldehyde (HCHO)
- Total volatile organic compounds (TVOC) and specific volatile organic compounds (VOC)
- Nitrogen dioxide (NO_2)
- Radon (Rn)
- Additional environmental and biological indicators such as airflow rates, fungal spores, dust mites, and various semi-volatile organic compounds (SVOCs)
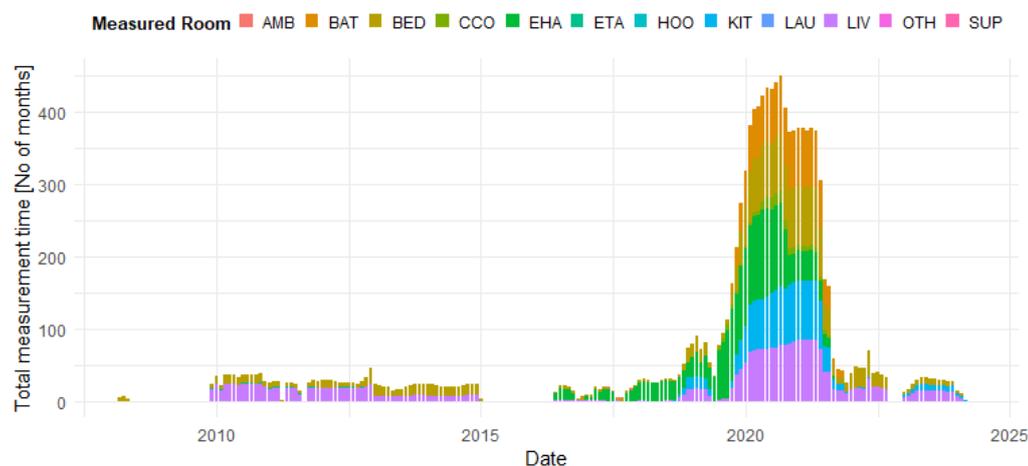

Figure 3.20: Overview of the available data set. Timely distribution of total number of months where IAQ parameters have been measured in different rooms of different dwellings.

Additionally, the dataset includes the operational data from mechanical ventilation devices covering airflow, CO_2, T, and relative humidity from >8500 Belgian homes.

Note: It is intended that this dataset will also be included in the IAQ database currently under development (not part of Annex 86 activities), see https://iaqdb-dev.epfl.ch/.

3.3.3.2 IAQ data analysis repositories

The analysis repositories include the programming scripts (mostly in R) that were developed to process and analyze IAQ measurement data provided by ST2 participants. Two git repositories have been created to publish these scripts:

R package for processing individual IAQ measurement data

R package repository on GitHub: https://github.com/IEA-EBC-Annex86/annex

The R package annex (described in section 3.3.2.3) provides a series of functions and methods to easily process measurement data in a standardized manner as defined in the IEA EBC Annex86 project. It also includes functions for writing (and validating) the final files that form the IAQ database repository hosted on Zenodo.

Collection of scripts for IAQ analysis

ST2 analysis scripts on GitHub: https://github.com/IEA-EBC-Annex86/ST2analysis

A collection of scripts and functions to analyze data from the IAQ database repository. They include the scripts used to generate the summary tables and figures provided in section 3.3.4.

It also collects pre- and postprocessing scripts (in R and Python) that were developed within ST2 to process the original (raw) timeseries data (applying the R annex package) to produce the IAQ database repository.

3.3.4. Meta-analysis over IAQ database

The IAQ data repository presented was analyzed with the objective to extract typical concentrations of the most relevant pollutants in residential settings. Therefore, the results from different homes and IAQ studies were aggregated as described in section 3.3.4.1. A summary of the results is provided in section 3.3.4.2.

3.3.4.1 Aggregating results from different studies

The data contained in the IAQ data repository provides various possibilities on how the data can be combined and aggregated for the meta-analysis. Each datapoint contains the mean of all the available recordings for the respective room-month combination. In other words, for every distinct room (of all studies) the mean for every month of the year where measurements were performed is available. However, the measurement duration (per room) varied strongly between studies, i.e. from two days to over two years. So, the question arises if measurements from rooms with many "month-representative" data points should count more than rooms were only one "month-representative" data point is available. For example, if the results of homes with different ventilation types, different building type, etc. are to be compared one can generate the:

- boxplot of **means of unaggregated data** (one mean per room-month combination)
- boxplot of **means of data aggregated by room** (one mean per room)

The aggregated mean value for each room is calculated as weighted mean applying the fraction of the month where measurement data was actually collected as a weighting factor (w_i). This factor ranges between 0 and 1 and represents the relative data availability when generating each room-month datapoint. For more details, see [Rojas, et al., to be published]. This way, each room will count equally in the statistical meta-analysis, e.g. comparing different ventilation types. Figure 3.21 displays the boxplots for the mean CO_2 concentrations in bedrooms, during nights of the colder months of the year (October through May) for the unaggregated and aggregated dataset. In this example, notable differences can be observed, in particular for the "hybrid/mixed mode ventilation" group. To avoid bias towards studies with long measurements, the remaining summary of results will focus on the aggregated dataset, i.e. with one mean value per distinct room. Since the window airing behavior will differ substantially during the warmer time of the year, the dataset has been filtered to only contain data covering the months October through May before aggregation for the results in section 3.3.4.2. This selection of months is based on the results shown in [Rojas, et al., to be published], where the variation of CO_2 concentration throughout the year was investigated, with statistically significant lower values during the months June through September. Note that only homes located in the northern hemisphere are covered in this meta-analysis.
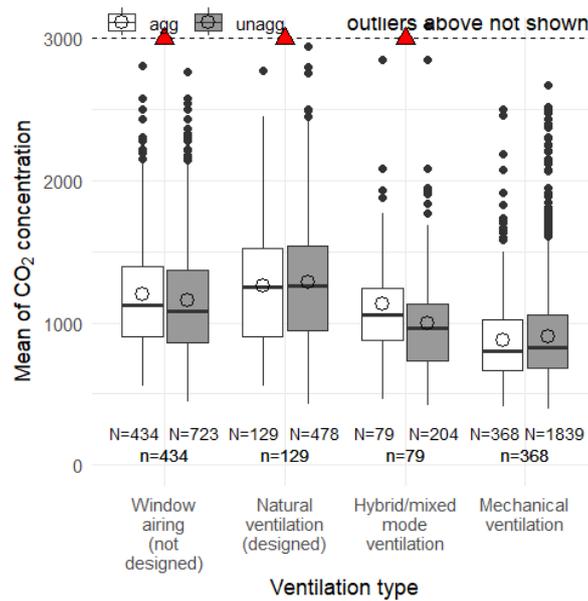
Figure 3.21: Boxplots of mean CO_2 concentration in bedrooms at night (Oct – May) of aggregated (1 data point per room) and unaggregated (1 data point per room-month) data.

Additionally, the IAQ data repository also provides the empirical cumulative distribution function (eCDF, in the form of percentiles) for each datapoint, i.e. for each room-month combination. That allows for further options when performing a meta-analysis, e.g. generating a

- boxplot of **95th percentiles of (un)aggregated data**
- boxplot, eCDF (or ePDF) representing the **mixture distribution of the (un)aggregated data**

The eCDF of the aggregated group is calculated as the finite mixture of the eCDF's of the data points that are being aggregated also applying the same weighting factor (w_i) as for the weighted mean.

$$P_{ag} = \sum_{i=1}^{N} w_i \cdot P_i$$

Here, P_i and P_{ag} represent the eCDF for each month-room and the aggregated room data point, respectively. This eCDF is numerically defined by a vector with >100 bins over the relevant range, e.g. for CO_2, each eCDF entry is the cumulative relative occurrence of CO_2 concentrations below 300, 330, 360, etc, or 5000 ppm. N is the number of months for which measurements for the respective rooms are available. Further details are documented in [Rojas, et al., to be published].

3.3.4.2 Summary of typical indoor pollutant concentrations and indoor conditions

To estimate the typical concentrations of relevant pollutants in residential homes, a series of boxplots showing the statistical measures of the mean values during non-summer months (aggregated dataset, i.e. one value per distinct room, representing the period Oct. through May) have been produced. See Figure 3.22 through Figure 3.25. The results are also summarized in tables A4.1 through A4.11 in Appendix 4. The results are grouped by ventilation and room type. Depending on the room type the following time of day (tod) was filtered to create the boxplots and summary tables.

- bedroom: mean of nighttime hours (23:00 - 07:00 local time)
- living room, kitchen, home-office rooms and other undefined living areas: mean of daytime hours (07:00 – 23:00 local time)
- central corridor and measurements in dwelling-central extract ducts: mean of day- and nighttime hours (00:00 – 24:00)

This approach is assumed to yield results that are "more" representative of human exposure estimates.

Figure 3.22 shows that bedrooms are clearly the most under ventilated rooms in residential setting, with mean and median CO_2 concentration well above 1000 ppm for ventilation concepts that mostly rely on natural forces, i.e. window airing, designed natural ventilation and hybrid / mixed mode ventilation. In contrast, around 75% of all investigated

bedrooms with mechanical ventilation had a mean CO_2 concentration <1000 ppm during non-summer nighttime hours. For living rooms, the difference between ventilation types is small, only the variance of window aired homes is notably larger. However, note that the sample size is small compared to the sample size of mechanically ventilated living rooms.
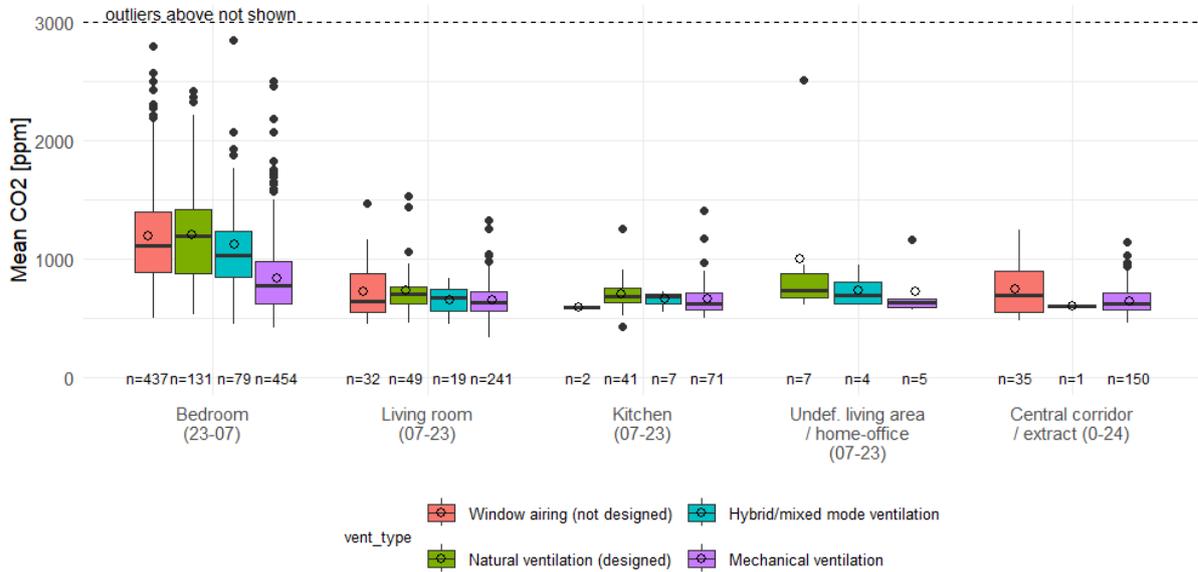
Figure 3.22: Boxplots of mean CO_2 concentration (Oct – May) for different measurement locations (room type, time of day) and for different ventilation types. The number of data points (n: nr of distinct rooms) is also provided.

Looking at the mean $PM_{2.5}$ concentration in Figure 3.23, one can observe a different picture. Here the kitchen sticks out as the room with highest concentrations. Also noteworthy is the large difference between mean (circle) and median (horizontal bar) values, indicating a strongly distorted distribution where only small fractions of the homes seem to have relatively high concentrations. For bedroom and kitchen this is particularly pronounced for mechanically ventilated homes. One should note that the sample size for the kitchen measurements is rather small, stemming from three smaller studies [AMR, SF1, SC1] and the high mean is a result of 5 homes with mean values >100 µg/m³ (up to 376 µg/m³).
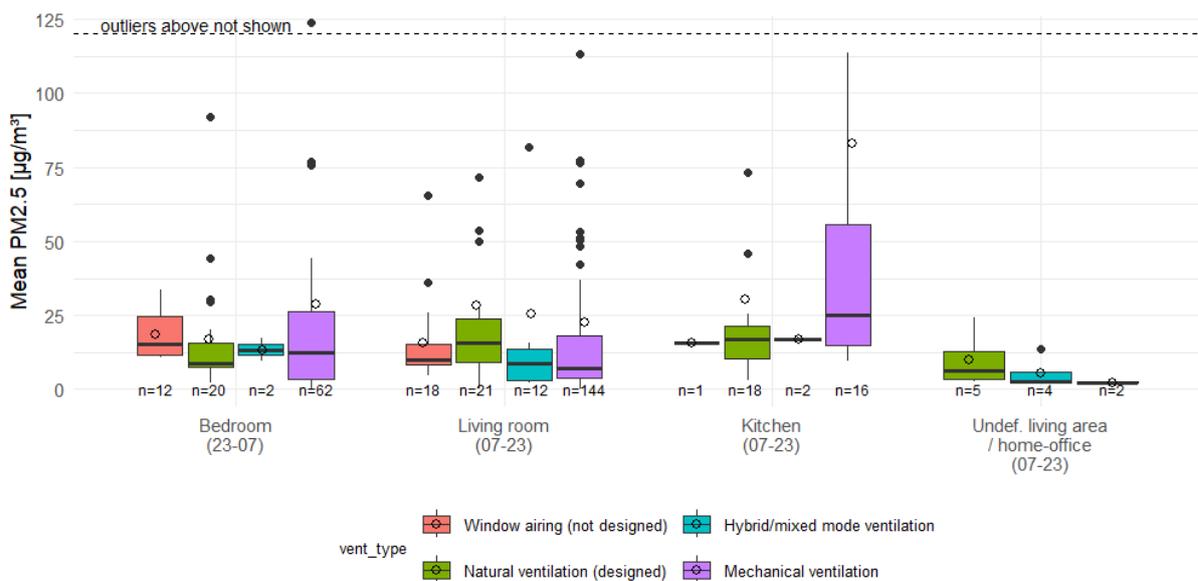
Figure 3.23: Boxplots of mean PM$_{2.5}$ concentration (Oct – May) for different measurement locations (room type, time of day) and for different ventilation types. The number of data points (n: nr of distinct rooms) is also provided.

Figure 3.24 (left) shows the results for (T)VOC concentrations obtained from time series measurements of low-cost sensors from eight different studies (ARDEN, HomeOffice_COVID, VALIDate, AMR, ALIVE, MX1, SC1, SF1). Acknowledging sample size and value range, bedrooms seem to experience the highest concentrations of VOC's (detectable with low-cost sensors). The relatively low values in the bedroom of window aired homes are dominated by the results of one particular study (9 out of 12 bedrooms from the ARDEN study) with relatively low values compared to the other studies. Figure 3.24 (right) summarizes the sorption tube measurements of one study (Lueftung3.0) investigating new single-family homes 15 months after occupation.
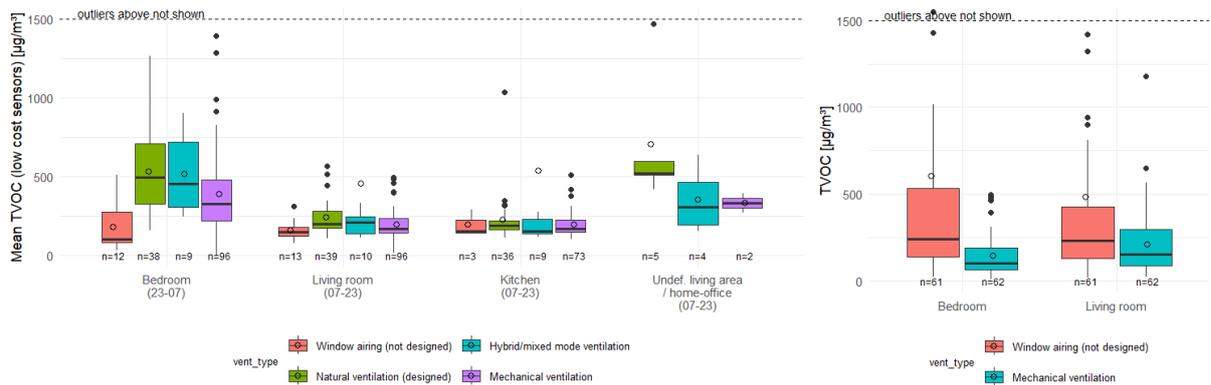
Figure 3.24: Total volatile organic compound (TVOC) concentration in different rooms and for different ventilation types. Left: Mean concentration obtained from continuous measurements with low-cost sensors (Oct – May, tod as indicated). Right: Concentrations from 1-time measurements with sorption tubes. The number of data points (n: nr of distinct rooms) is also provided.

The mean formaldehyde concentrations in Figure 3.25 (left) are clearly lower in mechanically ventilated homes. However, they stem from only three studies (HENGH, HomeOffice_COVID, LIA), with the great majority of data points in bed- and living rooms coming from the two studies investigating homes in California (70 out of 72 and 90 out of 91, respectively, from HENGH or LIA projects). Sorption tube measurements from the "Lueftung3.0" study exhibit similar values for mechanically ventilated homes Figure 3.25 (right). A similar observation can be made for radon levels (Figure 3.26), with lower median values in dwellings with mechanical ventilation. Except for the results of the continuous measurements of window aired homes, which don't allow any conclusion due to a very small sample size.
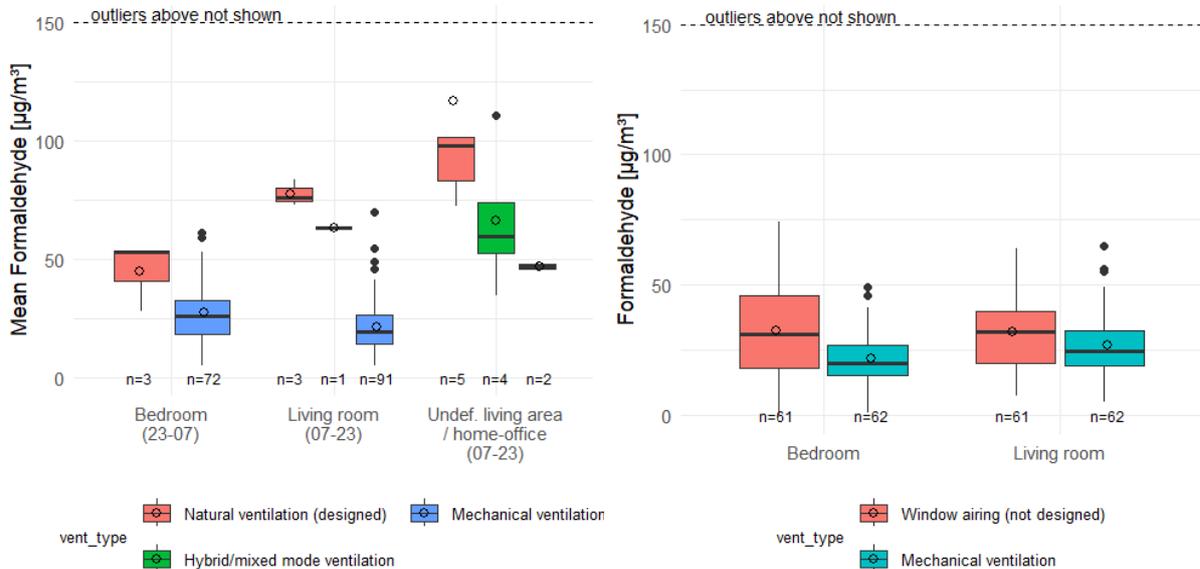
Figure 3.25: Formaldehyde concentration in different rooms and for different ventilation types. Left: Mean concentration obtained from continuous measurements (Oct – May, tod as indicated). Right: Concentrations from 1-time measurements with sorption tubes. The number of data points (n: number of distinct rooms) is also provided.
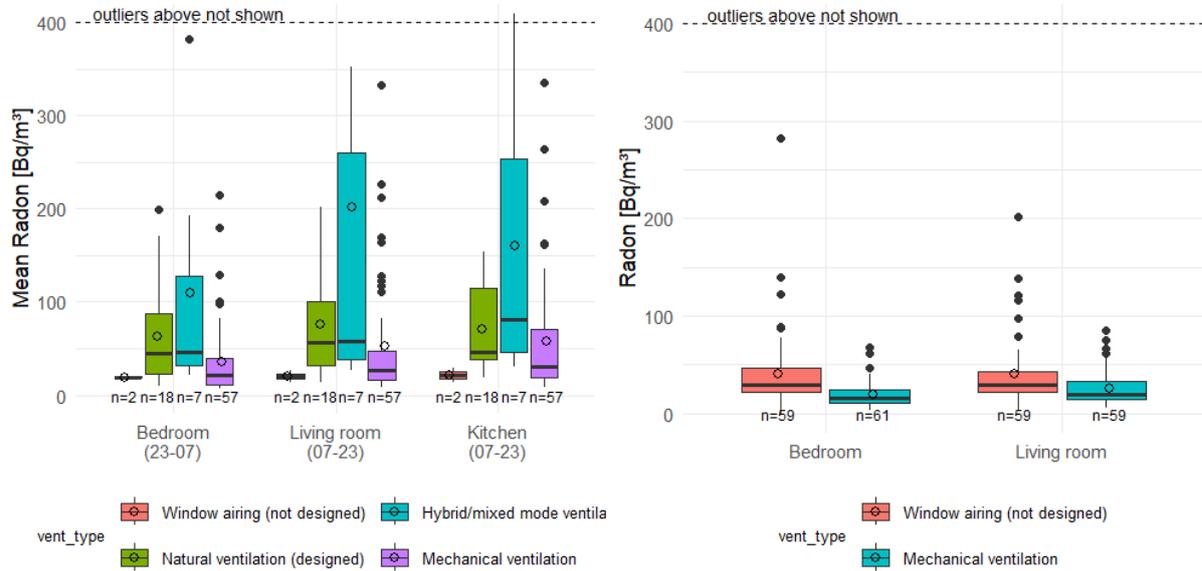
Figure 3.26: Radon concentration in different rooms and for different ventilation types. Left: Mean concentration obtained from continuous measurements (Oct – May, tod as indicated). Right: Concentrations from 1-time measurements. The number of data points (n: nr of distinct rooms) is also provided.

3.3.4.3 Exemplary estimation of formaldehyde and TVOC emission rates

To showcase further applications for the IAQ database repository the emission source strength of indoor air pollutants was estimated using data from the study "Lueftung3.0" (Wallner et al. 2015). This emission rate estimation, performed as part of this project, is documented in more detail in (Rojas et al. 2025). This Austrian cohort study proved suitable as it contained measurements in 123 homes of formaldehyde (HCHO), total volatile organic compounds (TVOC) and ventilation rates, determined using a tracer gas technique (and pressure compensated flow hood in mechanically ventilated homes). VOCs were measured using active sorption tube sampling (Anasorb 747) + GC/MS analysis. TVOC was determined as the total peak area using toluene as a calibration standard. HCHO was sampled using DNPH-cartridges and HPLC analysis. Data were collected at two time points: three months after move-in and one year after the first measurement. The areas-specific emission rate ER_{area} was calculated for each bedroom (one per home) using the measured pollutant concentration c_{pol}, the average ventilation air flow $\dot{V}_{air}$ and the room floor area A according to the following formula:

$$ER_{area} = c_{pol} \frac{\dot{V}_{air}}{A}$$

The results are summarized in Figure 3.27 and in Table A4.11. They show a clear decrease between the two measurement dates. Fifteen months after move-in, the median floor-area specific emission rate of formaldehyde was 24.1 µg/(m²h). Note that the formaldehyde emission rates are substantially higher, with 29.0 µg/(m²h) in mechanically ventilated compared to window aired homes with 16.4 µg/(m²h) (p<0.001). Nevertheless, the indoor concentrations are significantly lower in mechanically ventilated bedrooms, see Figure 3.25 (right). This is due to the fact that the emission rate of formaldehyde will increase as ventilation is increased (and concentration is reduced). See e.g. emission rate model developed by (Zhao et al. 2022). The median floor-area specific emission rate of TVOC was around 150 µg/(m²h) for the later date independently of ventilation type.
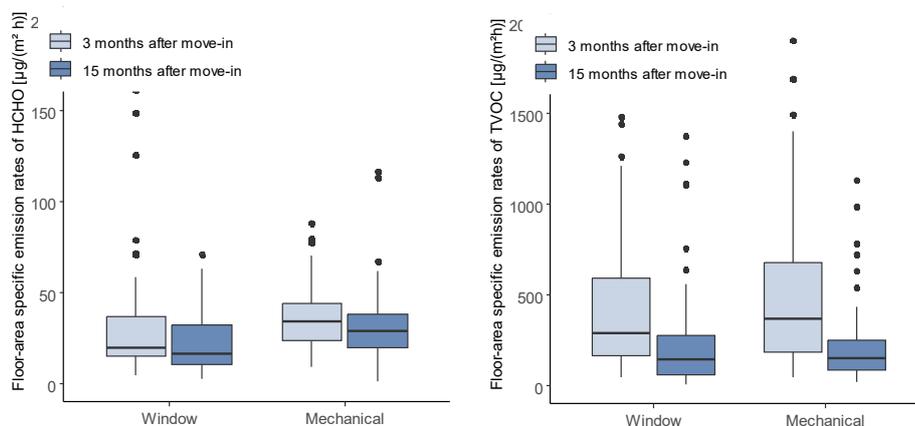
Figure 3.27: Estimated floor-area specific ER of formaldehyde (left) and TVOC (right) for window and mechanically ventilated homes, three and 15 months after occupant move-in.

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Appendices

Appendix 1. IEA EBC Annex 86 – ST2: Additional information about the original papers

Appendix 2. IEA EBC Annex 86 – ST2: Summary of analyzed studies

Appendix 3. IEA EBC Annex 86 – ST2: Standardized analysis workflow

Appendix 4. IEA EBC Annex 86 – ST2: Detail results of meta analysis

4. Smart materials as an IAQ management strategy

Editors: Menghao Qin and Jianshun J. Zhang

4.1. Introduction

4.1.1. Global context of indoor air quality

Indoor air quality (IAQ) is a critical global public health issue, as indoor environments can harbor a variety of pollutants with significant implications for human health, well-being, and comfort. According to the World Health Organization (WHO, 1989; Franklin et al. 2013a-c; WHO, 2018; WHO, 2025), air pollution, both outdoor and indoor, refers to the presence of harmful chemical, biological, or physical agents in the air that may adversely affect human health, ecosystems, or the climate (.Unlike outdoor air pollution, which has been widely studied and addressed through regulatory frameworks, indoor air pollution received limited attention until the early 2000s, despite the fact that people spend 80–90% of their time indoors whether at home, in schools, workplaces, or public spaces (Dimitroulopoulo et al. 2023).

Indoor air pollution can have serious consequences for both health and comfort, ranging from minor irritations to life-threatening conditions. The effects include respiratory issues, asthma, allergies, cardiovascular diseases, chronic obstructive pulmonary diseases (COPDs), and even cancer (Zhang & Smith, 2003; Park et al. 2017; Bruce et al. 2000; Faustini et al. 2013; Ruckerl et al. 2006; Castana-Vinyals et al. 2008; Jiang et al. 2016; Scarborough et al. 2012). According to the World Health Organization (WHO), air pollution contributes to approximately 7 million deaths annually, with over 90% of the global population living in areas where air pollution exceeds safe limits (WHO, 2018).

Ambient and indoor air pollution is one of the leading causes of premature death (all deaths occurring before the age of 65) worldwide. Although ambient and indoor air pollution is often invisible and overlooked as a risk, it has devastating consequences on the health of millions of people.

Air pollution can damage the lungs, heart, brain, and other organs in the human body, leading to acute, chronic, and irreversible health effects. There is clear evidence establishing a link between exposure to air pollution and premature deaths, as well as reduced life expectancy. Air pollution is a major cause of acute lower respiratory infections in children, chronic bronchitis in adults, and lung cancer. It is one of the leading global causes of noncommunicable diseases (NCDs) such as strokes, heart disease, and chronic obstructive pulmonary disease (COPD) in adults. Even at low concentrations, air pollution can pose a serious threat to human health. Exposure to air pollution occurs through inhalation, but it can also occur in the womb. There is a clear link between maternal exposure and adverse effects such as congenital heart disease (CHD) (Zhang et al. 2016), stillbirth, premature birth, and low birth weight (Yang et al. 2018). Other adverse health effects include neurodevelopmental disorders and cognitive impairments. Exposure to air pollution (polycyclic aromatic hydrocarbons, PAHs) is associated with the development of cataracts, the leading cause of blindness in adults.

The pollutants of greatest concern for public health are fine particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2). Other important pollutants include sulfur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs) (Franklin et al. 2013a-c). Among VOCs, formaldehyde (FA), a major indoor pollutant, is particularly concerning due to its toxicity, persistence, and was classified as a probable human carcinogen (WHO, 1989; Kielhorn et al. 2006; IARC, 2004; US EPA).

In confined spaces, sources of pollution can originate from outdoor air or from the desorption of molecules present in the building materials (lacquers, adhesives, textiles, artificial leathers, etc.). Emissions from these materials are particularly significant when the premises are new and the ambient temperature is high. It should also be noted that additional pollution may come from the occupants (such as in the case of smokers, for example). Pollution from outdoor air contains pollutants typical of the location of the dwelling. The most critical areas are those with high traffic, where pollution typically includes compounds such as particulate matter (PM), nitrogen oxides, carbon monoxide, and volatile organic compounds (VOCs), with this phenomenon being intensified near industrial zones or on days with high

widespread pollution in the area The first national measurement campaign conducted by the Indoor Air Quality Observatory (OQAI), a French organization responsible for monitoring and studying indoor air quality, took place from 2003 to 2005. It revealed the predominance of volatile organic compounds (VOCs), with aldehydes, particularly formaldehyde, showing the highest concentration. This was followed by hexanal, toluene, and acetaldehyde (Fig. 4.1) (Kirchner et al. 2006).
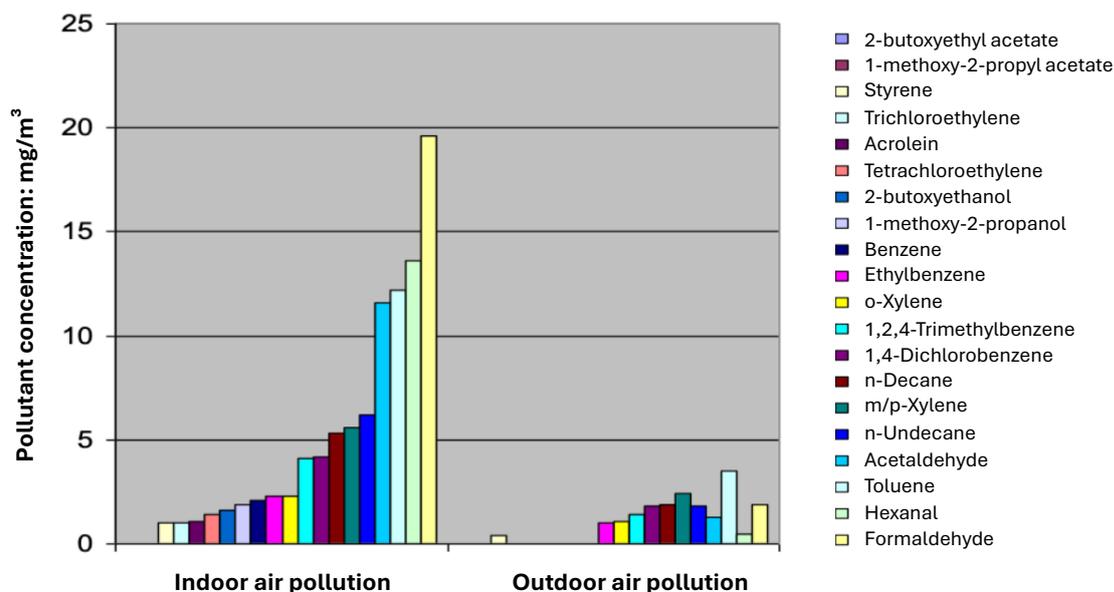
Figure 4.1: Median concentrations of volatile organic compounds in the air of French homes (master bedroom) and outdoors (garden, courtyard, balcony, or windowsill) (2003-2005). (Kirchner et al. 2006; PDL, 2021)

These results underscore the need to address indoor air quality, especially as new buildings, designed for energy efficiency, often exacerbate pollutant accumulation due to their airtight construction. Beyond health implications, IAQ management must also align with global sustainability targets, as the building sector is a major contributor to energy consumption and greenhouse gas emissions. According to the International Energy Agency (IEA), the operation of buildings accounted for 30% of global final energy consumption and 27% of total energy sector emissions. Of these emissions, 8% came from direct sources within buildings, while 19% were indirect emissions from the production of electricity and heat used in building operations (IEA, 2025). This highlights the urgent need for sustainable IAQ management solutions that not only improve health outcomes but also contribute to reducing energy consumption and emissions.

4.1.2. Traditional methods of air quality management

Activated carbon filters are widely used in air filtration systems and are known to provide short-term protection against harmful gases (Marsh & Rodriguez-reinoso, 2006). However, they suffer from several limitations that reduce their effectiveness in purifying indoor air in confined spaces. Specifically, activated carbon lacks sufficient selectivity to ensure the efficient capture of small volatile organic compounds (VOCs) such as formaldehyde. The gas adsorption mechanism in activated carbon is primarily governed by physisorption, making it reversible. As a result, adsorbed pollutants can be released back into the air due to changes in temperature, humidity, or the chemical composition of the surrounding environment (Sadovnik et al. 2024). For instance, the presence of a second gas with a higher affinity for the adsorbent may displace previously captured pollutants.

In general, temperature and humidity variations negatively affect the adsorption capacity of activated carbons (London,, 1937; Delage et al. 2000; Groszek & Aharoni, 1999). Even a slight temperature increase —potentially caused by water adsorption (Groszek & Aharoni, 1999) — can reduce their ability to retain pollutants, or even trigger desorption. Activated carbon typically exhibits a higher affinity for compounds with high molecular weight, low vapor pressure, and high melting points, whereas its interaction with formaldehyde is notably weak (Zou et al. 2019). Moreover, non-functionalized activated carbons are particularly unsuitable for humid environments, further limiting their effectiveness

indoors (Kania, 2010). These shortcomings necessitate the use of a relatively large quantity of activated carbon to achieve a reasonable filtration lifespan.

To overcome these limitations, functionalization (adapting the adsorbent to more efficiently capture the pollutant) techniques have been developed, involving the grafting of specific chemical groups (such as amines) onto the adsorbent material to enable irreversible fixation of targeted pollutants (Miclo et al. 2015; Bromberg & Hatton, 2011; 毛兰群 et al. 2011). Although this approach enhances selectivity, it introduces new challenges. The regeneration of functionalized materials is often difficult, as the chemical stability of grafted groups can be compromised during regeneration cycles. In some cases, the compounds used for functionalization are themselves toxic, raising concerns about their safe use in indoor environments (Bromberg & Hatton, 2011).

4.1.3. Recent advances in air quality management

In response to the limitations of traditional adsorbents, recent research has explored advanced materials capable of addressing complex indoor air pollutants, especially formaldehyde. Studies conducted by Lamonier and colleagues have highlighted that an effective adsorbent for formaldehyde should combine small pore sizes with a high specific surface area (Bellat et al. 2015; 2019). Additionally, the presence of specific metals such as aluminum, silver, or copper can significantly enhance adsorption performance (Bellat et al. 2015).

Lamonier's team compared sodium-doped faujasite zeolites (NaX and NaY) with activated carbon (Bellat et al. 2015). Their findings revealed that in dry conditions, sodium-doped zeolites exhibited excellent formaldehyde adsorption performance, thanks to strong interactions between formaldehyde molecules and extra-framework cations. Conversely, activated carbon demonstrated poor adsorption capacity for formaldehyde. The researchers also observed that formaldehyde can polymerize into paraformaldehyde within the pores of zeolites, leading to the retention of some adsorbed molecules at temperatures above 200°C. However, these zeolites also exhibited high hydrophilicity, resulting in competitive adsorption between water and formaldehyde in humid environments[46]. This trade-off often necessitates a dehumidification step before effective formaldehyde removal. Hydrophobic dealuminated zeolites have been proposed as alternatives, although their affinity for formaldehyde is reduced (Bellat et al. 2019).

Beyond zeolites, the functionalization of porous materials with amine groups has proven particularly effective in improving aldehyde adsorption. For example, the modification of MIL-101(Cr) with ethylenediamine (ED) has been shown to significantly enhance formaldehyde adsorption, increasing the capacity from 3.34 mmol for pristine MIL-101(Cr) to 5.49 mmol for its ED-functionalized counterpart (Wang et al. 2016). This improvement is attributed to the formation of stable chemical interactions between amine groups and formaldehyde molecules, including the formation of hemiaminal intermediates, which subsequently dehydrate to form imines. Notably, MIL-101-ED exhibited good cycling stability, retaining 86% of its initial adsorption capacity after five adsorption/regeneration cycles, although some loss of performance was linked to partial desorption or detachment of the ED molecules (Wang et al. 2016). The moderate toxicity of ED also raises potential concerns for indoor applications (Yangt et al. 1983).

Studies on the adsorption of other VOCs, such as acetaldehyde and acetic acid, have further emphasized the importance of structural and chemical fine-tuning in adsorbent design. Alvarez *et al*. (2016) demonstrated that efficient acetaldehyde adsorption requires the presence of metallic sites with moderate Lewis acidity, while Dedecker *et al*. (2018) showed that hydrophobicity, small pore sizes, and specific functional groups (e.g., perfluorinated moieties) enable effective capture of acetic acid even under humid conditions. Particularly promising materials include MIL-140B and UiO-66-2CF$_3$, which combine hydrophobic surfaces and confined pore geometries, facilitating selective VOC adsorption.

More recently, Vikrant *et al*. (2019) confirmed the strong performance of amine-functionalized metal-organic frameworks (MOFs) such as UiO-66-NH$_2$ for formaldehyde capture at low concentrations in humid environments. The superior performance was linked to van der Waals interactions and coordination between formaldehyde and Zr^{4+} Lewis acid sites in the MOF structure. These findings collectively highlight the transformative potential of functionalized MOFs for selective VOC adsorption in real-world indoor air purification applications.

Indoor air pollution is one of the major threats in developed countries, notably due to high concentrations of formaldehyde, a harmful molecule difficult to eliminate. Addressing this purification challenge while adhering to the principles of sustainable development requires the use of innovative, advanced sustainable materials. In this context, some of us have developed an advantageous mild chemisorption synergistic mechanism using porous metal (III or IV) pyrazole-dicarboxylate based metal-organic frameworks to trap formaldehyde in a reversible manner, without incurring significant energy penalties for regeneration. A straightforward, environmentally friendly, and scalable synthesis protocol was established for the porous, water-stable aluminum pyrazole dicarboxylate known as Al-3.5-PDA or MOF-

303, capable of functioning as a highly efficient and reusable filter. It demonstrates selectivity and high storage capacity for formaldehyde under conditions typical of severe indoor use, such as in housing or vehicle cockpits, including varying VOC mixtures and concentrations, humidity, and temperature, without any accidental release (Sadovnik et al. 2024; Daturi et al. 2020).

Altogether, these studies point toward promising opportunities for the future development of MOFs as smart materials for indoor air quality (IAQ) management, offering both selective pollutant capture and the potential for real-time sensing, regeneration, and adaptive filtration capabilities.

4.1.4. Objectives of Subtask 3

The primary goal of Subtask 3 is to explore the potential of smart materials, particularly metal-organic frameworks (MOFs) in energy-efficient indoor air quality (IAQ) management. This report will assess the feasibility of incorporating MOFs into IAQ management systems, evaluate their adsorption performance under typical building environments, assess the associated challenges, and propose effective strategies for their implementation in modern building environments. Finally, numerical simulations have been carried out to study the energy saving and exposure reduction potential of the MOF materials in residential buildings under different climatic conditions. Specific attention will be given to MOFs used for formaldehyde (FA) adsorption, particularly within membrane structures, and how these systems can contribute to healthier and more energy-efficient buildings.

4.1.4.1 Feasibility of MOFs in IAQ management

This report will investigate the practical feasibility of integrating MOFs into IAQ systems, particularly within membranes designed to capture indoor air pollutants such as formaldehyde (FA). Several experimental protocols have tested the adsorption performance of MOFs incorporated into these membranes over multiple days, simulating real-world conditions where residual formaldehyde pollution is present. These tests have been conducted using varying concentrations of FA in controlled environments, allowing for the analysis of MOFs' adsorption capacities and their long-term stability in maintaining air quality. The report will also examine the selectivity of MOFs for FA and other pollutants in mixed indoor air environments, evaluating how MOFs perform over extended periods, including their efficiency over time and regeneration capabilities.

4.1.4.2 Challenges associated with MOFs

While the integration of MOFs into IAQ management systems holds significant promise, several challenges must be addressed to enable their broader adoption. This report will examine these challenges, including the scalability of production for membrane-based MOF systems and the energy efficiency of MOF regeneration. Since membrane applications often involve long-term exposure to environmental factors such as humidity and fluctuating temperatures, it is crucial to assess how MOFs perform under these conditions, particularly in terms of durability and stability. Additionally, the potential toxicity or off-gassing from MOFs will be considered to ensure their safety in residential and commercial spaces.

4.1.4.3 Integration into IAQ management systems

One of the key objectives of this report is to explore how MOFs can be integrated into existing IAQ management systems, specifically focusing on membrane applications. Membranes embedded with MOFs have shown promising results for the selective removal of formaldehyde (FA) from indoor air. The report will present various experimental setups where MOFs incorporated into membrane structures have been evaluated in workplace settings with residual FA pollution. The adsorption capacities were modeled (extrapolated) over time to predict the material's long-term performance in real-world environments. Moreover, the report will evaluate the regeneration techniques for these MOF membranes, which include low-energy regeneration methods such as washing or mild heating, thus reducing energy consumption compared to conventional air purifiers.

In addition to their use in traditional filtration systems such as HVAC units, the report will consider the potential for innovative IAQ management solutions, such as integrating MOF membranes into building materials (e.g., wallboards, ceiling panels) or surface coatings. These materials could actively purify indoor air by adsorbing pollutants directly from the surrounding environment, offering continuous air purification in spaces like offices, meeting rooms, or homes, where FA and other VOCs are commonly found.

By investigating their adsorption performance, long-term durability, and energy-efficient regeneration, this report will highlight the potential benefits of MOFs in creating healthier indoor environments while reducing energy consumption and operational costs. Through modeling and experimentation, the report will address how MOFs can be successfully integrated into building systems, laying the groundwork for their widespread adoption in both commercial and residential

applications. By overcoming the challenges and capitalizing on the strengths of MOFs, this report will explore the future of air purification technology and its role in sustainable indoor environments.

4.1.5. Key outcomes

In conclusion, subtask 3 has highlighted the potential for integrating novel smart materials, particularly metal-organic frameworks (MOFs), into building systems, such as air purification and ventilation, to achieve energy-efficient indoor air quality (IAQ) management. The feasibility of passive applications, including innovative shaping approaches like wallpapers, wallboards, and sorbent-coated textiles, has also been explored.

Key outcomes of Subtask 3 include: i) A comprehensive review and evaluation of existing IAQ and ventilation technologies incorporating smart materials (sections 1, 2, and 3). ii) Characterization of novel materials' performance for VOCs sorption and filtration (section 4). iii) Modelling of the performance under typical residential conditions (sections 5.1 and 5.2). iv) Assessing energy-saving and exposure reduction potential through modelling (section 5.3).

Future work will concentrate on the development and identification of advanced smart functional materials capable of efficiently and selectively capturing a variety of indoor air pollutants. This includes the creation of both active and passive air cleaning technologies or systems utilizing these materials. Numerical simulations will be conducted to assess the energy-saving and exposure-reduction potential of these smart material-based purification technologies in residential buildings across different climatic conditions. Additionally, experimental studies will be carried out to evaluate the real-world performance of these functional materials in terms of energy efficiency and pollutant exposure reduction. Complementary modeling efforts will further explore their effectiveness under varying climate scenarios. To support these findings, case studies will be undertaken to collect practical data and demonstrate the overall impact of these novel air purification technologies on indoor air quality (IAQ) and energy conservation.

4.2. Smart materials for indoor air quality Management

4.2.1. Definition and role of smart materials

Smart materials are advanced substances designed to respond adaptively to external stimuli such as temperature, humidity, light, chemical substances, or mechanical forces. Their unique ability to modify their properties in real-time makes them particularly attractive for applications in indoor air quality (IAQ) management.

Unlike conventional filtration systems, which passively trap pollutants, smart materials offer active and selective pollutant capture, sometimes even neutralizing harmful substances dynamically. This makes them especially suitable for use in modern buildings, where air exchange is limited for energy efficiency.

4.2.2. Functioning principle of smart materials in pollutant adsorption

Smart materials function by exhibiting measurable physical or chemical changes when exposed to specific stimuli. In the context of IAQ, this means they can react to pollutants. Certain smart materials, especially those with functional groups or porous structures, can selectively adsorb airborne chemical contaminants.

Among these, Metal-Organic Frameworks (MOFs) stand out due to their crystalline, highly porous architecture and tunable chemical environment. Their functional versatility and low energy demand for regeneration allows them to act as efficient adsorbents, offering a highly promising solution for IAQ management.

4.3. Advantages of metal-organic frameworks (MOFs) for IAQ management

4.3.1. Why MOFs?

Metal-Organic Frameworks (MOFs) are a class of hybrid crystalline materials composed of metal ions or clusters coordinated to organic ligands, forming highly porous structures. These frameworks are characterized by their extraordinary surface areas (up to 7000 m²/g) (Liu et al. 2015; Wang et al. 2015; Férey et al. 2005) and tunable porosity,

which can be precisely tailored to specific applications (Kaskel, 2016). MOFs also exhibit a wide range of structural and chemical diversities, with more than 90,000 structures reported to date and over 500,000 predicted (Rungtaweevoranit et al. 2017; Moosavi et al. 2020). This tunability makes MOFs highly adaptable, allowing the design of pore sizes, shapes, and functionalities that are optimized for targeted applications such as gas storage, separation, pollution control, and indoor air quality (IAQ) management (Stassen et al. 2017; Miller et al. 2013; McKinley et al. 2013; Samokhvalov, 2017; Bai et al. 2016; Ricco et al. 2016; MacGillivray, 2010)

In the context of air purification, the unique combination of high adsorption capacity, selective pollutant targeting, and energy-efficient regeneration processes makes MOFs stand out compared to traditional adsorbents like activated carbon. Additionally, their ability to retain structural integrity under varying environmental conditions, such as humidity and temperature, further enhances their suitability for IAQ applications.
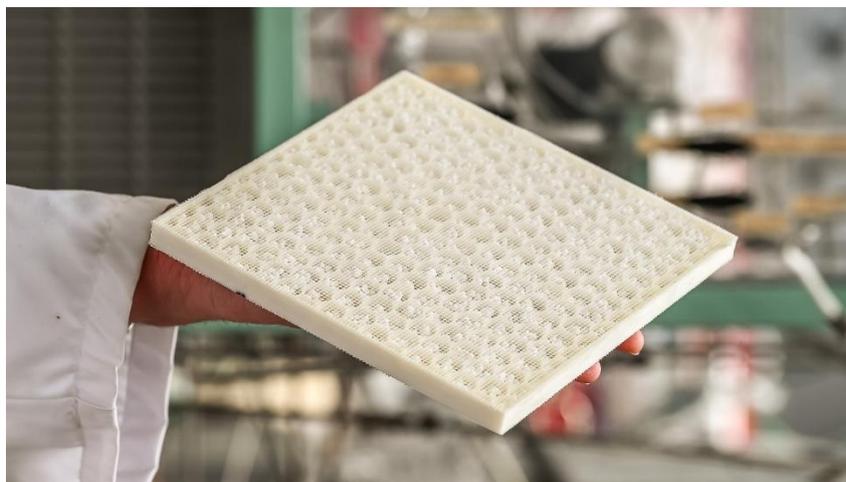
Figure 4.2: MOF (Al-3,5-PDA) filter for VOC adsorption

4.3.2.   Selective pollutant adsorption

Selectivity is one of the hallmarks of MOF performance in IAQ applications. Certain MOFs can be designed to target pollutants like formaldehyde (FA), VOCs, and carbon dioxide, even under real-world conditions that include the presence of moisture and competing gas species (Sadovnik et al. 2024; Sanchez-Serratos et al. 2016; Alvarez et al. 2017; Ibarra et al. 2016; Peralta et al. 2016).

A particularly promising example is Al-3.5-PDA, a pyrazole-based MOF formed from aluminum ions and 3,5-pyrazole dicarboxylate ligands. This material features microporous channels where accessible pyrazole groups serve as active sites for pollutant capture. Studies using in situ FTIR and density functional theory (DFT) simulations have confirmed that Al-3.5-PDA exhibits chemisorption of formaldehyde via both hydrogen bonding and covalent interactions. This robust mechanism remains effective even in the presence of water, CO_2, and other VOCs, illustrating the MOF's superior selectivity (Sadovnik et al. 2024).

4.3.3.   Low energy regeneration

MOFs also excel in energy-efficient regeneration compared to conventional adsorbents. Activated carbon, for instance, often requires significant energy for thermal desorption, (London, 1937), whereas MOFs like Al-3.5-PDA can be regenerated using milder methods. Remarkably, Al-3.5-PDA demonstrates reversible FA adsorption through simple water washing at room temperature. This process effectively restores the material's adsorption capacity without compromising its structural integrity, as confirmed by FTIR and X-ray diffraction analyses (Sadovnik et al. 2024; Daturi et al. 2020).

4.3.4.   High working capacity

MOFs and especially the pyrazole-based Al-3.5-PDA stand out as a transformative materials for formaldehyde (FA) capture, which is a significant concern in IAQ. Given Al-3.5-PDA exceptionally high adsorption capacity, a filter

containing 200 g of this material could operate continuously for approximately one year before reaching saturation (Alevantis & Belshé, 1996). Importantly, the material's energy-efficient regeneration achieved by washing in water at room temperature ensures a prolonged lifespan of up to 10 years. This longevity far exceeds conventional materials like activated carbon, offering an innovative and sustainable solution for IAQ challenges (Sadovnik et al. 2024; Daturi et al. 2020).

4.3.5. Durability and stability

Another critical advantage of MOFs is their ability to withstand challenging environmental conditions. Unlike activated carbon, which may release adsorbed pollutants under high temperatures or low pollutant concentrations, MOFs like Al-3.5-PDA retain FA up to 50°C and release it only at higher temperatures (~75°C). This ensures that MOF-based filters do not inadvertently become secondary pollution sources.

Furthermore, MOFs demonstrate high selectivity even in complex pollutant mixtures. For example, pyrazolate-based MOFs, such as Al-3.5-PDA, effectively adsorb formaldehyde (FA) in the presence of acetaldehyde, toluene, and CO_2, maintaining performance even under humid conditions. Computational and experimental studies confirm that CO_2, despite its potential for competitive adsorption, interacts weakly with the MOF compared to FA (Sadovnik et al. 2024; Li et al. 2023).

In summary, pyrazolate-based MOFs represent a transformative solution for IAQ management. Their high adsorption capacity, selective targeting, energy-efficient regeneration, and durability position them as a superior alternative to traditional materials. By addressing critical challenges in air purification, MOFs have the potential to significantly improve indoor environments, protect human health, and reduce the environmental footprint of air filtration systems.

The study of MOFs, specifically Al-3.5-PDA, directly addresses the focus on developing smart materials for indoor air quality (IAQ) management. MOFs emerge as functional, intelligent solutions for pollutant adsorption in residential and commercial environments.

4.3.6. Advancing smart IAQ materials

Al-3.5-PDA could be a highly promising candidate for integration into smart indoor air quality (IAQ) management systems, offering transformative potential for enhancing indoor environments. Its exceptional combination of high selectivity, long-term durability, low-energy regeneration, and compatibility with hybrid filtration approaches could represent a significant advancement in air purification technology. By addressing pollutants such as formaldehyde with precision, Al-3.5-PDA could not only improve indoor air quality but also reduce energy consumption, lower environmental impact, and enhance the performance of existing air filtration and monitoring systems.

In addition to its application in traditional filtration systems (such as HVAC systems), this MOF could be incorporated into innovative formats like wallboards, surface coatings, or building materials designed for direct pollutant removal at the source. These multifunctional materials could offer continuous air purification in residential, commercial, and industrial environments, ensuring effective and sustainable pollutant control. By integrating MOFs like Al-3.5-PDA into everyday infrastructure, indoor air quality management could evolve from isolated devices to integrated systemic solutions, providing superior air quality and healthier indoor environments.

4.4. Experimental tests of MOFs for VOC adsorption

4.4.1. Small-scale chamber test of MOF Al-PDA papers for formaldehyde removal

A microporous aluminium dicarboxylate MOF, Al-3,5-PDA, was identified as an ultra-selective, efficient formaldehyde (FA) adsorbent (Sadovnik et al. 2024; Daturi et al. 2020). Its high efficiency stems from a novel sorption mechanism, where FA reacts with pyrazole groups in the micropores, enabling high capacity even at high humidity, leak-free properties, and regenerability at elevated temperatures or in water at room temperature.

MOF Al-PDA was processed into paper sheets with a high MOF loading (75 wt %) using a green one-pot method, maintaining FA sorption properties and good mechanical strength. Large-scale sheets (>20 × 20 cm) were distributed under Annex 86 for independent evaluation under real-world conditions, including temperature, humidity, FA levels, and co-pollutants.

Testing was conducted in 50-L stainless steel chambers at Syracuse University (SU) and the National Research Council Canada (NRC). At NRC, two sheets were placed at the chamber bottom with one side exposed, whereas at SU, a single sheet was positioned on a rack with both sides exposed. Test conditions included 1 air change per hour, 23 °C, 50% RH, and ~50 µg/m³ formaldehyde (FA) over a 7-day adsorption and 4-day desorption period (Test 1a and 1b in Table 4.4.1). Long-term studies extended up to 28 days at FA concentrations of ~50 and 500 µg/m³. Relative humidity (RH) (10–70% in Tests 2–4) and temperature (16–30 ºC in Tests 5–8) were varied to assess environmental effects. The SU experiments were conducted at two formaldehyde concentration levels (115 µg/m³ and 321 µg/m³). After a 28-day adsorption test, a 7-day desorption phase at 50% relative humidity was implemented to assess secondary release risks. To evaluate the potential interference of other chemicals on FA removal efficiency, 13 volatile organic compounds (VOCs) (acetaldehyde, acetone, hexanal, heptane, toluene, o-xylene, tetrachloroethylene, ethylcyclohexane, α-pinene, d-limonene, hexamethylcyclotrisiloxane, decamethylcyclopentasiloxane, and naphthalene at ~60 µg/m³ each) and CO_2 (~1600 ppm) were introduced alongside FA (Tests 9 and 10).

One set of paper sheets were used in all tests. They were initially activated via static regeneration at 104−107°C and -700 mbar for 4 h in a vacuum oven. For subsequent tests, they were soaked in 4 L of distilled water per sheet for 1 day, air-dried for 12−24 h, and vacuum-dried at 110°C and -700 to -970 mbar for 5 h. FA was generated via a paraformaldehyde permeation tube (VICI Metronics), while 13 VOCs were delivered by evaporating a liquid mixture of 13 VOCs using a syringe pump.

The FA removal efficiency $(1 - C_{out}/C_{in})$ was calculated based on the inlet (C_{in}) and outlet (C_{out}) concentrations periodically measured with a DNPH (2,4-dinitrophenylhydrazine) cartridge sampling and high-performance liquid chromatography (HPLC). Additionally, concurrent sampling was conducted using thermal desorption tubes (Tenax TA), followed by gas chromatography–mass spectrometry (GC/MS) analysis to quantify interfering VOCs and potential by-products.

4.4.1.1   Removal efficiency from 28-day tests

The tests at four concentrations (~50, 115, 321, and 500 µg/m³) were conducted for 28 days. Figure 4.3a shows the long-term removal efficiency measured at NRC, which was relatively constant until 7 or 14 days, followed by a steady decrease of ~7% every week. Figure 4.3a also indicates that the removal efficiency was similar for both FA concentrations (~50 and 500 µg/m³).

Figure 4.3b presents the FA removal efficiency measured at SU over a 28-day test period at two different concentrations. The removal efficiencies varied from 72% to 49% (at 115 µg/m³) and from 77% to 55% (at 321 µg/m³), corresponding to the initial day (1 day) and the final day (28 days), respectively. Overall, the removal efficiencies at SU were slightly lower than the NRC tests. The FA removal efficiency at the higher concentration appears to be slightly higher with no statistical significance.
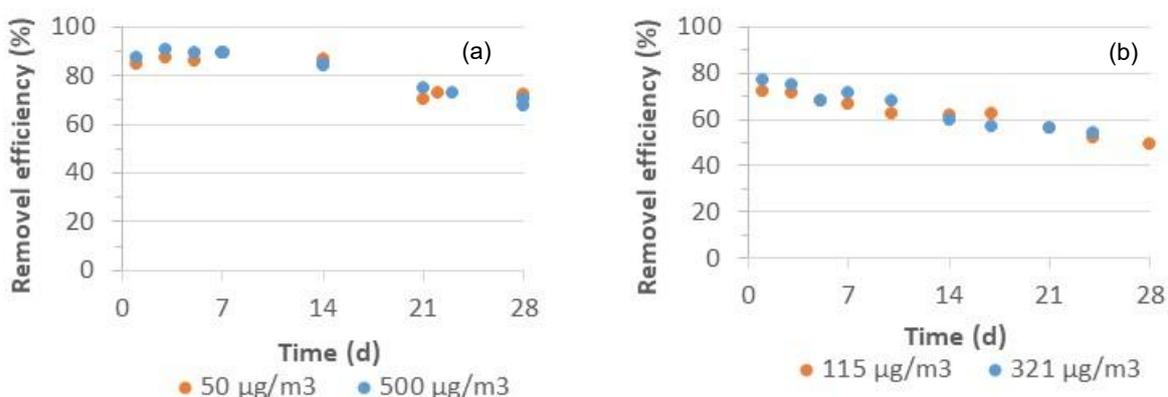
Figure 4.3: FA removal efficiencies at different FA concentrations during a long-term test (28 days) at (a) NRC and (b) SU

4.4.1.2 Removal efficiency from 7-day tests

Table 4.4.1 summarizes the test conditions and the formaldehyde (FA) removal efficiency (RE) averaged over 1 to 7 days under various environmental conditions and in the presence of different gases. Under typical indoor conditions (23°C, 50% RH), the mean RE was 87.5% and 84% in two separate tests. The slightly lower RE in Test 1b may be attributed to differences in exposed surface area and/or degradation from multiple uses of the same specimens.

The RE across different RH levels ranged from 84% to 92.8%. While RE slightly decreased as RH increased from 10% to 50%, the variations were within the experimental error margin. A decreasing trend was observed with increasing temperature, but the maximum difference (~7%) was within expected experimental variations. The presence of 13 VOCs and CO_2 did not significantly affect RE.

Table 4.4.1: Test conditions and FA removal efficiency

| Test ID | Test conditions | | | | Mean removal efficiency (%) from 1 to 7 days |
	Temp (ºC)	RH (%)	13 VOCs	CO$_2$	
Test 1a	23	50	No	No	87.5 ± 0.5
Test 1b	23	50	No	No	84.0 ± 1.0
Test 2	23	10	No	No	92.8 ± 0.9
Test 3	23	30	No	No	92.0 ± 0.7
Test 4	23	70	No	No	89.5 ± 0.4
Test 5	16	50	No	No	88.4 ± 0.7
Test 6	19	50	No	No	88.1 ± 0.5
Test 7	26	50	No	No	82.1 ± 3.1
Test 8	30	50	No	No	80.8 ± 1.1
Test 9	23	50	Yes	No	85.6 ± 1.6
Test 10	23	50	Yes	Yes	83.7 ± 0.5

4.4.1.3 Summary of small-scale chamber tests with MOF Al-PDA papers

The MOF-Al-PDA paper sheets tested in small-scale chambers exhibited high formaldehyde (FA) removal efficiency (>80%) over seven days at two FA concentrations (~50 and 500 μg/m³) and under varying relative humidity (10%–70%), temperatures (16–30°C), and the presence of 13 VOCs and CO_2. No by-products were detected. The consistent removal efficiency across different conditions indicates that MOF-303 maintains its effectiveness across a wide range of indoor environments and climates.

However, long-term testing at NRC revealed a gradual decline in FA removal efficiency, reaching ~70% after 28 days. While this remains a high removal rate, extended testing is necessary to better understand the material's performance over its expected lifetime, which, based on theoretical capacity calculations, could span several years.

Overall, the MOF-Al-PDA paper sheets exhibited excellent FA removal capabilities, robust stability, and resistance to co-pollutants, reinforcing their potential for real-world air purification applications.

4.4.2. Adsorption performance of MOF MIL-101 (Cr) for indoor toluene

Due to the large specific surface area, high porosity and adjustable pore structures, Metal organic framework (MOF) has shown great potential in VOCs adsorption. To investigate their performance in indoor air purification, this study examines the adsorption capacity of MOFs toward ppb-level VOCs.

Three chemically stable MOF materials were synthesized, with toluene selected as a representative VOC for evaluation. The breakthrough curve method was employed to compare the adsorption capacities of the synthesized

MOFs with those of activated carbon. This work aims to provide experimental data to support the development of novel indoor air purification materials.

4.4.2.1   Experimental method

The schematic diagram of the breakthrough method in this study is shown in Figure 4.4
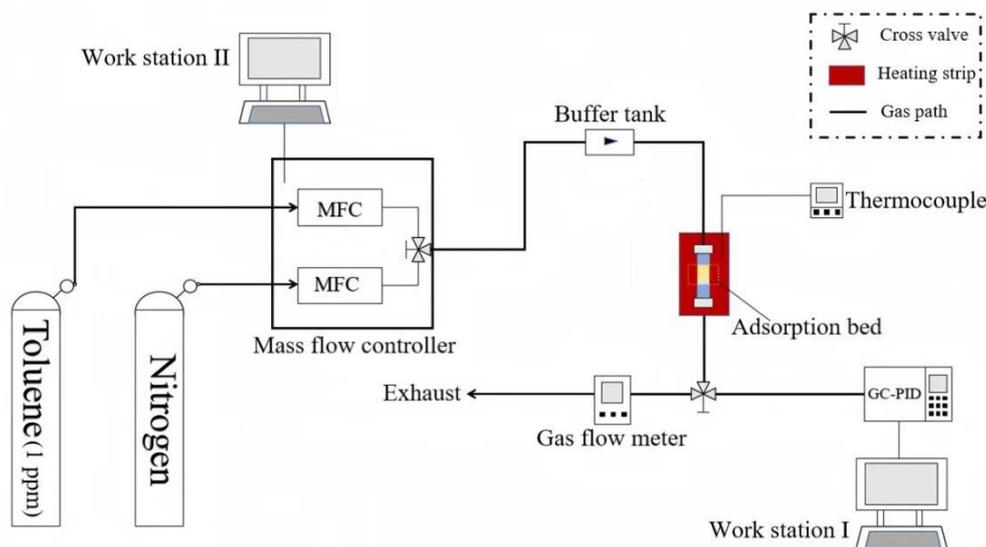
Figure 4.4: The schematic diagram of the toluene adsorption experiments.

The entire experimental system can be divided into three parts: gas distribution, adsorption, and detection systems. Firstly, the standard toluene-nitrogen gas is mixed with pure nitrogen in different proportions to obtain gas with different toluene concentrations by adjusting the mass flow controllers. The mixed gas is then introduced into the adsorption bed, which is filled with adsorbent material. The constant temperature heating strip is used to control the temperature of the adsorption bed. After passing through the adsorption bed, the toluene concentration in the gas is measured by GC-PID to obtain the adsorption breakthrough curve.

The equilibrium toluene adsorption capacity can be calculated by Eq. (4.1).

$$q_e = \frac{Q \times C_0 \times 10^{-6}}{W \cdot M} \cdot \left[t - \int_0^t \frac{C_t}{C_0}(dt) \right] \tag{4.1}$$

Where q_e is the equilibrium adsorption capacity, mg/g; Q is the flow rate, mL/min; W is the adsorbent weight, g; M is the relative molecular weight of toluene; C_0 is the initial toluene concentrations, mg/m^3; C_t is the detected toluene concentrations, mg/m^3; t is the saturation time, min.

4.4.2.2   Results

The toluene adsorption capacities of four materials at a concentration of 500 ppb are shown in Fig. 4.5. Al-fumarate exhibited the highest adsorption capacity of 199.07 mg/g, significantly outperforming MOF-303(Al) (102.03 mg/g) and UIO-66(Zr) (23.3 mg/g). The adsorption capacities of all three MOF materials are better than that of activated carbon (10.75 mg/g). These results demonstrate the superior toluene adsorption potential of MOFs, particularly Al-fumarate, suggesting their promising applicability in air purification.
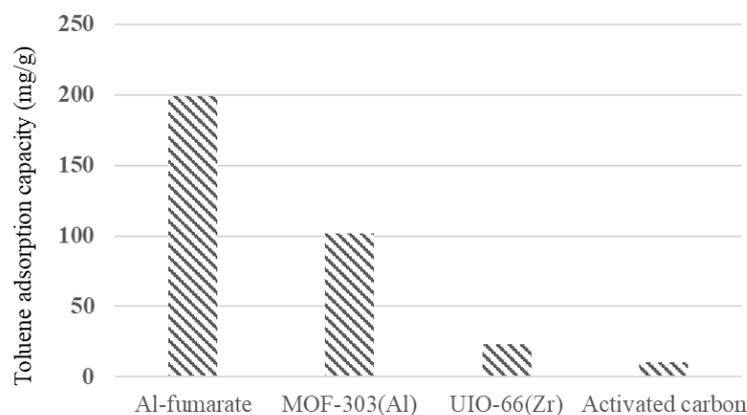
Figure 4.5: Toluene adsorption capacity of materials at 500 ppb toluene concentration.
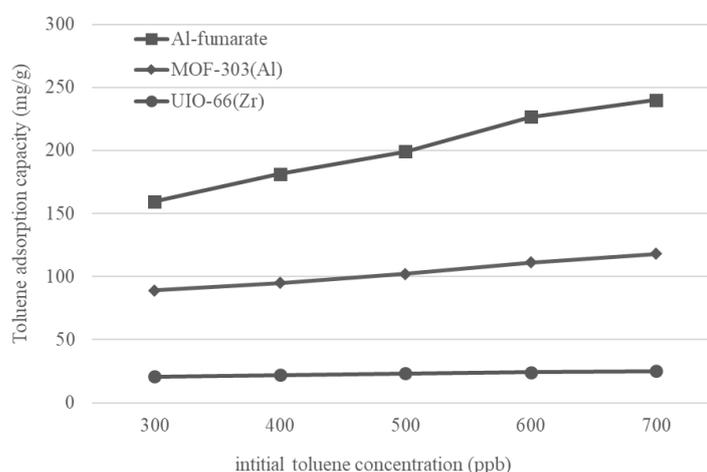
Figure 4.6: Toluene adsorption capacities of MOFs at different toluene concentrations.

The adsorption capacities of the three MOFs at different toluene concentrations have been further studied. The results are shown in Fig. 4.6. Al-fumarate consistently exhibited the highest adsorption capacity, increasing from 159.68 mg/g at 300 ppb to 240.02 mg/g at 700 ppb, demonstrating a concentration-dependent enhancement in adsorption efficiency. Similarly, MOF-303(Al) showed a gradual rise in capacity from 89.08 mg/g (300 ppb) to 118.01 mg/g (700 ppb), while UIO-66(Zr) displayed a more modest increase from 20.91 mg/g to 25.11 mg/g over the same concentration range. These results underscore the superior and scalable toluene-adsorbing capability of Al-fumarate compared to other MOFs, particularly under higher VOC concentrations. The observed trends suggest that adsorption performance correlates with both material-specific properties and ambient toluene levels, reinforcing the potential of Al-fumarate for practical applications in air quality management. Further studies on adsorption kinetics and isotherm modeling are warranted to optimize material design for targeted VOC removal.

4.4.3. Comparative tests of MOF Al-PDA and MnOx catalysts for formaldehyde removal

4.4.3.1 The tested materials

The activated carbon used in this study was obtained from Nanjing Wanqing Chemical Glass Instrument Co., Ltd. (China), with a particle size of 20-50 mesh. The active manganese decomposition sheets were acquired from Nanjing Yujie Environmental Technology Co., Ltd. (China), under the product patent number ZL 2013 1 0139928.3. These sheets consist of high-molecular-weight polyethylene terephthalate fibers as the carrier, onto which MnOx crystals are loaded. The fiber diameter ranges approximately between 15 and 20 μm, and the specific surface area of the MnOx particles is 202.89 m²/g, with pore diameters predominantly ranging from 4 to 6 nm. Each sheet has dimensions of 125 mm × 180 mm. Images of these materials are shown in Figure 4.7.

Figure 4.7: The images of the (a) activated carbons, (b) MnOx catalysts, and (c) Al-MOF materials used in the experiments.

Prior to the experiment, both the Al-MOF and activated carbon samples must be subjected to activation in a vacuum drying oven. Heat treatment combined with vacuum extraction effectively desorbs impurities adsorbed within the pores of the samples. Specifically, the Al-MOF was activated at 102°C under a vacuum pressure of 800–850 mbar for 5 hours. For the activated carbon particles, the activation process involved exposure to 102°C under a vacuum pressure of 500 mbar for 16 hours. When reused after adsorption, the Al-MOF requires regeneration at 102°C under a vacuum pressure of 500 mbar for 16 hours. In all experiments, a consistent mass of 12 grams was maintained for each material.

4.4.3.2   The measurement method

The formaldehyde removal efficiency of the three materials under static conditions was evaluated in a 500 L (780 mm × 800 mm × 800 mm) airtight environmental chamber maintained at a constant temperature of 25°C. The natural decay rate of formaldehyde in the chamber, in the absence of any test materials, was determined to be 0.013 h^{-1}. To achieve a high initial formaldehyde concentration, 2.5 mL of a 1000 mg/L formaldehyde standard solution was evenly distributed into a glass dish positioned centrally within the chamber. A small heating pad placed beneath the glass dish was activated for 30 minutes to accelerate the evaporation of the formaldehyde solution. Subsequently, the circulating fan within the chamber was turned on, and the formaldehyde solution was allowed to volatilize for an additional 2 hours. Once complete volatilization was confirmed, the initial formaldehyde concentration in the chamber was measured using the 3-methyl-2-benzothiazolinone hydrazide spectrophotometric method. The chamber door was then opened, and the test material was promptly placed on the stainless steel shelf at the center of the chamber before closing the door again. Formaldehyde concentrations were periodically sampled at the chamber outlet using a QC-3 pump (Beijing Institute of Labor Protection) operating at a flow rate of 0.3 L/min for 5 minutes. The formaldehyde concentration was subsequently analyzed by a spectrophotometer (UNIC 7200, China) at a wavelength of 630 nm.

4.4.3.3   Measurement results

The decay pattern of formaldehyde concentration and the removal efficiency of activated carbons, MnOx catalysts, and Al-MOF under static testing conditions are presented in Figure 4.6. In the presence of MnOx catalysts and Al-MOF, the formaldehyde concentration within the chamber decreased rapidly before stabilizing at a relatively low level. Specifically, one hour after introducing Al-MOF, the formaldehyde concentration dropped from an initial value of 2416.0 µg/m³ to 477.4 µg/m³, corresponding to a reduction of 1938.6 µg/m³ (79.8%). The concentration then gradually decreased further, reaching 112.78 µg/m³ after 3.3 hours. Similarly, in the presence of MnOx catalysts, the formaldehyde concentration also decreased rapidly; one hour after introduction, it fell from an initial value of 2818.3 µg/m³ to 704.3 µg/m³, representing a reduction of 2114.0 µg/m³ (75.0%). After 3.6 hours of MnOx catalyst exposure, the concentration had further decreased to 208.0 µg/m³. In contrast, the rate of decrease was more gradual with activated carbons. The initial formaldehyde concentration was 2741.9 µg/m³ and decreased to 2449.9 µg/m³ one hour after introducing the activated carbons, corresponding to a reduction of only 292.0 µg/m³ (10.6%). By 3.4 hours into the test, the concentration had decreased to 1513.78 µg/m³.
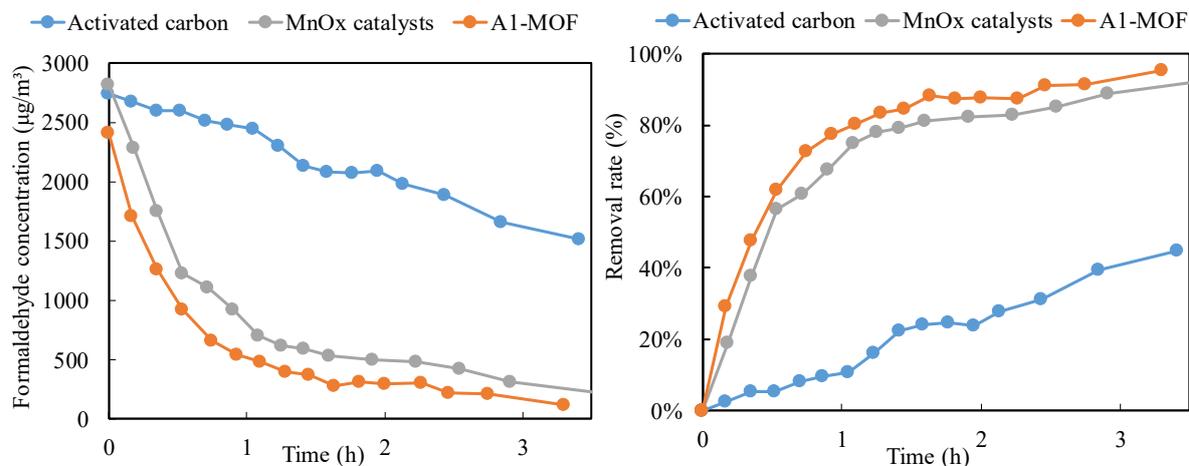
Figure 4.8: (a) The decay pattern of formaldehyde concentration and (b) the removal efficiency of activated carbon, MnOx, and Al-MOF in static testing conditions.

The removal efficiency of the materials was quantified by comparing the decay in concentration relative to the initial value. As shown in the figure, both A1-MOF and MnOx catalysts demonstrated rapid initial increases in formaldehyde removal rates, followed by a gradual stabilization phase. Among the three materials, A1-MOF achieved the highest formaldehyde removal rate of 96.0% at 3.3 hours, highlighting its exceptional performance in static formaldehyde purification. The trend for MnOx catalysts paralleled that of A1-MOF, achieving a removal rate of 92.6% at 3.6 hours, which indicates effective purification albeit with a slightly delayed onset compared to A1-MOF. In contrast, activated carbons exhibited a steady but slower increase in formaldehyde removal throughout the testing period, reaching only 44.8% at 3.4 hours.

4.5. Modelling and simulation

Al-3,5-PDA is a water-stable, microporous metal-organic framework (MOF) featuring one-dimensional hydrophilic channels. This material exhibits a distinctive affinity for formaldehyde through chemisorption, as recently demonstrated (Sadovnik et al., 2024). Notably, formaldehyde adsorption is enhanced in the presence of water, suggesting synergistic interaction between the adsorbate and the hydrophilic framework.

The adsorption process involves two key steps: (1) formaldehyde transport from bulk air to the material's external surface, and (2) diffusion through the porous network of Al-3,5-PDA. These sequential processes collectively determine the overall adsorption rate, highlighting the importance of understanding both mass transfer and chemical reaction kinetics.

The Equivalent Diffusion Model (EDM) treats adsorption as a diffusion-controlled process, focusing on the transport of formaldehyde molecules through the MOF's porous structure. While this approach effectively describes mass transfer limitations, it does not fully account for the chemical interactions governing surface adsorption. In contrast, the Empirical Surface Adsorption Model (ESAM) provides an empirical correlation between the surface properties of Al-3,5-PDA and its formaldehyde uptake capacity. This model quantitatively links surface concentration to adsorption efficiency, offering a more mechanistic interpretation of the experimental data.

Equivalent Diffusion Model

The EDM is a mechanistic model used to describe formaldehyde adsorption on Al-3,5-PDA. In the EDM, formaldehyde first adsorbs onto the exposed surface of Al-3,5-PDA. This process is governed by the partition coefficient (K_{ma}), which represents the ratio of formaldehyde concentration on the surface ($C_{m,s}$) to its concentration at the air-material interface (C_s). The partition coefficient quantifies the total adsorption capacity of the surface. For chemical adsorption, the partition coefficient of Al-3,5-PDA is expected to be significantly higher than that of typical building materials, which rely solely on physical adsorption.

Once adsorbed, formaldehyde diffuses into the deeper layers of the material. This diffusion process is governed by the diffusion coefficient (D_m), which controls the rate at which formaldehyde moves from one layer to another within Al-3,5-PDA. The EDM assumes that the diffusion rate away from the surface equals the rate of the chemical reaction, as

formaldehyde is removed from the surface. The model also assumes one-dimensional diffusion along the thickness of the thin sheet-like sample, given its minimal thickness. Additionally, the EDM presumes homogeneity in the Al-3,5-PDA sample, with a uniform initial formaldehyde concentration of zero.

The in-material diffusion of formaldehyde is described by Eq. (5.1), as established in prior studies (Deng & Kim, 2004; Petigny et al. 2021).

$$\frac{\partial C_m}{\partial t} = D_m \frac{\partial^2 C_m}{\partial y^2}$$

(4.2)

where C_m is the formaldehyde concentration in the material ($\mu g/m^3$); D_m is the diffusion coefficient of the VOC in the material, assumed constant (m^2/s); t is the elapsed time (s); and y is the vertical coordinate from the center to the top surface of the material (m).

Empirical Surface Adsorption Model

This study adopts the ESAM from Pétigny et al. (2021), designed to model formaldehyde adsorption by active wall/ceiling materials. This technology involves an additive that chemically converts formaldehyde into an inert compound. Given the similarity between Al-3,5-PDA's adsorption behavior and that of active wall materials, the ESAM is used here to focus on surface reactions rather than in-material diffusion, as described by the EDM.

The ESAM treats sorption as an instantaneous process due to its significantly faster timescale compared to mass transfer[75], consistent with the mechanism observed in formaldehyde chemical adsorption (Pei & Zhang, 2010). This rapid equilibration establishes equilibrium conditions between the gas phase and the adsorbed phase. The equilibrium state is quantified by the relationship between the adsorbed mass concentration per unit surface area (M_s) and the gas-phase concentration at the interface (C_s.), referred to as the material's sorption characteristics or sorption function.

Pétigny et al. (2021) found that the sorption characteristics of active wall materials are best represented by a polynomial function, providing a robust framework for modeling Al-3,5-PDA adsorption:

$$M_s(C_s) = aC_s^2 + bC_s$$

(4.3)

where a and b are constants from the regression analysis of the M_s vs. C_s data obtained from the saturation tests conducted in the small-scale chambers.

Model for a Single Zone

This study comprehensively analyzes Al-3,5-PDA performance in both controlled chamber environments and real-world scenarios. EDM and ESAM were applied to investigate formaldehyde adsorption behavior on material. An indoor air quality (IAQ) model was then implemented to predict formaldehyde concentrations in a single zone, extending chamber test conditions to equilibrium and applying the results to practical settings.

The methodology employs a mass balance equation (Eq. 5.3) to model formaldehyde concentration in air, assuming perfect mixing in the single zone. The equation states that the rate of change in total formaldehyde mass equals the difference between external introduction and exhaust removal, accounting for surface adsorption. Surface adsorption is treated as a sink term dependent on material surface area and adsorption rate.

In chamber tests using stainless-steel chambers with minimal formaldehyde adsorption properties, interior surfaces contributed negligibly to adsorption. Thus, Al-3,5-PDA served as the primary adsorption sink. However, in real-world environments such as rooms, multiple sinks including Al-3,5-PDA, carpets, walls, and furniture significantly influence formaldehyde levels.

The governing equation for formaldehyde concentration in a single zone is:

$$V\frac{\partial C_{a,i}}{\partial t} = Q(C_{a,o} - C_{a,i}) - \sum_{1}^{N} A_i S_i$$

(4.4)

where V was the volume of the single zone (m^3); Q was the ventilation flow rate (m^3/s); $C_{a,o}$ was the formaldehyde concentration in the inlet air which was typically equal to the outdoor air concentration in real building scenario ($\mu g/m^3$); $C_{a,i}$ was the formaldehyde concentration in the single zone ($\mu g/m^3$); A_i was the material surface area of the adsorption sink (m^2); S_i was the adsorption rate of the adsorption sink ($\mu g/(m^2 \cdot s)$); and N was the total number of adsorption sinks.

The Al-3,5-PDA sink term was determined by EDM and ESAM. The adsorption rate depends on convective mass transfer, describing formaldehyde transport from bulk air to the air-material interface, controlled by the mass transfer coefficient and concentration gradient:

$$S_{MOF} = h_m(C_{a,i} - C_s)$$

(4.5)

where, h_m was the convective mass transfer coefficient (m/s); C_i was the concentration of formaldehyde at the interface (μg/m^3). C_s was correlated to concentration of formaldehyde on the material surface, which can be derived from the EDM and the ESAM.

4.5.1. Modeling and simulating the effectiveness of novel materials under a standard small-scale chamber test condition

This study estimates model parameters derived from chamber test data and assessed the ability of different models to represent formaldehyde adsorption behavior on Al-3,5-PDA. The analysis builds on prior findings by Won et al. (2024), which provided baseline adsorption data under controlled conditions. Experiments exposed Al-3,5-PDA to various formaldehyde concentrations from ~50 to 500 μg/m^3. As shown in Fig. 4.1 in Section 4, none of experiments approached the material's adsorption capacity. These tested concentrations substantially exceed typical indoor formaldehyde levels in U.S. buildings, where reported percentiles are 4.4 µg/m³ (5th), 15 µg/m³ (50th), and 32 µg/m³ (95th) (Summarized Data of the Building Assessment Survey and Evaluation Study, n.d.) (Liu et al, 2020; US EPA, 2023).

Increasing chamber formaldehyde concentrations correlated with reduced adsorption rates, demonstrating that adsorbed formaldehyde obstructs subsequent adsorption. Two models—EDM and ESAM—were used to quantify this effect. For EDM, as shown in Figure 5.1, parameters K_{ma} and D_m were derived via regression analysis using the methodology of Liu et al. (2020). The K_{ma} values for EDM were 1.47×10^5 from 115 μg/m^3 test and 3.24×10^5 from 321 μg/m^3 test, indicating a pronounced surface-mediated effect relative to conventional building materials. This aligns with observations that adsorption occurs primarily through surface chemical reactions, forming a high-capacity thin adsorbed layer. In contrast, D_m values differed significantly between concentration conditions, suggesting that in-material diffusion does not dominate formaldehyde adsorption on Al-3,5-PDA. EDM effectively simulated both adsorption and desorption phases in chamber tests, proving valuable for analyses challenging to conduct experimentally but feasible through modeling.
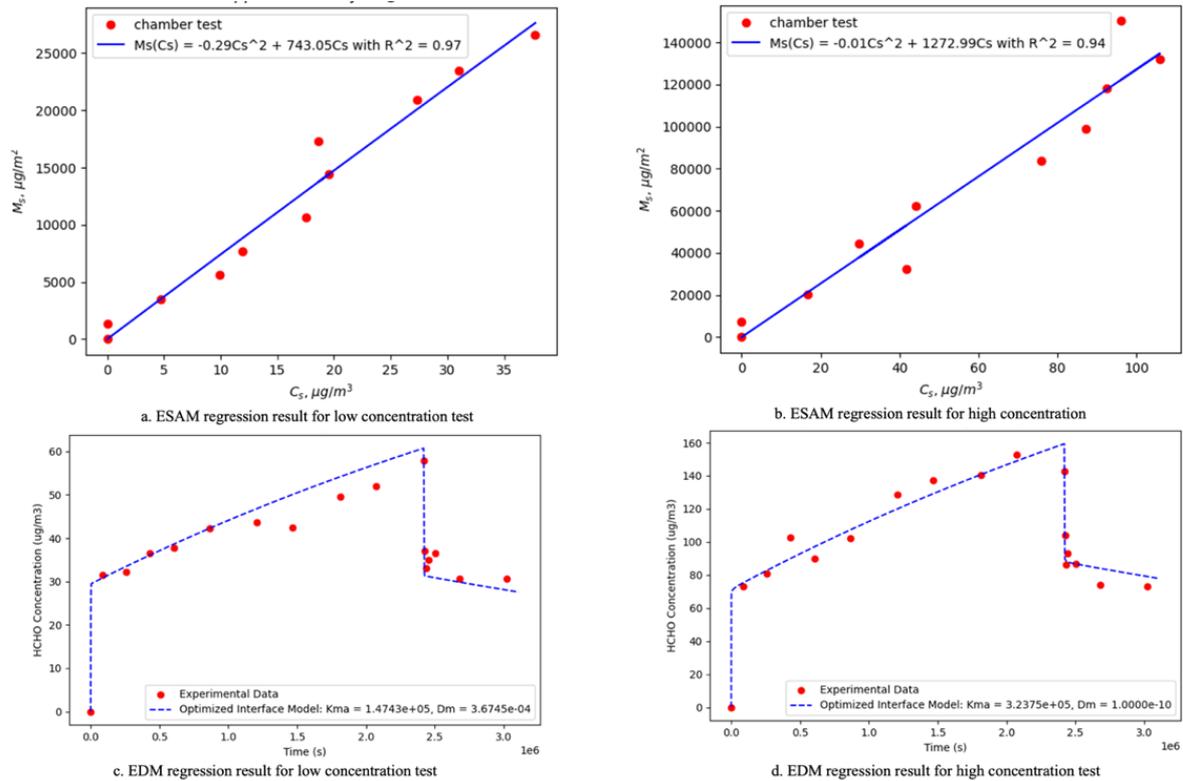
Figure 4.9: Regression test results of the ESAM and the EDM under low and high formaldehyde concentration tests. (a) Results for ESAM under low concentration test. (b) Results for ESAM under high concentration test. (c) Results for EDM under low concentration test. (d) Results for EDM under high concentration test.

For ESAM, parameters M_s and C_s were calculated from chamber data. Results revealed that parameter a was markedly smaller than b, indicating that the first-order adsorption-desorption model adequately describes initial adsorption dynamics. The equilibrium constant $K_e = M_s/C_s$ maintained relative stability over the 28-day testing period, consistent with a dynamic equilibrium between adsorption and desorption.

4.5.2. Modeling and simulating the effectiveness of novel materials under a standard full-scale room condition

This study evaluates the performance of Al-3,5-PDA as a formaldehyde adsorbent under realistic indoor conditions. A simulated 30 m³ room, representative of a small office space, was modeled by replacing a 10 m² gypsum wall with Al-3,5-PDA wallpaper. The initial formaldehyde concentration was set to 32 µg/m³, reflecting the 95th percentile of residential exposure levels in the United States (Summarized Data of the Building Assessment Survey and Evaluation Study, n.d.). Ventilation adhered to ASHRAE 62.1 standards, maintaining an air exchange rate of 0.68 per hour to replicate typical office airflow. Simulations were conducted at 23°C and 50% relative humidity, conditions representative of indoor environments.

Results in Figure 5.2 demonstrate that Al-3,5-PDA effectively reduces formaldehyde concentrations via adsorption, exhibiting a biphasic pattern: an initial rapid uptake phase followed by a gradual approach to equilibrium. Equilibrium is attained after approximately 150 days, indicating the material's capacity for sustained formaldehyde mitigation in indoor environments. These findings underscore Al-3,5-PDA's potential as an alternative to conventional gypsum-based walls, offering a passive and efficient strategy for improving indoor air quality. The simulation further validates the feasibility of deploying Al-3,5-PDA materials in real-world applications requiring prolonged formaldehyde control.
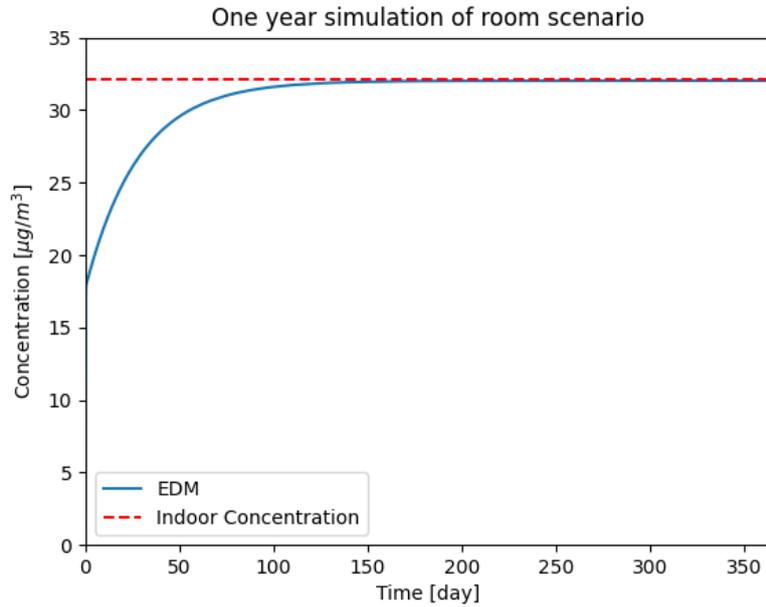
Figure 4.10: One-year simulation of formaldehyde adsorption in a room scenario

4.5.3. Predicting the potential impact of the MOF materials in energy saving and IAQ improvement in residential buildings

To simulate real living environments, this study selected a test house located on the J.J. Pickle Research Campus at the University of Texas at Austin, with a layout that represents the characteristic of single-story apartments or detached single-family houses. The primary advantage of using this building lies in its ability to compare and validate model effectiveness against existing experimental results under identical conditions. With a total floor area of 111 m² (volume: 250 m³), the house features an open-plan living room/kitchen, three bedrooms, and two bathrooms.
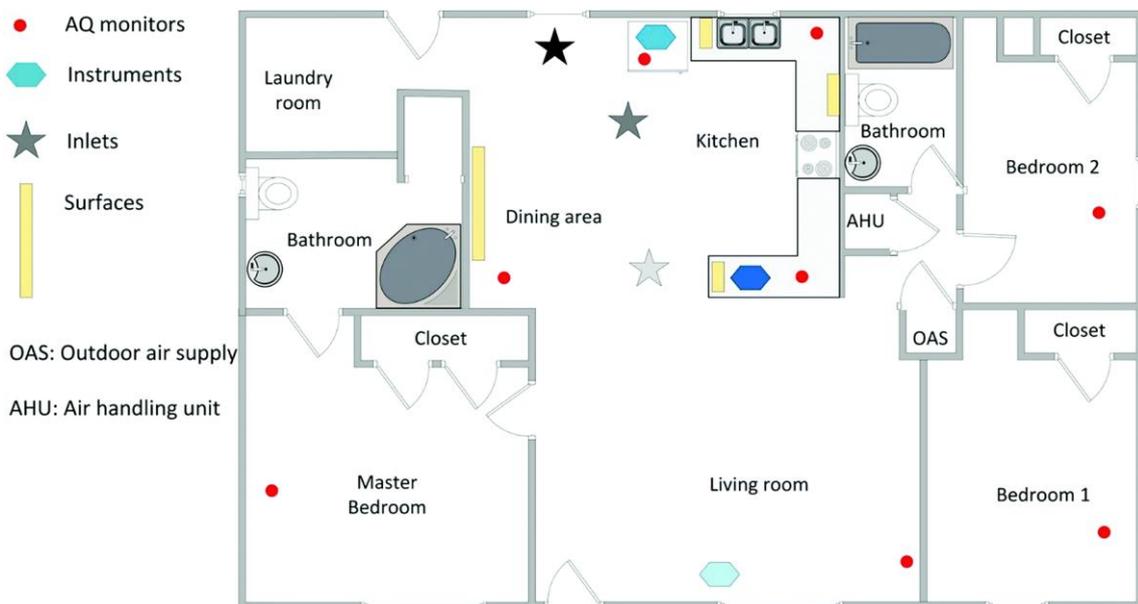
Figure 4.11: Floor plan of the test house with instruments from published peer-review paper. Source: (Farmer et al. 2019)

In the simulation, the initial formaldehyde concentration was set at 15 μg/m³ before Al-3,5-PDA installation, representing the 50th percentiles of indoor formaldehyde concentrations in the U.S (United States Environmental Protection Agency,

n.d.). Formaldehyde release was assumed to be uniformly distributed, based on the HVAC system's air supply characteristics. A dedicated outdoor air supply maintained positive pressurization when doors and windows were closed, minimizing ventilation rate fluctuations caused by temperature differences and wind. Outdoor air was introduced near the HVAC return, mixed with room air, and then conditioned and distributed. The HVAC fan operated continuously at 2000 m³/h (8 air changes per hour) to ensure rapid mixing under heating or cooling conditions, guaranteeing perfect formaldehyde mixing before Al-3,5-PDA took effect. HVAC filters were assumed not to remove formaldehyde, isolating the Al-3,5-PDA's adsorption effect. Since Section 4.4 and the Common Exercise address scenarios with coexisting formaldehyde and other VOCs, this simulation focuses solely on formaldehyde.

The simulation replaced the master bedroom wall material with Al-3,5-PDA paper sheet. The Equivalent Diffusion Model (EDM) assessed long-term exposure effects, while the CONTAM multizone model analyzed formaldehyde distribution across rooms. The EDM was integrated into CONTAM simulations via Python and the CONTAM API. Health impacts were evaluated using Disability-Adjusted Life Years (DALY). The intake-DALY (ID) approach for DALY calculation can be simplified as DALYs per intake multiplied with the total intake amount of a specific pollutant (Yang et al. 2001), as shown in Eq. (5.5). The DALY per intake is based on studies of carcinogenic and noncarcinogenic causes for each pollutant with an age-dependent adjustment factor (ADAF).

$$DALYs = \left[\left(\frac{\partial DALY}{\partial intake} \right)_{cancer} \times ADAF + \left(\frac{\partial DALY}{\partial intake} \right)_{noncancer} \right] \times intake \tag{4.6}$$

where $\left(\frac{\partial DALY}{\partial intake} \right)_{cancer}$ and $\left(\frac{\partial DALY}{\partial intake} \right)_{noncancer}$ are the cancer and noncancer mass intake–based DALY factors; ADAF, developed by the U.S. EPA (2005), represents cancer health effects as a function of exposure age and is reported as 1.6 of a population average, and *intake* is the mass of pollutant that an individual inhales over a given time.

The *intake* can be calculated as follows in Eq. (5.6):

$$intake = C_{indoor} \times Q_{intake} \times \Delta t \tag{4.7}$$

where Q_{intake} is the volume of air intake by a person per day, reported as 14.4 m³/day for the U.S. population average air intake; and Δt is the exposure time of a person.

DALY metrics provide a quantitative measure of health benefit resulting from reduced formaldehyde exposure. These non-energy benefits should be systematically integrated into life-cycle cost analysis when evaluating Al-3,5-PDA applications. The monetization of DALY involves assigning an economic value to each DALY lost, representing the societal direct medical costs, productivity losses, and society's willingness to pay for health improvements.

The concentration reduction factor (CRF) and clean air delivery rate (CADR) were used to evaluate the overall Al-3,5-PDA's formaldehyde removal performance in residential buildings.

$$CRF = \frac{C_{w/oMOF} - C_{w/MOF}}{C_{w/oMOF}} \tag{4.8}$$

$$CADR = Q \frac{C_{w/oMOF} - C_{w/MOF}}{C_{w/MOF}} \tag{4.9}$$

Where, $C_{w/oMOF}$ and $C_{w/MOF}$ are steady state formaldehyde concentrations with and without Al-3,5-PDA in the master bedroom. Q is the outdoor air ventilation rate, m³/h.

CADR represents the equivalent reduction in outdoor air flow rate required to maintain equivalent formaldehyde concentrations. Because outdoor air conditioning consumes electricity power or fossil fuel of HVAC, EnergyPlus simulations were used to compared pre- and post-reduction ventilation scenarios to quantify energy savings. Simulations covered ASHEAE climate zones 1A (very hot humid), 3A (warm humid), and 5A (cool humid) to evaluate energy benefits comprehensively. The impact of humidity on formaldehyde adsorption was not considered, as Section 4 and Common Exercise demonstrated minimal effects within a 10% to 70% humidity range.

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5. Ensuring performance for smart ventilation

5.1. 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 chapter 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)

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

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

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

5.2.1.1 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 analyze these strategies' effectiveness in improving indoor environmental quality without compromising occupants' health or minimizing energy consumption.

5.2.1.2 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.

5.2.1.3 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 analyzing 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.

Occupant behavior, and pollutant generation scenarios

The occupant's behavior 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 behavior enables the prediction of occupant exposure to pollutants. Many efforts have been devoted to addressing occupant behavior in residential buildings, including monitoring the occupancy, developing occupant behavior 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 analyzing 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.

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, mold development, annual cost analysis and financial payback time of a ventilation system, are also used to assess ventilation performance.

Indoor air quality
- CO_2: concentration, unmet hours; cumulative exposure exceeding the reference value (ppm.h); percentage of time that CO_2 concentration is above a threshold;
- $PM_{2.5}$: exposure exceeding the reference value;
- Formaldehyde: exposure exceeding the reference value;
- TVOC and VOCs: cumulative exposure per person;
- Generic pollutants;

Comfort
- Temperature: % of time that temperature is outside the reference range; unmet hours;
- Relative humidity: unmet hours; 30% < RH < 70%;
- Overheating risk;

Ventilation
- Air exchange rate;
- Air flow rates;

Assessment criteria

Energy savings
- Annual ventilation energy savings;
- Reduced total energy consumption by all appliances and ventilation system;
- Space heating and ventilation energy savings;
- Fan energy savings;
- Cooling energy;
- Primary energy consumption;

Health impacts
- Relative exposure;
- DALYs;

Others
- Building material condensation (RH > 70%);
- Mould development (time duration of RH above 75%);
- Annual cost analysis;
- Financial payback time of operation of a system;
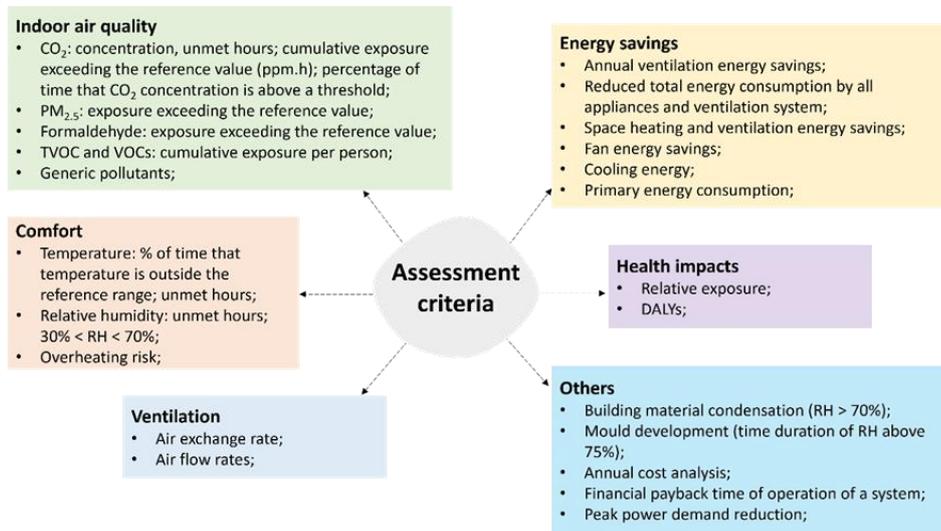- Peak power demand reduction;

Figure 5.1: Performance indicator summarized from the reviewed simulation studies

Table 5.1: 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 from 1.86 e-4 m^3.s⁻¹ to 9.69e-4 m^3.s⁻¹ depending on the activity level, varying from 15 dm³.h⁻¹ to 35 dm³.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 dm³.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⁻¹m⁻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 activitie: 70 µg.min⁻¹ – vacuuming 10 µg.min⁻¹ - oven 283 µg.min⁻¹ – grilled, 1483 µg.min⁻¹- fried	
Generic contaminant		18 µg/m²/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 dishes 1200 µg.h⁻¹ for shower (soap/shampoo), 2000 µg/event for deodorant	
Naphthalene		3.76 µg.h⁻¹ Shower (soap/shampoo)	

5.2.1.4 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.

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 CO_2 (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%.

In addition to the aforementioned literature, the following IEA IBC projects are also highly relevant with respect to cooling by ventilation. The IEA EBC Annex 61 (www.venticool.eu) aimed to develop, evaluate, and demonstrate design methods, tools, and guidelines for predicting cooling needs, integrating ventilative cooling into building performance standards, and enabling flexible, climate-resilient solutions that ensure thermal comfort and energy efficiency. Furthermore, IEA EBC Annex 80 (annex80.iea-ebc.org) had a goal to evaluate, advance, and promote resilient cooling technologies by identifying performance indicators, overcoming design and integration challenges, and providing regulatory and practical guidance through research, case studies, and implementation strategies. Lastly, the recently started IEA EBC Annex 97 (annex97.iea-ebc.org) focuses on increasing international knowledge about effective heat mitigation and sustainable cooling in cities with special focus on the interaction between heat mitigation in outdoor spaces and cooling of buildings.

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) analyzed 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.

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.

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) analyzed 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.

5.2.1.5 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.

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

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5.2.2.1 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.

5.2.2.2 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).

5.2.2.3 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 5.2, source: Poirier et al., 2021).
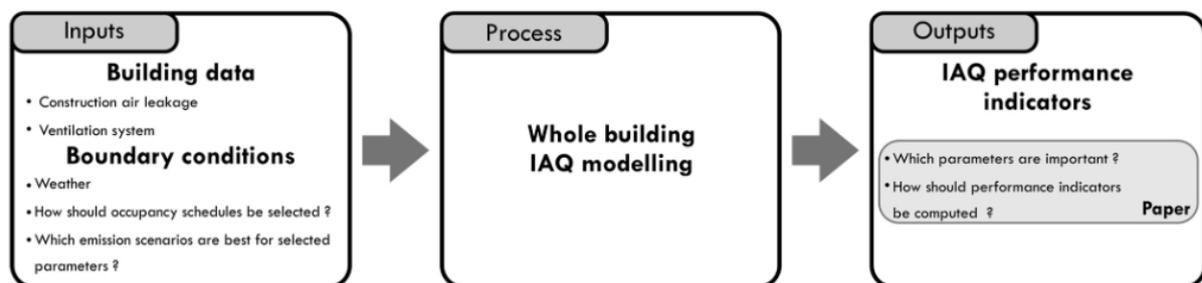
Figure 5.2: Schematic diagram illustrating a performance-based approach for ventilation at the design stage of a residential building

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?

5.2.2.4 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.

5.2.2.5 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.

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

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

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5.3.1.1 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.

5.3.1.2 Methods

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.

5.3.1.2.1   Target contaminants and collected data

Table **5.2** 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 5.2: 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.

All the ventilation strategies must be evaluated by the performance indicators described in **Table 5.3**.

Table 5.3: 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]	95th 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.

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.

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 5.4**).

Table 5.4: 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

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.

$$IRD_{sys} = 100.\frac{I_{sys} - I_{ref}}{I_{sys} + I_{ref}} \qquad (5.1)$$

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.*

5.3.1.3 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.

Overview of results data – participants, strategies, basic data

Figure 5.3 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.
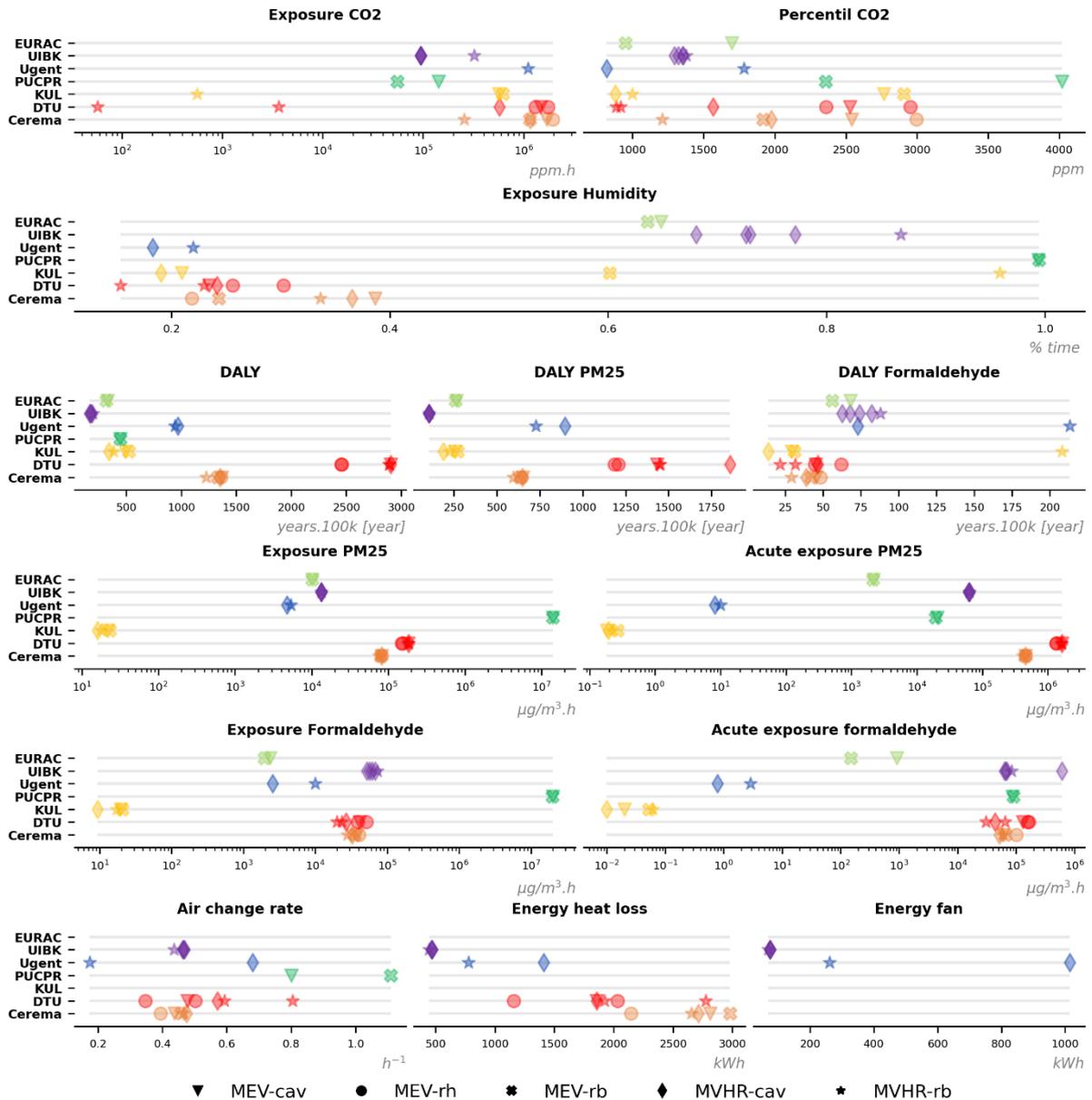
Figure 5.3: Overview of all data provided by the contributors

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.

Relative performance direction-IRD by contributor

Figure 5.4 represents the IRD (equation 3-1) by contributor, for all indicators. The color 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 5.5). 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.
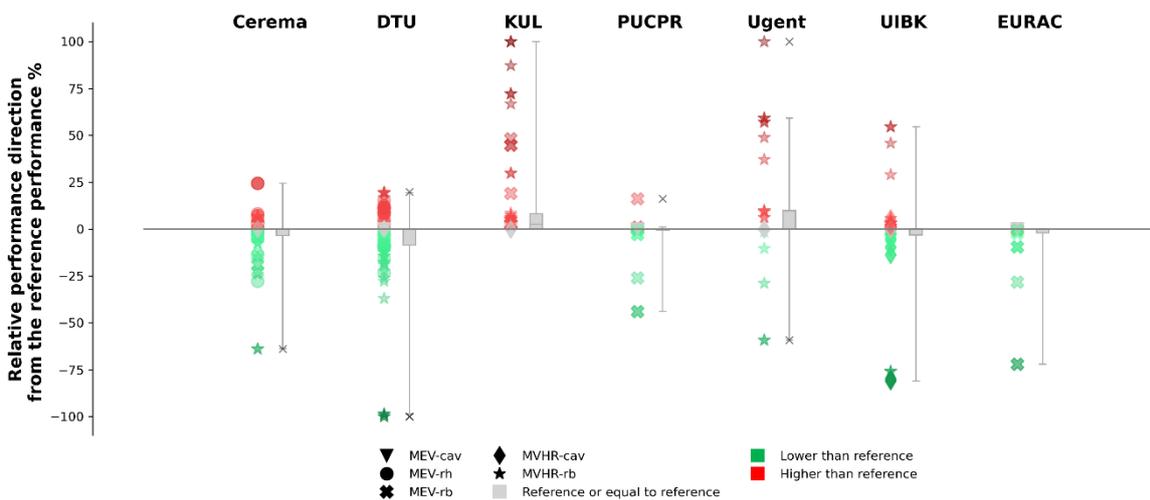
Figure 5.4: Relative performance direction-IRD" by contributor

Table 5.5: 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

Relative performance direction-IRD by performance indicator

The plotted points in Figure 5.5 are the relative performance direction named IRD (equation 5.1), already plotted in Figure 5.4, 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 color and relative direction are the same. Only the $PM_{2.5}$/HCHO acute exposure indicators highlight different tendencies, in comparison with the DALY indicator.
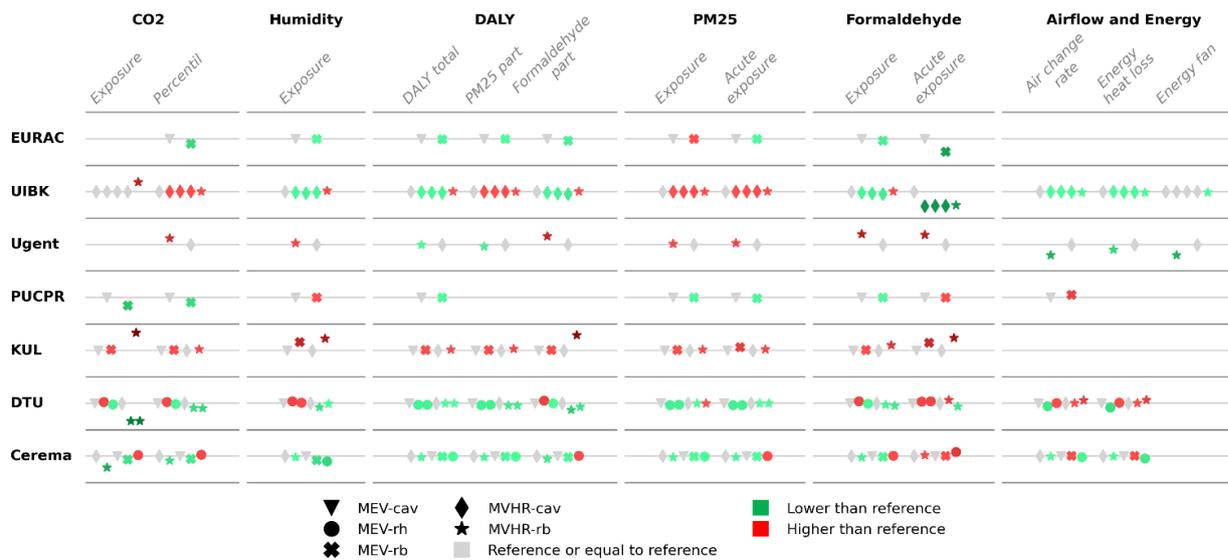- Air change rates and energy benefits give the same ranking in all cases.

Figure 5.5: Relative performance direction-IRD" by performance indicator

It is clear that IDR, with its color 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).

5.3.1.4 Conclusions and perspectives

An internationally based performance-based approach has been developed for assessing smart ventilation performance using multicriteria approach that is further implemented through participation in the relevant working groups in ISO and CEN. 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.

Ideally, the performance-based approach should be implemented in ventilation standards on the international level. However, further testing and qualified debate is needed before such implementation can happen.

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.

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

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5.3.2.1 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.

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).

"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).

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.
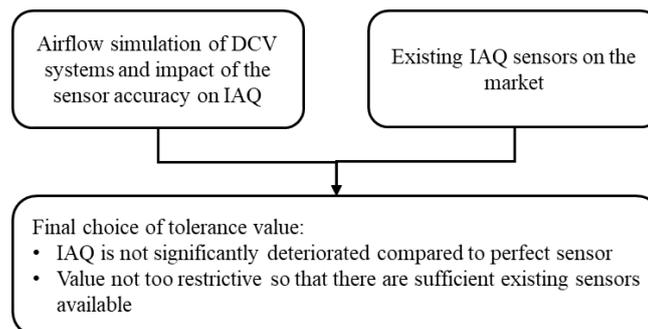

Figure 5.6: Determination of sensor tolerance in Belgium

Others

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

5.3.2.2   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.

5.3.2.3   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.

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

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5.4.1. 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.

5.4.2. European framework for ventilation inspection

The main directives and standards concerning European ventilation inspection are gathered in Table 5.6.

Table 5.6: European framework considering inspection of stand-alone ventilation systems in residential buildings
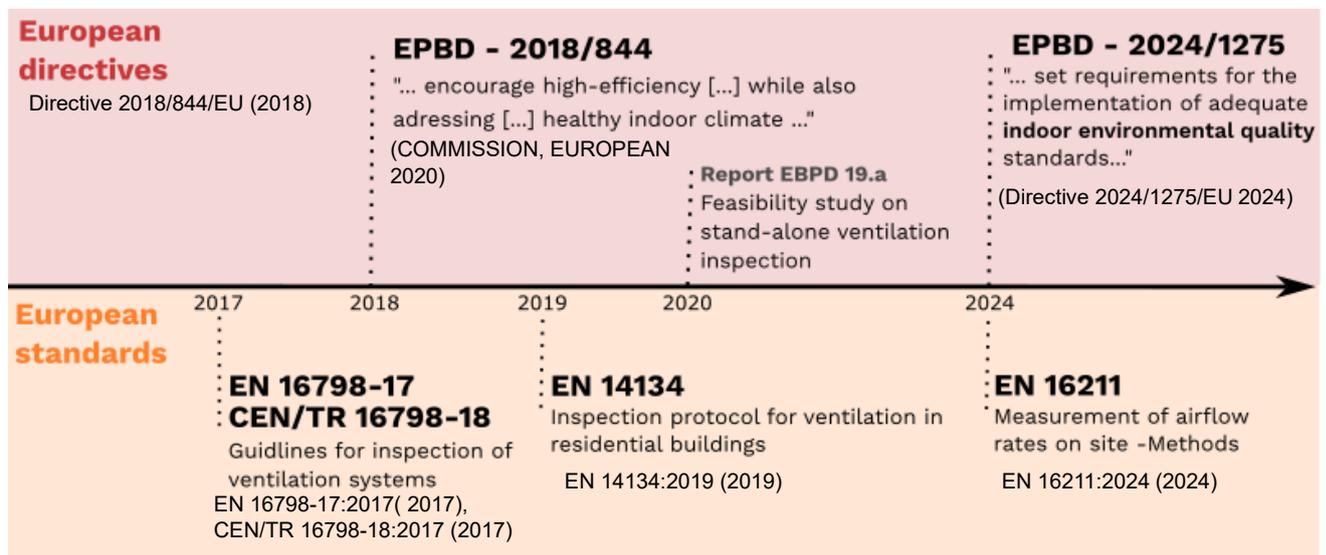
5.4.2.1 EPBD – 2018/844

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.

5.4.2.2 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).

5.4.2.3 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.

5.4.3. 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 5.7.

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 5.7: 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).

5.4.4. 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 5.4.2.3, e.g., certification of products, calculation notes, etc.).

5.4.4.1 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, as summarized in the **Table 5.8**, 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 5.8 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 5.8: 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	Continuous	Yes	Yes	No	+++
	IAQ measurements	Continuous				
Approach 2 **Optimal**	Maximal or nominal flow rate	Spot/discrete	Yes	Allows to observe major problems	Yes	++
	IAQ measurements	Continuous				
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.

5.4.4.2 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.

5.4.5. 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.

5.5. 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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Appendices

Appendix 5. IEA EBC Annex 86 – ST4: Smart ventilation. Results of the ST4 survey January 2022.

Appendix 6. IEA EBC Annex 86 – ST4: Smart ventilation. First common exercise. Instructions and template for collection.

Appendix 7. IEA EBC Annex 86 – ST4: Smart ventilation. Results of the survey on inspection. January 2025.

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