# IAQ in residence


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For those that never heard the phrase, an artist '*in residence*' is the hip, cultural equivalent of the old religious retreat or the academic sabbatical. It is a period in which an artist temporarily relocates to a cultural institution for an intense focus on developing a new piece or exploring new turn in their oeuvre. It may seem surprising to invoke this practice as the title for an article on indoor air quality in residential buildings, but we would like to claim that the way we, as HVAC engineers, approach IAQ needs a fundamental shift. It is time to retreat, rethink and reinvent our craft.

## The state we 're in

While within leading bodies like the UN and WHO, good air quality is increasingly recognized as a human right, for too long now, IAQ management, the art of designing a desirable indoor environment in terms of that air quality, has been reduced to a single, simple question: What rate?

While ventilation remains the primary strategy for IAQ management, complementary technologies such as advanced air filtration, smart materials and air cleaning systems are increasingly available and used. Despite this growing diversity of approaches, standards, the touchstones to which we orient our practice, offer little to no guidance on how to integrate these different IAQ management strategies. Every day, 1000's of researchers are producing insights into the complex interactions that govern the exposure of occupants to indoor pollutants, but these insights find little to no practical application because our standards simply state an airflow rate requirement per type of space.

This is perhaps, you may protest, a somewhat disingenuous depiction of the state of affairs. Do standards not include options like Method 2 in the current EN 16798-1:2018 that allow you to determine the required design ventilation rate based on the dominant pollutant? Yes, the standards provide this option, but no, they do not practically allow you to actually use it, With no guidance on pollutant selection, source strength or emission scenario, essential building blocks for their application are missing. And so, in a world where AI can build you a website in a few seconds and your clients get personalized tips on how to tweak their breakfast rituals to boost their productivity from a free app on their phone, we seem to still believe it is ok for a professional, after 4 or 5 years of engineering school, to to look up a number in a table, pat themselves on the back for a job well done and charge their clients a premium for their effort.

Against this backdrop, IEA-EBC Annex 86 was the residency that provided me and the other participants in it with the opportunity to explore how the humble residential setting provides the perfect environment to put in place what we need to meaningfully move towards IAQ management strategies worthy of the science and IAQ engineering that we can proudly charge for. Now that its final reports are published, let me give you a tour of our conclusions.

## The challenge of the residence

Before we dive into the outputs of the Annex, let's first take a bit of time to explain why we decided to focus on residential buildings. Not an obvious choice, since ventilation approaches for dwellings are highly standardized, and budgets for engineering on residential projects are notoriously low. Nevertheless, residential buildings not only by far represent the largest share of the overall buildings stock in Europe, both in terms of number of buildings and floor area, they also typically provide a more complex set of interactions between occupants, the built environment and the buildings services then in non-residential settings.

An obvious case in point is the fact that occupants spend about half the time in their dwellings asleep, a condition we still know too little about and that deserves its own separate article. But there is much more: in contrast to the design of ventilation in non-residential systems, airflows in residential systems are typically designed to serve multiple spaces, entering the dwelling in living spaces, transitioning to circulation areas and exiting the building in service areas such as bathroom and kitchens, picking up diverse pollutants along the way and requiring careful planning of that sequence (Rojas et al., 2015). Similarly, occupants can be expected to frequently change spaces, open windows based on their own personal habits (Verbruggen et al., 2021) and engage in activities that produces highly peaked pollution events such as cooking (O'Leary et al., 2019), cleaning (Kolarik et al., 2023) or showering (Davis et al., 2016)short-term inhalation exposures to airborne contaminants could occur as the result of domestic water use. The most important domestic sources of such exposures are likely to be showering and the use of aerosol-producing humidifiers, i.e., ultrasonic and impeller (cool-mist. Moreover, in countries with mild climates, the push towards higher energy performance has sparked the large scale adoption of sophisticated smart controls for residential ventilation systems (Guyot et al., 2018). Combining this complexity within a small spatial footprint, dwellings are the perfect experimental playground for testing interventions in the web of interactions that impact IAQ, and extract strategies for applications in other contexts from those tests.

An important observation is that indoor air quality exerts a direct and measurable influence on human health, yet most building regulations still address ventilation without setting explicit objectives, criteria, or indicators for this health impact. Annex 86 fills this critical policy and technical gap by developing and testing new performance-based methods to quantify the health, functional, and economic consequences of exposure to indoor air contaminants.

One of the most significant achievements of the Annex is the adoption of Disability-Adjusted Life Years (DALYs) as a common metric for quantifying the health burden of exposure to contaminants in indoor air. This enables the comparison of different contaminants on a unified scale and supports prioritization based on actual harm. Particulate matter and formaldehyde were identified as the dominant contributors to this health burden. The developed methodology underpins the world's first harm-based compliance pathway incorporated into ASHRAE Standard 62.2-2025, representing a major advancement in the alignment of building standards with public health objectives.

Beyond health metrics, the Annex developed and tested a set of metrics for multi-criteria assessment frameworks that evaluate IAQ management strategies across multiple performance dimensions, including energy efficiency, cost, resilience, and robustness. Simulation studies explored how different system types perform against different metrics under typical constant and variable, dynamic conditions, while a resilience framework was created to assess system responses to shocks such as outdoor pollution events, indoor emission peaks, and power outages. These approaches enable decision-makers to assess not only average system performance but also reliability under stress.

The Annex further quantified the economic and social costs of poor IAQ, revealing that productivity losses associated with Sick Building Syndrome constitute the largest share of the total burden, followed by chronic disease impacts primarily linked to particulate matter exposure. Case studies demonstrated that interventions such as the use of low-emission materials, filtered ventilation, and optimized airflow rates can substantially reduce these costs, strengthening the case for performance-based regulation.

Because simulation plays a pivotal role in implementing performance-based methods, a second major achievement was the creation of two open datasets compiling global literature on pollutant sources, typical exposure levels, and concentration distributions. These datasets are supported by analytical tools that allow modelers to perform uncertainty and sensitivity analyses, ensuring the robustness of their results. The underlying data schemas accommodate both small-scale experimental data and large-scale IoT-based data collection, enabling scalable and adaptive modelling approaches. The datasets and associated algorithms, publicly accessible through the *Pandora* and *Global IAQ* databases, form a critical foundation for future data-driven IAQ management.

A third major contribution lies in the proof-of-concept development of novel smart materials as active components in IAQ management strategies. The Annex identified Metal–Organic Frameworks (MOFs) as a particularly promising class of materials for indoor pollutant removal. Experimental studies demonstrated that MOFs can outperform conventional sorbents by up to an order of magnitude and can be engineered for easy regeneration and targeted performance. Simulation models were subsequently developed to incorporate these materials into integrated IAQ design frameworks. The research findings directly inform the objectives of IEA-EBC Annex 92, focused on advancing smart materials for heating, cooling, and air quality control in residential buildings.

Finally, the Annex assessed the implementation potential of performance-based IAQ approaches in the design of residential buildings through surveys, simulation exercises, and field investigations of smart ventilation systems. The results underscore the importance of continuous verification throughout a system's life cycle. Regulatory frameworks should therefore provide not only performance criteria and indicators but also mechanisms for verification, validation, and stakeholder support across all stages — from design to operation.

## A performance based IAQ ecology

Likely the most significant outcome of the work done by the over 100 researchers from over 50 organizations in 27 countries during the 5 years of Annex 86, in addition to all the excellent material that is captured in the reports and deliverables, is the insights that, in a field that is evolving so quickly, the only viable strategy to provide practitioners with sustained support is to move away from prescriptive standards and adopt performance-based design practices and that what is needed for that transition is not a single, prescribed tool that will allow them to apply lessons learned, but rather an open, coordinated framework of interoperable components, a suite of methodological building blocks to strengthen the confidence of all stakeholders involved in this new approach.

The first part of this insight, the need to move to performance-based IAQ design is far from new. Already in 1981, ASHRAE introduced the 'Air Quality Procedure' in its ASHRAE 62 standard. The objective of the work in IEA-EBC Annex 9 (1982-1986) was to ensure that the concentrations of the main indoor air pollutants should not exceed levels likely to damage the health of occupants, cause annoyance or reduction in amenity or cause damage to the building fabric. The objective of IEA EBC Annex 23 (1990-1996) was to develop a multizone air flow model incorporable in building energy simulations and provide input data necessary to use the model (e.g. wind pressure distribution, default values for leakage of building components, material properties like absorption and desorption). Together, these efforts provide the essential tools to put performance based assessment into practice and it has been successfully adopted in a number of countries (Guyot et al., 2019).

Nevertheless, this application has essentially remained limited to research studies in practice, where a limited number of experts use a specific tool within a restricted set of conditions to produce preformatted results that are then assumed to be valid for general use. This use of performance-based methods was confronted with the need for ad-hoc updates and revisions each time a new technology or application was implemented, making it slow and inflexible. To move to a true, wide scale adoption of performance-based design, European standards lack coherent, generalized guidance on how to set up dynamic multi-zone simulation models, methods to select appropriate inputs for the simulations, procedures for performance assessment in use and a clear process to define relevant, comparable, non-biased and project specific performance objectives for IAQ management.

Annex 86 made important steps in that direction by introducing a clear process to select design pollutants based on the estimated harm to occupants, the combined effect of dose and Harm Intensity, and suggesting the use of a harm budget as a Key Performance Indicator (KPI) for IAQ design. Focusing on the development of highly innovative smart materials, it demonstrated how a technology neutral performance-based approach contributes to the introduction of cost-effective ways to reduce the exposure to these priority pollutants in the built environment. It highlighted good practices and challenges in assessing and maintaining performance over the lifetime of the systems. Drawing on the large-scale availability of data from field monitoring and lab test, it also compiled datasets of input variables and provided code and algorithms to extract their distributions to support accurate and reliable modelling. These building blocks enable stakeholders to adopt, test, and refine performance-based approaches in a mutually reinforcing way, fostering the evolution of a robust, evidence-driven ecosystem for IAQ management.

## Where do we go from here?

Participants in Annex 86 continue to advance this vision for a new approach to IAQ engineering through their contributions to CEN TC 156 WG 25 (updating the IAQ part of EN16798-1:2018), ASHRAE Environmental Health Committee (EHC) and ISO TC 163/WG4- JWG of ISO/TC163&205 TG5 (on revision of ISO17772-1 which is the ISO version of EN16798-1), ensuring its integration into emerging European and international standards. While we go through this transition, we can take inspiration form a rich pallet of fellow engineering fields that have long since used performance-based targets and procedural rigour as their maps and compass. Think of structural engineering or, closer to us, energy performance calculations, and thermal comfort analysis.

But dwelling on such matters inevitably also leaves us with more questions. Some are technical and right up our alley. New IEA-EBC annexes[1] on the applications of MOF, the performance assessment of air cleaning technology and co-benefits of IAQ interventions have been started. Other questions will require reaching out to other fields, such as better understanding the causal mechanisms that underpin the link between exposure and harm, an essential step to effectively design efficient interventions. Some of the new questions are political, like harmonizing acceptable harm across fields, and some, like the result of any journey into the deep, are almost existential. What does it mean for each stakeholder in the built environment if good air quality is a human right? What does it mean for us, those that claim to know how to achieve it? Are we ready to abandon prescriptive requirements that fail to provide it? And if not, what does it mean for our relevance as a profession?

For the mentioned IEA-EBC Annexes, see: https://www.iea-ebc.org/ ■

1 IEA-EBC Annex 92, IEA-EBC Annex 99 and an annex proposal on co-benefits of IAQ management