ANNEX 5

EBC

Energy in Building and Communities Programme

Annotated Bibliography 14

Retrofitting the Building Stock: Challenges and Opportunities for Indoor Environmental Quality – Overview of the AIVC 2024 Conference sessions

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Participating countries in the EBC: Australia, Austria, Belgium, Brazil, Canada, P.R. China, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

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Preface

The International Energy Agency

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

The IEA Energy in Buildings and Communities Programme

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

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

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

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

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

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

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

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

The Executive Committee

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

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

Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling (*)
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: EBC Annex 90 / SHC Task 70 Low Carbon, High Comfort Integrated Lighting
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy-Efficient Heating, Cooling and IAQ Control in Residential Buildings
Annex 93: Energy Resilience of the Buildings in Remote Cold Regions
Annex 94: Validation and Verification of In-situ Building Energy Performance Measurement Techniques
Annex 95: Human-centric Building Design and Operation for a Changing Climate
Annex 96: Grid Integrated Control of Buildings
Annex 97: Sustainable Cooling in Cities

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

IEA EBC Annex 5: Air Infiltration and Ventilation Centre

EBC Annex 5 was first established in 1979 under the name "Air Infiltration Centre" undertaking technical activities and providing information services with the task of minimizing air infiltration energy losses. In 1986, the name was changed to "Air Infiltration and Ventilation Centre" to reflect the importance of the coupling of a good airtightness with appropriate ventilation. Over time, the AIVC has been continuously evolving to respond to emerging concerns, challenges and opportunities. We have now entered the 46th year of the AIVC's existence and the Centre's main goal is to provide reference information on ventilation & air infiltration in the built environment with respect to efficient energy use and good Indoor Environmental Quality (IEQ).

In November 2020, the Executive Committee approved the continuation of the AIVC for the period 2022-2026. Peter Wouters and Arnold Janssens are on behalf of INIVE the operating agents for this period.

The AIVC holds a conference each year in September/October in one of the AIVC participating countries. More information can be found here: www.aivc.org/events/conferences

The AIVC organizes 1 to 2 workshops per year. More information can be found here: www.aivc.org/events/workshops

The AIVC organizes a number of webinars per year. More information can be found here: www.aivc.org/events/webinars

The AIVC has formal collaborations with the TightVent platform (https://tightvent.eu/), the venticool platform (https://venticool.eu/) and the IEQ-GA (https://ieq-ga.net/).

If you want to be kept informed on the activities of AIVC and related platforms, you can subscribe here.

Table of content

Introduction

On 9-10 October 2024, the AIVC – TightVent - venticool 2024 joint Conference "Retrofitting the Building Stock: Challenges and Opportunities for Indoor Environmental Quality", was organised by the International Network on Ventilation and Energy Performance (INIVE) on behalf of the Air Infiltration and Ventilation Centre (AIVC), the Building and Ductwork Airtightness Platform (TightVent Europe) and the international platform for ventilative cooling (venticool).

The University of Galway, the Maynooth University and the Sustainable Energy Authority Of Ireland (SEAI) were also key organisers. This successful event brought together over 180 participants, including researchers, engineers, architects, policymakers, manufacturers, stakeholders, and international organizations from 26 countries.

The conference programme featured three parallel tracks with approximately 150 presentations across the key themes of Smart Ventilation, Indoor Air Quality (IAQ) and Health, Building & Ductwork Airtightness, and Ventilative and Resilient Cooling. A special session of “90-Second Industry Presentations”, was organised to disseminate exclusive information from the event’s sponsors to the conference participants, in addition to the conference exhibition.

Additionally, the conference provided a vital forum for discussions on current projects, including the IEA EBC Annex 86, Energy Efficient Indoor Air Quality Management in Residential Buildings & IEA EBC Annex 87, Energy and Indoor Environmental Quality Performance of Personalized Environmental Control Systems.

The next chapters offer an overview of the main trends, ideas, and insights shared over the two-day conference, in relation to the three main themes:

- Smart Ventilation, IAQ & Health.
- Building and ductwork airtightness and ventilation system’s inspection
- Ventilative and resilient cooling.

1. Smart Ventilation, IAQ & Health presentations

The "Smart Ventilation, IAQ & Health" track at the conference was organised in 14 sessions, 5 of which were topical sessions with a number of invited presentations:

1. Exploring Challenges and Opportunities in Decarbonizing Buildings through Building Ventilation (Topical Session)
2. Smart ventilation strategieshis
3. Performance-based IAQ regulations in dwellings: present and future (Topical Session)
4. IAQ in schools
5. IAQ and ventilation
6. IEQ, HVAC and airtightness
7. IAQ assessment
8. Ventilation regulations in various countries (Topical Session)
9. The Challenges of Radon and Energy Retrofitting: Unravelling Complexities and Interaction within the Built Environment (Topical Session)
10. Performance evaluation of ventilation systems
11. IAQ in retrofit buildings
12. IAQ monitoring
13. What is new in the EPBD recast 2024 with respect to indoor environmental quality and ventilation? (Topical Session)
14. IEQ-Analysis and assessment methods

The chapter is structured into nine main themes:

1. Exploring Challenges and Opportunities in Decarbonizing Buildings through Building Ventilation
2. IAQ in Schools
3. Smart Ventilation
4. Performance based regulations (PBR)
5. IAQ assessment
6. Radon
7. Performance evaluation of ventilation systems
8. Retrofitting houses
9. What is new in the EPBD recast 2024 with respect to indoor environmental quality and ventilation?

1.1. Exploring Challenges and Opportunities in Decarbonizing Buildings through Building Ventilation

The workshop "Exploring Challenges and Opportunities in Decarbonizing Buildings through Building Ventilation" explored the intersection of building ventilation, decarbonization, including resilience, focusing on challenges and opportunities in energy retrofitting, ventilation, and emerging technologies (McGrath, 2024) (McGrath, 2024) (Molina C. , 2024) (Molina C. , 2024).

Key discussions highlighted the difference between optimizing energy use and minimizing CO_2 emissions, the role of electrification in improving indoor air quality by eliminating combustion-related contaminants, and the impacts of decarbonization on occupant health and resilience to extreme weather events.

Challenges included high costs, maintenance complexities, and social inequities, while opportunities emphasized reducing energy burden, improving public health, promoting workforce development, and enhancing climate resilience. The dialogue underscored the need for innovative technologies, effective occupant engagement, and industry involvement to achieve equitable and sustainable decarbonization outcomes.

1.2. IAQ in Schools

Handy & Burridge conducted a study in the framework of the Schools' Air Quality Monitoring for Health and Education (SAMHE) project focusing on evaluating particulate matter ($PM_{2.5}$) levels in classrooms across the UK during the 2023/2024 academic year (2024). Their findings show that classroom $PM_{2.5}$ concentrations are significantly influenced by outdoor $PM_{2.5}$ concentrations with outdoor air being a significant source of $PM_{2.5}$ (Handy, 2024). While long term exposure is predominantly due to "low concentration" days, "outdoor $PM_{2.5}$ events" (short periods of elevated concentrations) strongly correlate with peaks in classroom $PM_{2.5}$ levels and might contribute significantly to the long-term exposure to $PM_{2.5}$ over the academic year (Figure 1). These events, even when occurring during unoccupied times, permeate indoor spaces, indicating school buildings' susceptibility to outdoor pollutants. This study highlights the importance of using data-driven evidence to create guidelines for enhancing indoor air quality and inform future building, and retrofitting, of school buildings. Ventilation is a critical method for removing indoor pollutants from classrooms; however, caution is needed when addressing particulate matter, as outdoor air can be a significant source of PM pollution indoors.

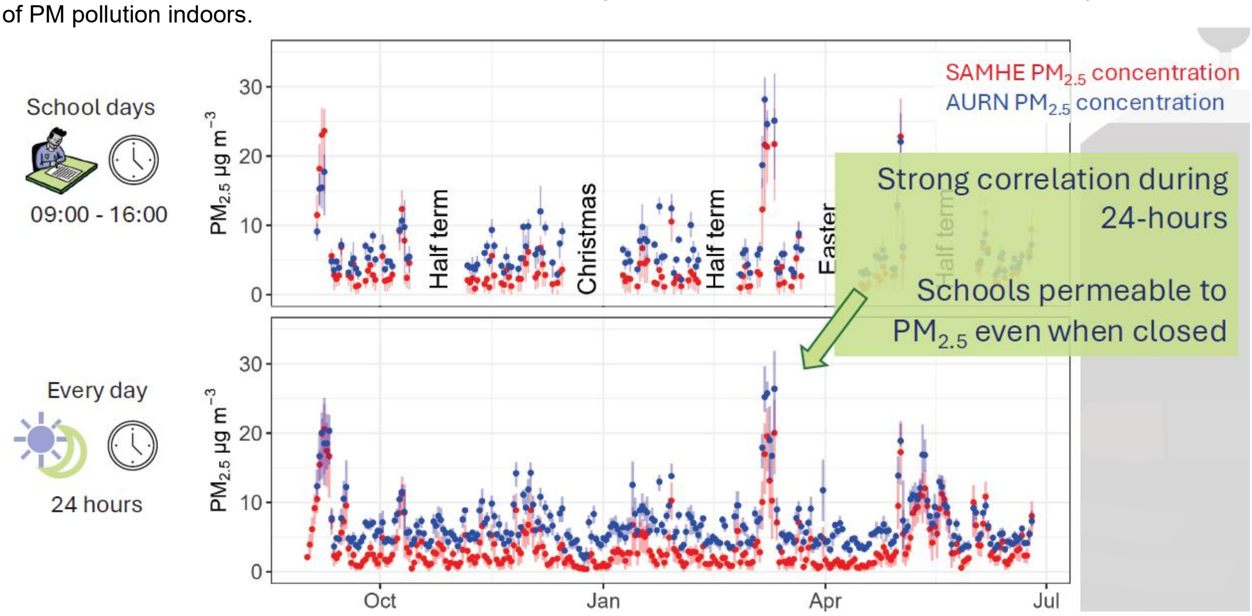

Figure 1: Temporal trends over the year (Handy, 2024)

A study by **Beck & Rojas** (2024) investigated the use of CO_2 feedback devices, or "traffic lights," to improve indoor air quality (IAQ) in Austrian school classrooms relying on window airing. These devices visually alert occupants when CO_2 concentrations exceed thresholds, prompting better ventilation. A quasi-experimental design monitored CO_2 levels before and after device implementation in selected classrooms, comparing them to control classrooms without devices (but the same awareness level). The analysis of CO_2 levels across various outdoor temperatures indicates that visual feedback devices significantly improve air quality in classrooms at lower ambient temperatures, supporting the validity of CO_2 traffic lights as an intervention. This finding is partially corroborated by comparisons with the control group, which exhibited no improvement in air quality at outdoor temperatures below 9°C in a hypothetical intervention scenario (Figure 2). The study concludes that visual feedback systems effectively reduce CO_2 levels during colder periods but highlights the need for further investigation into long-term impacts, including behavioural adaptations, thermal comfort, and energy consumption. Limitations include potential habituation to the devices and the late timing of the intervention, which complicates interpretation due to seasonal weather and behavioural variations.

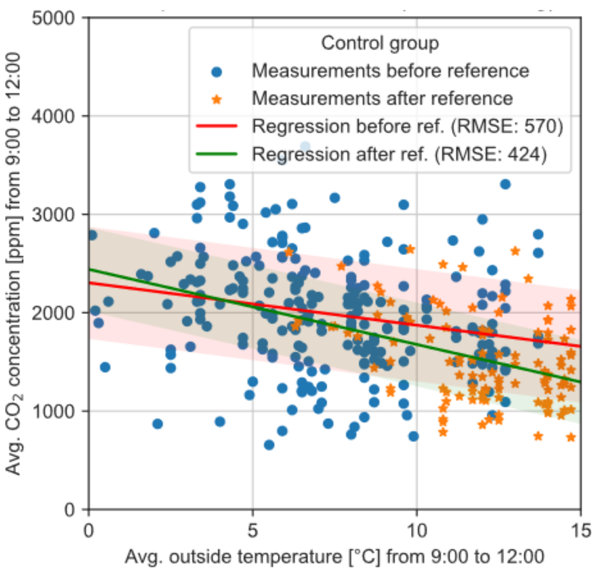

Figure 2: Correlation of outside temperature and inside CO_2 concentrations for classrooms (control group) (Beck, 2024).

Boulic et al. used computational fluid dynamics (CFD) to assess and improve classroom ventilation in three New Zealand cities (Auckland, Wellington, and Dunedin) (2024). Their study focused on evaluating trickle ventilators, with and without exhaust fans, as cost-effective alternatives to mechanical HVAC systems, especially relevant during winter when natural ventilation through window opening is inadequate. Their simulations revealed that while trickle ventilators can achieve acceptable airflow rates during summer in cities like Wellington, their effectiveness diminishes in winter due to reduced airflow and "CO_2 pockets" caused by poor air mixing. The study underscores the potential of integrating exhaust fans with trickle ventilators to meet recommended airflow rates year-round (Figure 2) and plans to validate findings through sensor deployment in classrooms.

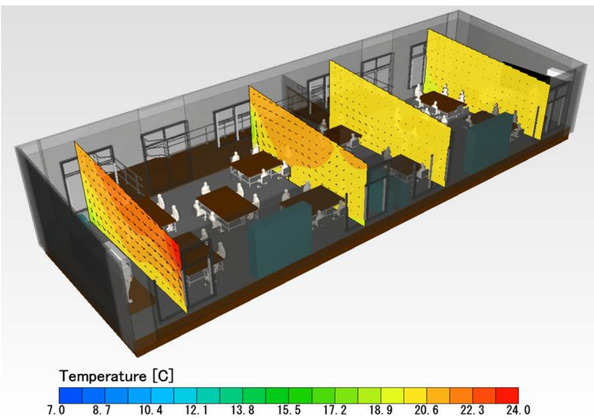

Figure 1: Temperature distribution (left, vertical plan)

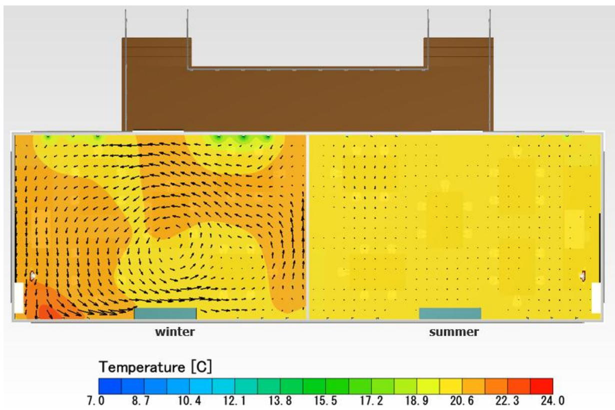

Figure 2: Temperature distribution (right, at 1.5 m from the floor)

1.3. Smart Ventilation

De Jonge introduced the Health-Equivalent Energy Efficiency Factor, a new metric designed to evaluate and balance the trade-offs between energy efficiency and health impacts in indoor air quality (IAQ) management systems (2024). Using metrics such as energy use and health impact indicators (expressed in Disability-Adjusted Life Years, DALYs), their study models and compares eight smart ventilation strategies, against predefined reference systems. It finds that using a reference line based on target values for energy efficiency and health impacts, results in greater versatility and wider applicability. The study highlights the importance of aligning IAQ strategies with both health and energy goals and supports adopting this metric in future regulatory frameworks to improve building ventilation systems.

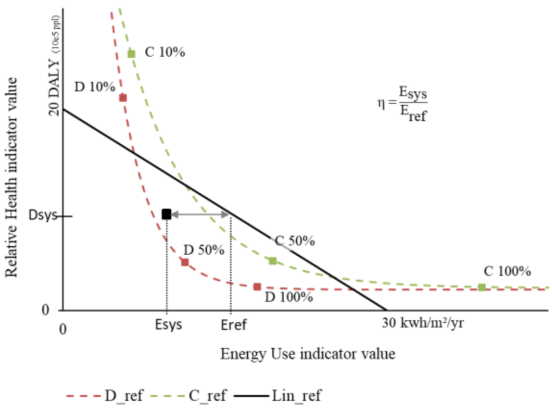

Figure 3: Plot graphically explaining the principle of the health-equivalent energy efficiency factor and the different investigated reference lines. The full line represents a linear reference line based on two target values. The dotted lines represent two reference lines based on simulations of two continuous airflow Belgian standard systems (system C- MEV and system D with heat recovery -MVHR) (De Jonge, 2024)

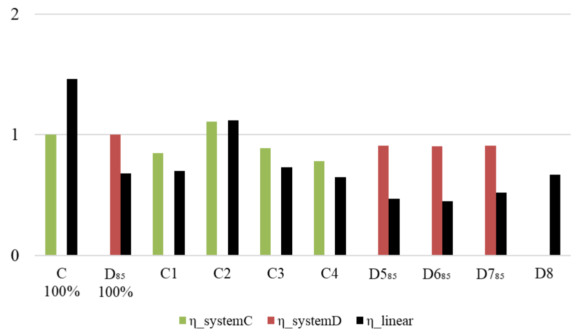

Figure 6: The different available Health-equivalent energy efficiency factors for each smart ventilation system and two reference systems (100%) (De Jonge, 2024)

The **SmartAIR French project** focuses on adapting the tools developed under Annex 86 (Energy Efficient Indoor Air Quality Management in Residential Buildings) to improve the energy efficiency of IAQ management strategies in operation (Andrade & Guyot, 2024). As part of this ongoing project, Andrade & Guyot, are evaluating the indoor air quality (IAQ) and energy performance of residential smart ventilation strategies in France, Denmark, Belgium, Brazil and Austria. Eight ventilation systems have been selected for simulation. The study involves collecting CO_2 and relative humidity concentration profiles, as well as exposure concentration profiles for various contaminants across all rooms in a standardized dwelling setup; these systems are assessed using various performance indicators such as DALY, cumulative formaldehyde and $PM_{2.5}$ exposures and energy losses. Raissa Andrade presented the methodology for assessing the sensitivity of all these indicators to entry data (Andrade & Guyot, 2024).

A study by **Cremers** explored the concept of implementing adaptive comfort technology in balanced ventilation systems, both with and without post conditioning (Cremers, 2024). They presented examples from monitored projects demonstrating how indoor temperature setpoints in adaptive temperature control vary in time. The data highlights how the bypass mechanism and postconditioning respond to variations in the temperature setpoints. Together, these components influence the supply air temperature, ultimately ensuring that indoor conditions remain comfortable. For ventilation units without postconditioning, the temperature setpoint influences the frequency of bypass operation (Figure 7) while for ventilation units with postconditioning (Figure 8), the temperature setpoint influences the frequency of bypass operation and the demanded heating use or cooling use.

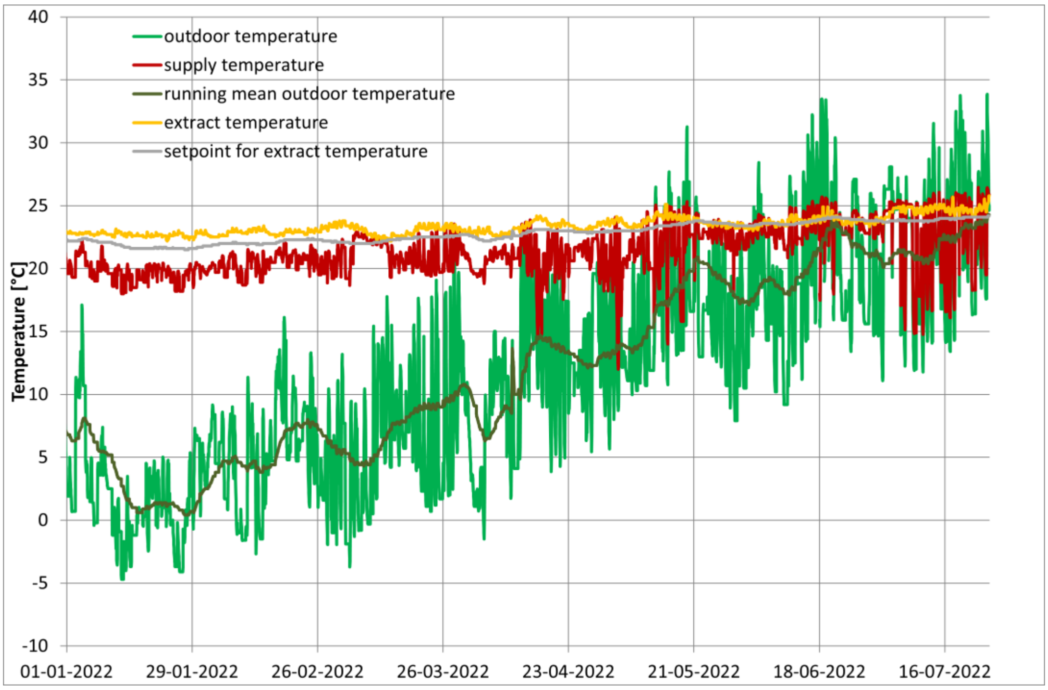

Figure 7: Monitored temperatures for a balanced ventilation system without postconditioning (Cremers, 2024)

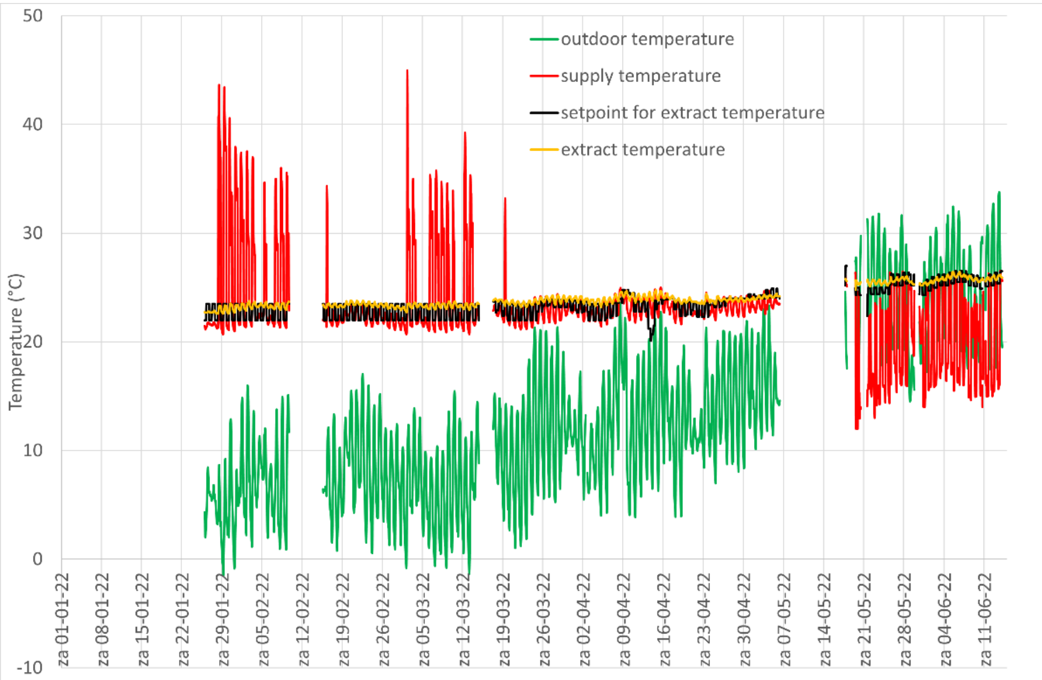

Figure 8: Monitored temperatures for a balanced ventilation system with postconditioning. Gaps in the chart are due to periods during which data transmission had failed (Cremers, 2024)

1.4. Performance based regulations (PBR)

Performance-based regulations define required results without specific direction on how those results are to be obtained. The topical session “Performance based IAQ regulations in dwellings: present and future” considered this concept.

Guyot and Leprince opened the session with an overview of the development and application of performance-based approaches in research projects since 2016 and their integration into standards and regulations (Guyot & Leprince, 2024). They emphasized the significance of these approaches in addressing indoor air quality (IAQ) and energy efficiency for residential ventilation systems. While prescriptive ventilation rates remain prevalent, smart ventilation systems—designed to optimize airflow based on actual needs—are gaining attention for enhancing IAQ while reducing energy consumption. According to the presenter with the same airflow/air change rate, you can reach different level of IAQ criteria whilst with a lower mean airflow, you can improve the level of IAQ (Guyot & Leprince, 2024).

Linares-Akemparte & Garcia-Ortega (2024) reviewed Spain's performance-based IAQ regulations, focusing on their evolution, application challenges, and future anticipated changes. They detailed the transition from prescriptive to a fully performance-based approach in the Código Técnico de la Edificación (CTE), with CO_2 as the primary IAQ indicator, setting thresholds such as a maximum annual average concentration of 900 ppm and an annual accumulated concentration limit. Furthermore, they listed specific issues identified in CTE’s applications, which primarily relate to the consideration of smart ventilation systems in energy assessment tools and the rise of condensation risk in renovations. Anticipated updates focus on revising the energy performance assessment tool (Herramienta Unificada Lider-Calener - HULC) to reflect more accurate ventilation flow rates and better integrate demand-controlled ventilation systems (Linares-Alemparte, 2024). Additionally, the presenters emphasized the need to move beyond CO_2 as the sole indicator of IAQ and the setting of thresholds levels for additional pollutants. While a major challenge in implementing this change is to establish the correlation between pollutant concentration and its impact on occupant health, research is currently underway to investigate the generation of the most common pollutants in dwellings, their concentration and their impact on occupant health in terms of DALYs.

A presentation by **Garcia-Ortega** focused on assessing IAQ in existing residential buildings within a performance-based regulatory framework through a predictive model (2024). Traditional ventilation in Spanish dwellings relied on passive stack ventilation- employing the principles of thermal buoyancy and the Venturi effect to remove stale air from wet rooms- which has limitations such as poor performance in low wind or thermal inversion conditions and high thermal losses. Research by the Instituto de Ciencias de la Construcción Eduardo Torroja (CSIC) explores correlations between measurable factors (e.g., season, dwelling’s surface area, permeability, occupancy) and real CO_2 measurement outcomes, bypassing detailed occupant behaviour. Their study leverages easily obtainable parameters like floor area, construction year etc. to develop predictive statistical models for IAQ, avoiding reliance on field measurements. These models aim to inform the development of IAQ regulations, guidelines, and building renovation plans by assessing neighbourhood-level IAQ potential, identifying building typologies prone to IAQ issues, and evaluating how occupant behaviour varies with geography, climate, and socio-economic factors.

Leprince & Poirier presented a methodology for developing performance-based ventilation regulations in France, offering an alternative to the existing prescriptive regulation of 1982 (2024). The proposed framework includes key performance indicators (KPIs) to assess ventilation systems' effectiveness in maintaining indoor air quality (IAQ) concerning health, well-being, and building durability. The KPIs cover parameters like CO_2 concentration, relative humidity, proxy pollutants and air renewal, tailored for simulation and validation rather than on-site measurements. Simulations of typical French ventilation systems were conducted to define threshold values and to check the impact of the various input parameters and target values for the KPIs were defined. They also defined a structured validation process for industrial and project-specific systems. France is set to introduce performance-based regulations for ventilation in dwellings, providing an alternative to prescriptive standards. This approach will foster a more open market for smart ventilation systems, enabling solutions that maintain or enhance indoor air quality (IAQ), minimize energy consumption and embodied energy, and are specifically tailored to the needs of each project (Leprince & Poirier, 2024).

A presentation and **study by Poirier** looked into the uncertainty of IAQ and energy performance schemes for residential smart ventilation (Poirier, Guyot, & Woloszyn, 2024). Their study quantified the uncertainty of a new recent performance assessment method using RBD-FAST sensitivity analysis to evaluate the variations of impacts of input data such as: the pollutant emissions scenarios - moisture, formaldehyde and particle matter $PM_{2.5}$ -, model input parameters and ventilation strategies (Figure 4). For this sensitivity analysis, five ventilation systems were studied on a French low energy house: 2 with constant airflows, 1 humidity-based exhaust-only smart ventilation and 2 humidity+CO_2 based smart ventilation. The study found that occupant bio-effluent, formaldehyde, and $PM_{2.5}$ emission rates contributed 11% to 87% of the uncertainty in IAQ performance indicators, with $PM_{2.5}$ deposition velocity parameter alone accounting for 50% of the uncertainty in the $PM_{2.5}$ indicator. Moreover, they highlighted the energy benefits of the humidity-based ventilation, with heat losses on average 20% lower than those obtained with equivalent constant airflow ventilation and noted that some smart ventilation strategies offer clear IAQ benefits without significantly increasing energy demand.

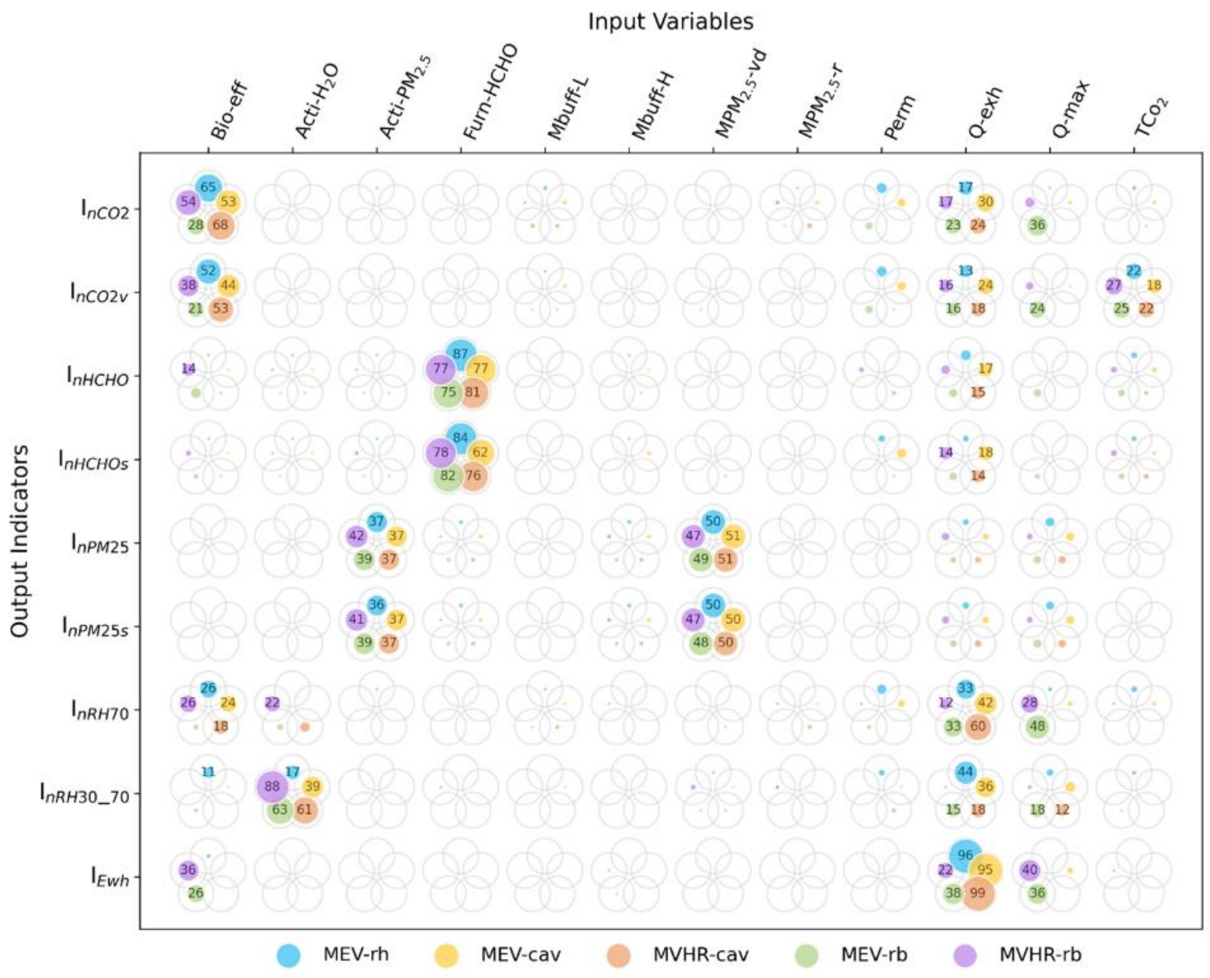

Figure 4: Display of the sensitivity indices calculated for the 5 ventilation strategies (Poirier, Guyot, & Woloszyn, 2024)

A number of presentations considered harm as a basis for regulation.

A paper by **Jones et al.** (Jones B. , Morantes, Molina, Sherman, & McGrath, 2024) evaluated the protection from chronic harm provided by exposure limit values (ELVs) for indoor air contaminants set by regulatory bodies across member countries of the Air Infiltration and Ventilation Centre (AIVC). Significant variability in the regulated harm levels from ELVs across countries for the same contaminants underscores inconsistencies in public health protection. Their study also introduced the concept of a Regulated Harm Budget (RHB) to quantify the total allowed harm from regulated contaminants implicitly set by a regulatory body and highlighted that the RHBs of most countries exceed harm levels associated with smoking and alcoholism. This signals a need for intervention to mitigate indoor air contaminant harm and reduce it to acceptable levels that are comparable to other regulated risks. Spain's RHB of 2400 DALYs/10^5 person/year for $PM_{2.5}$, NO_2, and formaldehyde is particularly noteworthy (Table 1).

Table 1: Regulated harm budgets for selected contaminants, by country. Highest to lowest median harm. DALYs/105 person/year (Jones B. , Morantes, Molina, Sherman, & McGrath, 2024)

Contaminants	Country	Regulated Harm Budget	Geometric Standard Deviation
HCHO, NO_2, $PM_{2.5}$	Spain	2400	1.3
NO_2, $PM_{2.5}$	China	3600	1.2
	Spain	2400	1.3
	Norway	1500	1.2
HCHO, $PM_{2.5}$	USA	2200	1.2
	Spain	1200	1.2
HCHO, NO_2	Sweden	7300	1.5
	Spain	1100	1.7
	France	570	1.8
	UK	280	1.6

Another presentation and study by **Jones et al.** showed how a harm budget (an acceptable limit of population harm) might be used to regulate Indoor Air Quality in dwellings at the global north (Jones B. , Morantes, Molina, & Sherman, 2024). They quantified chronic harm from long-term exposure to 45 common indoor air contaminants using DALYs and identified $PM_{2.5}$, $PM_{10-2.5}$, NO_2, formaldehyde, radon and O_3 as the most harmful contaminants, accounting for over 99% of total harm (Figure 5). By prioritizing these contaminants, the study demonstrated that complying with ASHRAE Standard 62.2 could reduce population harm by approximately 70%, setting an acceptable harm budget of 610 DALYs/10^5 person/year. Harm is shown to be a way of prioritising the contaminants that cause the greatest chronic harm to populations of people, and the harm budget quantitatively establishes acceptable IAQ based on exposure to airborne contaminants in buildings.

Molina et al. used year-long data collection in 15 dwellings in Santiago, Chile, to investigate the relationship between indoor air quality (IAQ) and thermal comfort and the houses' typology (Molina, Jones, Garrido, & Morantes, 2024). Significant variability in particulate matter ($PM_{2.5}$ and PM_{10}) concentrations and thermal comfort was observed. While PM concentrations were below the global representative value, maximum values exceeded the representative maximum. The associated health harm was quantified as 1271 DALYs/10^5 person/year for $PM_{2.5}$ and 683 DALYs/10^5 person/year for PM_{10}. Notably, WHO 2021 annual recommendations were not met, with the daily mean met by 25% of the measured days for $PM_{2.5}$ and 72% for PM_{10}. Acceptable thermal comfort levels were achieved just 56% of the measured time (Figure 6). The study emphasizes the need for a comprehensive regulatory framework that optimizes energy efficiency and prioritizes occupant well-being, providing valuable insights for addressing competing objectives in residential architecture and guiding strategic, impactful interventions.

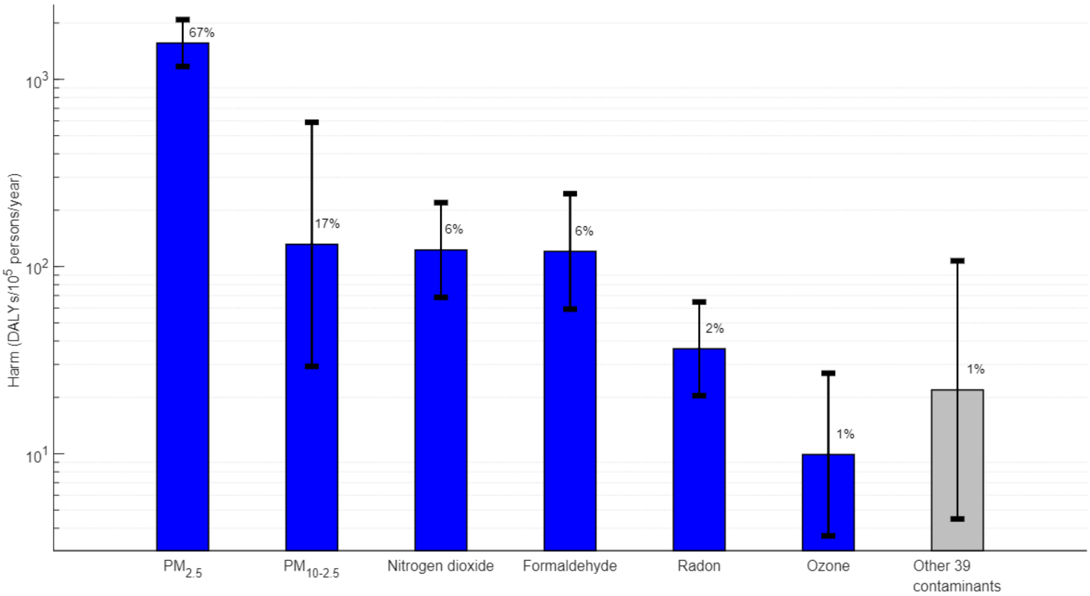

Figure 5: Harm caused by contaminants of concern. Median (bar) & GSD (error bar). Percentage contribution for total harm (Jones B. , Morantes, Molina, & Sherman, 2024)

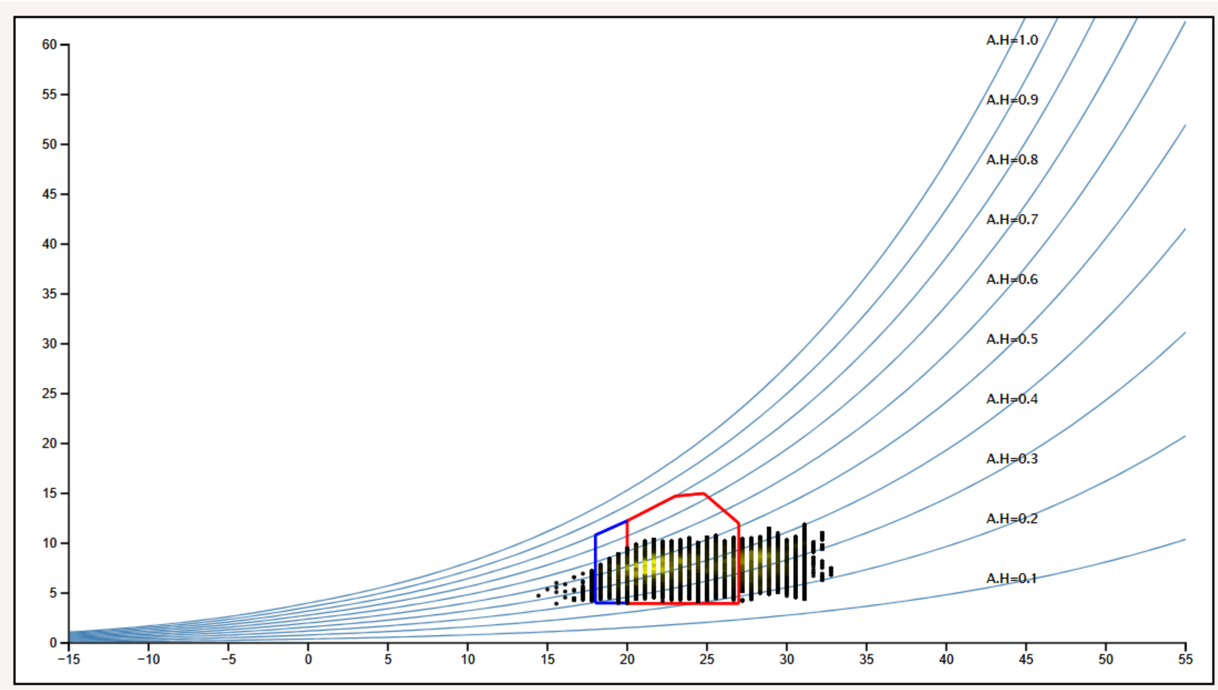

Figure 6: Psychrometric chart for one sensor, showing the data within the thermal comfort zone—red area for summer and blue and red area for winter. Gradients of yellow indicate data saturation (Molina C. , 2024)

1.5. IAQ assessment

Kosonen et al. investigated the airborne transmission and infection probability in a six-person meeting room using an overhead perforated duct (OPD) and low-velocity unit (LVU) (2024). Using tracer gas (SF6) generated by a thermal breathing manikin to simulate droplet nuclei from an infected individual, the study examines the effects of heat gain, airflow rate, and the infector's location. The average contaminant removal efficiency with OPD was between 0.9 and 1.1 while the infection probability was quite uniform (SD=0.1%), especially at a higher heat gain level (60 W/m^2) (Figure 7). In contrast, LVU displayed significant variability (spatial & temporal) in contaminant removal (0.2–10.1) and infection risk, ranging from 0.3% to 4%, depending on the infector's location, with its best and worst scenarios surpassing OPD performance when properly designed. Locating the infector near the exhaust minimized infection probability with heat gain levels of 38 W/m², highlighting that effective air distribution combined with local exhaust placement is most effective for source removal.

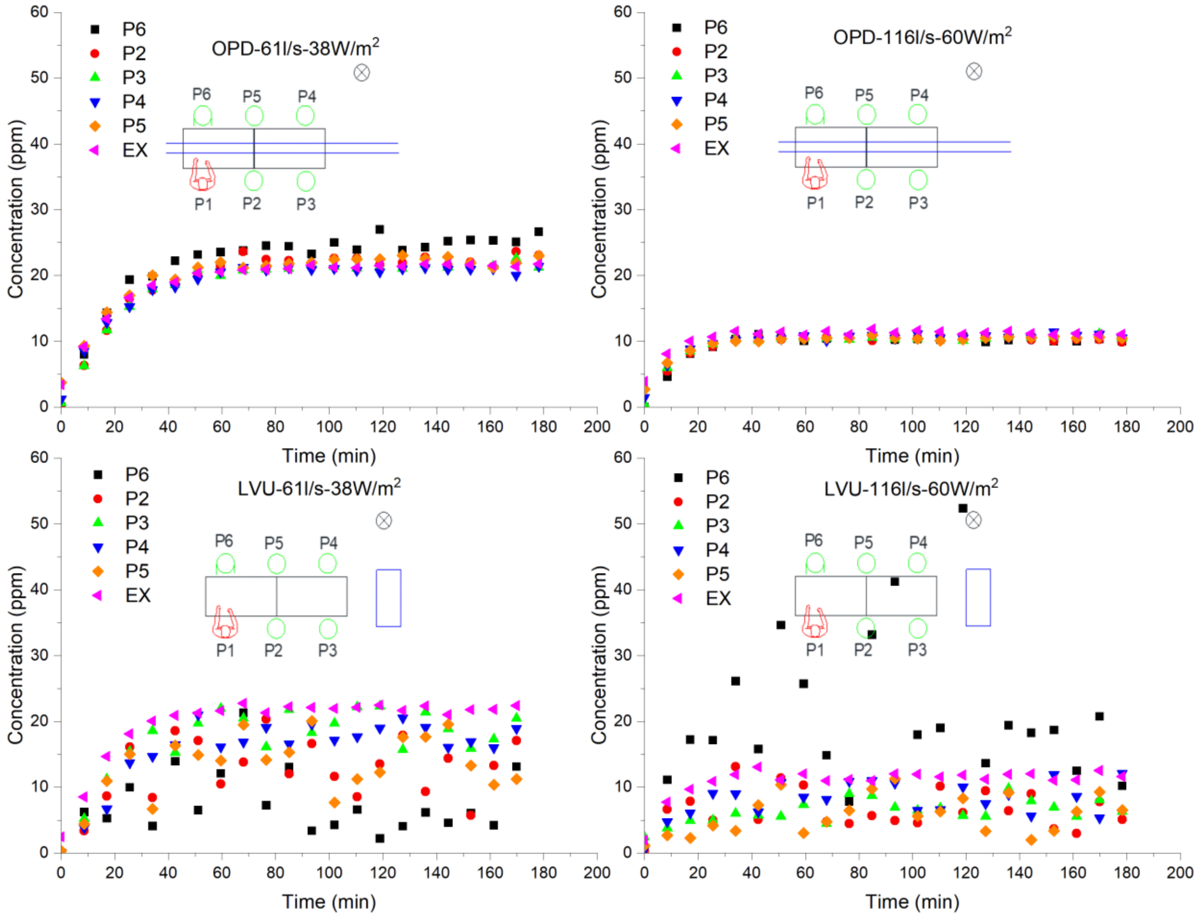

Figure 7: The concentration distribution of tracer gas at different locations when the manikin was at P1 with OPD and LVU with two heat gains of 38 W/m^2 and 60 W/m^2 (Kosonen, Zhao, Kilpeläinen, & Jokisalo, 2024)

A study by **Murga et al** focused on optimizing airflow rate in displacement-ventilated room to minimize particle inhalation risk and control energy consumption using computational fluid dynamics (CFD), virtual manikins, and a genetic algorithm (Murga, Nakagawa, Bale, & Tsubokura, 2024). The research investigated how building parameters, such as inlet/outlet sizes, inlet/outlet location, and airflow rates, impact airborne viral density and energy use. The optimization process achieved a 50% reduction in particle number when comparing the worst-case scenario (P1) with an optimized solution maintaining the same power consumption (P2). Notably, particles remained at breathing level in non-optimized conditions but were effectively removed after optimization (Figure 8). Then, optimization algorithms can be joined to virtual manikins to improve building design and minimize airborne transmission while managing energy consumption.

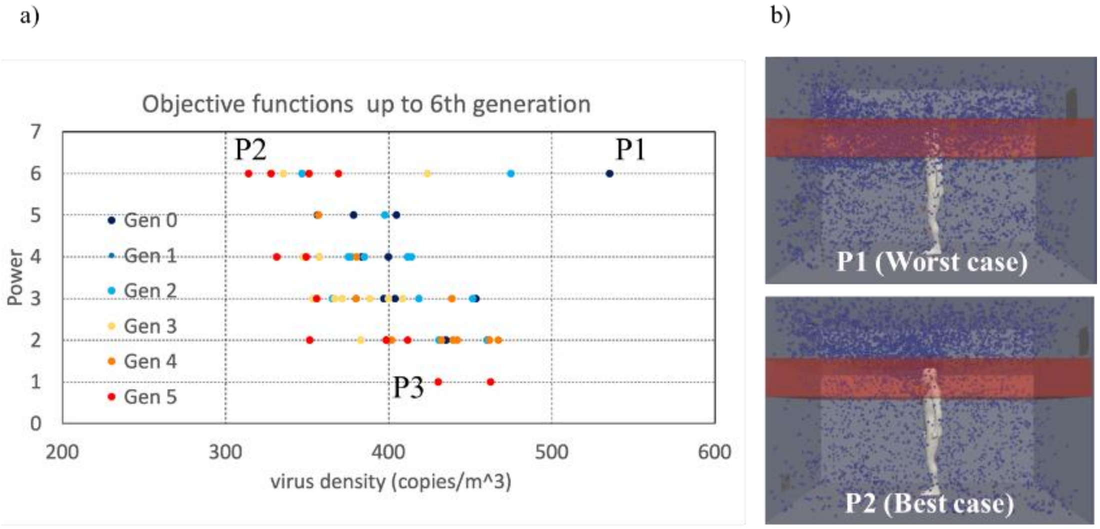

Figure 8: a) Pareto solution and b) Comparison of P1 and P2 (Murga, Nakagawa, Bale, & Tsubokura, 2024)

Shin et al. (2024) assessed airborne cross-infection risk under different discharge angles (-20°, 0°, and +20°) and supply temperatures (18, 25, and 30 °C) of an air-conditioner, with various body orientations (face-to-face, side-by-side, and back-to-back) (Figure 9, Figure 10, Figure 11). They conducted field experiments on particle dispersion in a full-scale test chamber using a manikin-shaped particle generator and detector with simulated particles. Particle transmission trends initially differed depending on body orientations. Cross-infection risk was consistently lower at a discharge angle of -20° and higher at +20° when the supply temperature was 25°C, regardless of orientation. However, the discharge angles linked to increased or reduced cross-infection risks shifted with changes in supply temperature. These findings highlight the significant influence of body orientation on cross-infection risk and underscored the importance of carefully adjusting discharge angles and supply temperatures to mitigate airborne transmission in indoor airflow environments.

Figure 9: Experiment settings in the test chamber - Front-to-front (Shin H. W., Park, Park, & Kang, 2024)

Figure 10: Experiment settings in the test chamber - Side-by-side (Shin H. W., Park, Park, & Kang, 2024)

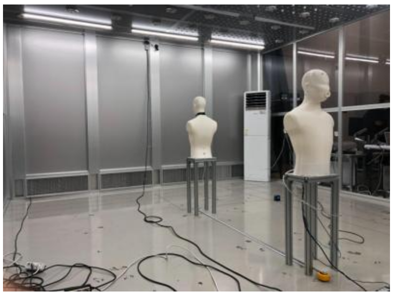

Figure 11: Experiment settings in the test chamber - Back-to-back (Shin H. W., Park, Park, & Kang, 2024)

Paralovo et al. reported on indoor air quality (IAQ) measurements and the presence of SARS-CoV-2 in 11 elderly care homes in Belgium (2024). Over seven days, CO_2, $PM_{2.5}$, temperature, and relative humidity were continuously monitored in selected rooms, while air and surface samples were analyzed for SARS-CoV-2 RNA. They found that particulate matter ($PM_{2,5}$) concentrations in all facilities were most of the time low, meeting indoor guideline values. CO_2 concentrations generally indicated acceptable levels of ventilation, with the lowest concentrations measured in mechanically ventilated facilities. During active COVID-19 outbreaks, all air samples and the majority of surface samples tested positive for SARS-CoV-2. In the absence of a reported on-going local outbreak, positive SARS-CoV-2 samples were found mainly on surfaces. The study highlights the value of assessing viral loads in both air and surface samples as an effective tool for evaluating infection risks in indoor spaces without requiring human sample collection. Expanding such studies to include additional pathogens could provide broader insights into exposure risks for vulnerable populations, such as the elderly, and facilitate the development of more precise prevention strategies. General recommendations for elderly care homes include regular testing of residents and staff (symptomatic or not), isolating positive cases, promoting the use of masks, and enhancing ventilation, particularly in shared spaces, to mitigate the spread of airborne infections.

De Jonge presented a measurement campaign aimed at supporting the implementation of Belgium's 2022 law to improve indoor air quality (IAQ) in public spaces following the COVID-19 pandemic (De Jonge & Janssens, 2024). The campaign involved monitoring CO_2, particulate matter ($PM_{2.5}$ and PM_{10}), temperature, and relative humidity across 11 Belgian public spaces with diverse functions, such as bars, gyms, and restaurants for a duration of at least 7 days in March 2024. The measurements reveal significant variation in IAQ parameters influenced by the building's usage, the presence of specific pollutant sources, and the availability of ventilation systems. Particular sources of particulate matter (PM) can substantially elevate indoor concentrations, often exceeding WHO Air Quality Guidelines for prolonged periods. Bars and restaurants recorded the poorest IAQ metrics, whereas most other locations with mechanical ventilation systems maintained acceptable levels of CO_2 and PM. These findings underscore the challenges in creating a uniform IAQ label suitable for all types of public spaces.

Robitu & Ginestet (2024) performed a study aiming to evaluate the effectiveness of stand-alone air cleaners (ACs) equipped with HEPA filters in reducing airborne particle concentrations within a mechanically ventilated meeting room. The assessment focuses on factors such as the number and type of devices, total airflow rate, their placement within the room, and the flow patterns of the devices. Six commercially available ACs, representative of the French market, were selected for the study, each characterized by unique airflow patterns for both air inlet and outlet. The filtration efficiencies of the ACs are nearly 100%, as expected for HEPA filters. The targeted airflow rates for this study — 80, 200, and 400 m^3/h, corresponding to 1, 2.5, and 5 volume per hour (vol/h), respectively—were achieved. However, the actual airflow rates were found to be 20% to 50% lower than the manufacturers' stated values. Additionally, the sound power levels and operating power of the air cleaners were measured. Numerical 3D simulations (CFD) were conducted to evaluate 66 configurations of ACs within the room. These simulations calculated airflow pattern, air velocity, and particle concentrations over time and at various locations within the breathing zone. The cleaning efficiency, defined as the ratio of particle concentration after 16 minutes of AC operation to the initial concentration, was evaluated. ACs placed in corners behind walls—a common positioning—demonstrated lower performance compared to other locations in the room. Higher airflow rates improved cleaning efficiency, as indicated by a decrease in the C16/C0 ratio. At 5 volumes per hour (vol/h), variations in particle concentrations across the room were weak, but became larger at 2.5 vol/h. Ceiling-type ACs achieved more uniform particle distribution throughout the room. However, most ACs studied produced sound levels exceeding 50 dB(A) at airflow rates above 200 m^3/h, potentially causing noise disturbances for occupants.

Oke & Persily (2024) evaluated the accuracy of predicting CO_2 emission rates of building occupants (VCO_2) using two estimation approaches: the ASHRAE Fundamentals Handbook (2021) and the Persily and de Jonge (PdJ) approach (2017). Experimental data from indirect calorimeter chambers involving 50 healthy participants performing activities like cycling, sleeping, and sedentary tasks were compared to predictions made using measured and literature-based inputs. During these activities metabolic parameters such as VCO_2, rate of oxygen consumption (VO_2), basal metabolic rate (BMR), respiratory quotient (RQ), and energy expenditure (EE) were collected. Results indicate that the PdJ method outperforms ASHRAE, with prediction errors of 6% (measured inputs) and 19% (literature inputs), compared to ASHRAE's 28% error. The findings highlight the importance of addressing the challenges in predicting VCO_2 to interpret indoor CO_2 concentrations.

Finneran & Burridge (2024) introduced a robust method for estimating the daily mean per-person ventilation rate ($\bar{Q}_{pp}$) in heterogenous rooms using point measurements of carbon dioxide (CO_2), without requiring assumptions regarding the ventilation provision throughout the day, nor requiring the room to be in a steady state, nor the air within to be well-mixed. Notably, the method facilitates ventilation estimates in operational spaces during normal use, not requiring the room to be unoccupied. Using UK secondary school classrooms as a case study, the study employs Monte Carlo to simulate CO_2 levels and derive a simplified calculation tool based on the CO_2 mass balance equation. The proposed method requires minimal contextual information (CO_2 levels, occupied time fraction, and average per-person CO_2 generation rate), achieving uncertainty reductions from 22% (no contextual data) to 12% with increased contextual data (information of occupants age and room activities, and using multiple CO_2 sensors) (Figure 12). The tool provides a practical means of calculating average per-person ventilation rates from CO_2 data.

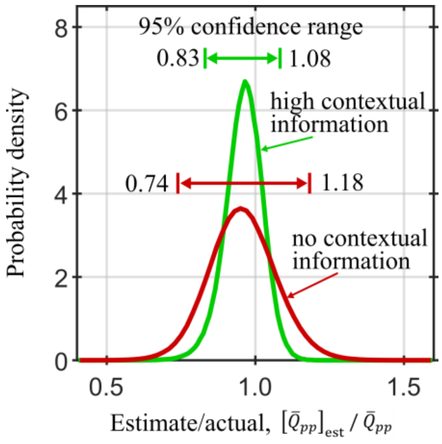

Figure 12: Probability density function for estimated Q¯_pp from the calculation tool/equation compared to the true value, for no and detailed contextual information scenarios

1.6. Radon

The topical session on "The Challenges of Radon and Energy Retrofitting: Unravelling Complexities and Interaction within the Built Environment" explored the intricate relationship between radon and the built environment, in the context of ventilation and indoor environmental quality.

Pourkiaei et al. used data from 87 Irish homes collected hourly between 2019 and 2021 and, looked at radon entry rates into buildings to identify factors driving the radon flux based on meteorological, environmental, and building characteristics using a statistical approach (Pourkiaei, Byrne, Murphy, & McGrath, 2024). Initial findings reveal considerable variability across the dwellings and within each dwelling, reflected by the wide distribution, highlighting the dynamic process (Figure 13).

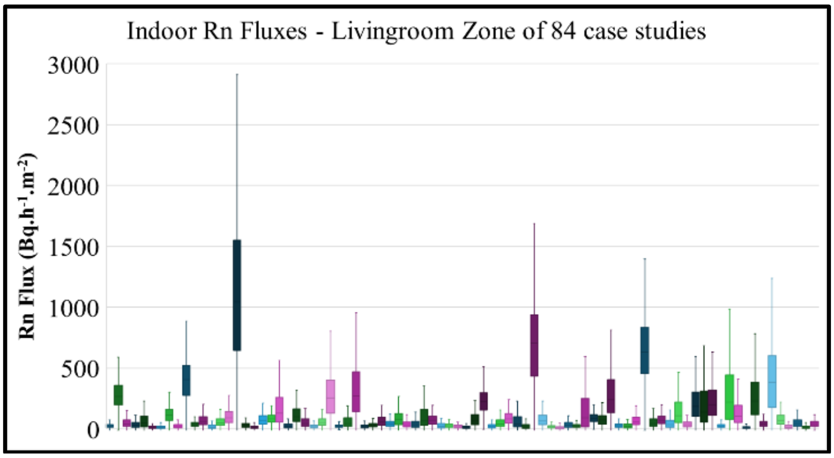

Figure 13: Box plots of radon fluxes distributions of 84 case studies over 18 months (Pourkiaei, Byrne, Murphy, & McGrath, 2024)

Zhou reported on the effects of ventilation approaches on indoor radon concentrations through controlled experiments conducted at the Canadian Centre for Housing Technology focusing on building depressurization & radon ingress, ventilation & indoor radon control (Zhou L. , Li, Gaskin, & Tardif, 2024). The study observed increased indoor radon concentrations during the depressurization testing with the highest levels recorded under lower depressurization caused by clothes dryers, cooker hoods, and bathroom exhausts, operating under typical mechanical exhaust-only ventilation (MEV) conditions. This outcome is likely attributed to increased dilution effects facilitated by enhanced envelope pressure differentials. Balanced mechanical supply and exhaust ventilation (MSEV) was identified as an effective strategy for mitigating radon levels.

Gaskin et al. conducted a field study on the effectiveness of heat recovery ventilation (HRV) systems in reducing moderate indoor radon concentrations in 16 houses in Canada's National Capital Region between 2020 and 2023 (Gaskin J. , Li, Brascoupé, & Zhou, 2024). HRVs were tested under various operational settings—off, periodic, and continuous operation at different fan speeds (high or low). The impact of the HRV system on indoor radon concentrations was assessed across sixteen houses, with an additional analysis comparing the combined operation of the passive depressurization system (PSD) for radon mitigation and the HRV. Results showed that continuous HRV operation achieved an average radon reduction of 40% in houses with forced air furnace heating systems, with reductions ranging from 20% to 56% (Figure 14). The highest reduction effectiveness (80%) was observed in a house with electric baseboard heating and an independently ducted HRV. An overall trend showed greater reduction effectiveness with continuous fan operation compared to periodic operation in houses where more than two HRV settings were evaluated. The presenters concluded that well-designed, properly installed, and regularly maintained HRV systems are effective in reducing moderate indoor radon concentrations. They emphasized that encouraging residents to operate HRV systems continuously can optimize radon reduction.

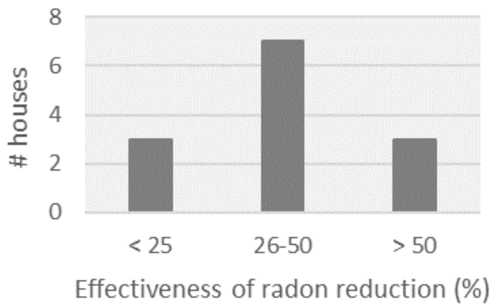

Figure 14: Histogram of HRV effectiveness (Gaskin J. , Li, Brascoupé, & Zhou, 2024)

Dowdall investigated the effectiveness of passive radon sumps, including those fitted with static cowls, as a low-cost method for reducing indoor radon levels in Irish dwellings (2024). A field trial was conducted on six identical houses to measure radon levels under three conditions: with the sump closed, the sump open, and the sump open with a static cowl. Results showed that passive sumps reduced radon levels by 65%, while the addition of a static cowl further increased the reduction to 75%. The percentage of observations exceeding the government's reference level of 200 Bq/m³ dropped from 38% to 0% when both measures were applied. The findings support the inclusion of passive sumps with static cowls as a cost-effective strategy for mitigating radon exposure in new Irish homes.

Table 2: Passive sumps field trail - Results (Dowdall, 2024)

Sump test condition	Average radon level (Bq/m³)	Percentage reduction in radon level	Percentage of daily observations above 200 Bq/m³
Standby sump (closed)	382	-	38
Passive sump (open)	135	65%	9%
Passive sump plus cowl (open)	94	75%	0%

1.7. Performance evaluation of ventilation systems

Note:

This section, was contributed by Arnold Janssens (Operating Agent AIVC, Research Group Building Physics, Ghent University, Belgium), who also chaired the corresponding session at the AIVC 2024 conference. This summary was originally published in the REHVA Journal under the title "Advances in performance evaluation of residential ventilation systems" (Janssens, 2025) and is reproduced here with permission to provide a comprehensive overview of the session's contributions. It is included here in its original form to maintain the integrity and perspective of the original contribution.

In many countries, existing houses are being retrofitted to achieve better energy efficiency levels. In this process, the building envelope's airtightness is usually improved, and a ventilation system becomes necessary to create and sustain a healthy indoor air quality (IAQ). However, standard ventilation system designs developed for new dwellings, are not always easy to integrate in existing houses. As a result, dedicated systems need to be developed with a potential for house retrofitting, and their performance need to be evaluated. This was the motivation for simulation studies on the performance of residential ventilation systems in France (Boulier, et al., 2024) and Chile (Flamant, Bustamante, Janssens, & Laverge, 2024).

Furthermore, ventilation standards in many countries use a prescriptive approach based on ventilation rates, while health issues relate to exposure of inhabitants to indoor pollutants of concern, with as most important one particulate matter ($PM_{2.5}$). A performance-based approach, predicting pollutant concentrations through simulations, is more adequate for assessing IAQ. This was the subject of a French simulation study, analysing the performance of ventilation systems in a multifamily building located in an urban location characterised by high $PM_{2.5}$ levels (Kiani, Nour Eddine, Taurines, Cordeiro Mendonça, & Abadie, 2024). Another French study used measurements to evaluate the long-term performance of mechanical extract ventilation systems in multifamily buildings 15 years after construction (Mélois, et al., 2024). A Dutch simulation study investigated the opportunities of a combined operation of effective range hoods and balanced mechanical ventilation with improved filtering, on the interior particulate matter concentration from indoor and outdoor sources (Jacobs, Kornaat, & Borsboom, 2024). The latter study also investigated the effect of window use.

The different studies used a performance based approach to predict or monitor the exposure to pollutant concentrations in dwellings. Performance was assessed by means of different sets of IAQ performance indicators:

- Cumulative or average exposure to $PM_{2.5}$ [(Boulier, et al., 2024), (Kiani, Nour Eddine, Taurines, Cordeiro Mendonça, & Abadie, 2024), (Mélois, et al., 2024), (Jacobs, Kornaat, & Borsboom, 2024)]
- Cumulative exposure to CO_2 above reference concentration [(Boulier, et al., 2024), (Kiani, Nour Eddine, Taurines, Cordeiro Mendonça, & Abadie, 2024), (Mélois, et al., 2024), (Flamant, Bustamante, Janssens, & Laverge, 2024)]
- Cumulative exposure to formaldehyde [(Boulier, et al., 2024), (Kiani, Nour Eddine, Taurines, Cordeiro Mendonça, & Abadie, 2024), (Mélois, et al., 2024)]
- TVOC-concentrations (P70) (Mélois, et al., 2024)
- Percentage of time in which relative humidity is outside a reference range [(Boulier, et al., 2024), (Kiani, Nour Eddine, Taurines, Cordeiro Mendonça, & Abadie, 2024), (Flamant, Bustamante, Janssens, & Laverge, 2024)]
- Ventilation heat loss [(Boulier, et al., 2024), (Kiani, Nour Eddine, Taurines, Cordeiro Mendonça, & Abadie, 2024), (Flamant, Bustamante, Janssens, & Laverge, 2024)]
- Fan energy use (Boulier, et al., 2024) (Kiani, Nour Eddine, Taurines, Cordeiro Mendonça, & Abadie, 2024)
- Mean air flow rate extracted or supplied (Boulier, et al., 2024)

The simulation studies used multizone software CONTAM (Boulier, et al., 2024) (Flamant, Bustamante, Janssens, & Laverge, 2024) , COMIS (Jacobs, Kornaat, & Borsboom, 2024) and HEAVENLY (Holistic Evaluation tool for Air VENtiLation sYstems) based on a TRNSYS-CONTAM (Kiani, Nour Eddine, Taurines, Cordeiro Mendonça, & Abadie, 2024). The latter study mainly applies concentrations in bedrooms for performance assessment. In the monitoring study (Mélois, et al., 2024) continuous measurements over a two-year period were conducted in buildings located in Lyon and Paris.

In general, according to the simulations, none of the different ventilation systems studied was superior to all others for all indicators. However, balanced ventilation systems with constant air volume and $PM_{2.5}$ supply filter (E65) presented good results overall for single-family dwellings (Boulier, et al., 2024).

The simulation study on multifamily buildings obtained a similar conclusion: a dual-flow ventilation system with 60% filtration effectively maintained CO_2 levels between 500 and 1000 ppm, significantly reduced peak $PM_{2.5}$ levels, and demonstrated superior energy efficiency, particularly with heat recovery system (Kiani, Nour Eddine, Taurines, Cordeiro Mendonça, & Abadie, 2024).

The Dutch study (Jacobs, Kornaat, & Borsboom, 2024) showed that good cooking extraction in combination with balanced mechanical ventilation and better filtering (F7) in the supply can significantly reduce exposure to particulate matter in homes, even when windows are open in the bedrooms for a large part of the year. This was mainly due to the much lower exposure in the living room. The use of better filters than F7 only had a limited effect as a result of the assumption that windows were open during part of the year.

Even though improved IAQ was obtained with balanced mechanical ventilation, these are typically systems which represent more difficulties to integrate in existing dwellings (Boulier, et al., 2024).

The Chilean study (Flamant, Bustamante, Janssens, & Laverge, 2024) therefore investigated how humidity controlled decentralized mechanical exhaust systems typically installed in kitchens and bathrooms in existing social houses in Chile may be optimized in terms of IAQ and energy use. Optimized systems were based on the extended cascade ventilation principle, or included the addition of an exhaust system specific to bedrooms.

Also the monitoring study (Mélois, et al., 2024) focused on the performance of humidity controlled mechanical exhaust systems in social multifamily buildings, 15 years after construction. Overall, the CO_2 concentrations were acceptable within the limits considered (800 ppm, 1000 ppm and 1500 ppm). The $PM_{2.5}$ measurements revealed significant concentrations primarily in dwellings occupied by smokers. Here the $PM_{2.5}$ concentrations regularly exceeded the WHO short-term guide value 15 µg/m^3. In non-smoking apartments, the indoor particle levels were generally lower than outdoor levels.

1.8. Retrofitting houses

The **HAVEN research project** (Health Impact Assessment of Energy Renovations on Irish Domestic Dwellings) investigated the health effects and benefits of energy renovations in Irish social housing. Coggins et al. analyzed indoor air quality measurements taken from a sample of Irish social housing properties before and after energy retrofits (Coggins, et al., 2024). The study highlighted that occupant behaviors, such as blocking wall vents and smoking indoors, can adversely affect indoor air quality. As part of the ventilation strategy, it is crucial to engage with tenants to identify the factors driving behaviors that contribute to poor indoor environmental quality. Given the vulnerability of many social housing residents, it is essential to ensure that retrofitting efforts do not compromise indoor air quality.

The **RENOVAIR project** investigated the impacts of energy renovations on airtightness, ventilation, thermal comfort, and indoor air quality (IAQ) in seventy social housing projects in France. Litvak presented the findings highlighting significant improvements in airtightness (Figure 15), particularly in homes transitioning from natural to humidity-controlled mechanical ventilation (CMV) (Litvak & Handtschoewercker, 2024). Post-renovation ventilation also improved with the installation of mechanical systems. While IAQ generally improved after renovations, temporary increases in VOC emissions were observed due to new building materials, and IAQ returned to pre-renovation levels over time. Thermal comfort varied, and the study recommended prioritizing living rooms for thermal comfort analysis, given their unique occupancy patterns compared to kitchens and bathrooms. The findings underscore the need to explicitly integrate airtightness, ventilation, and IAQ considerations into energy-efficient renovation strategies to ensure occupant health and comfort.

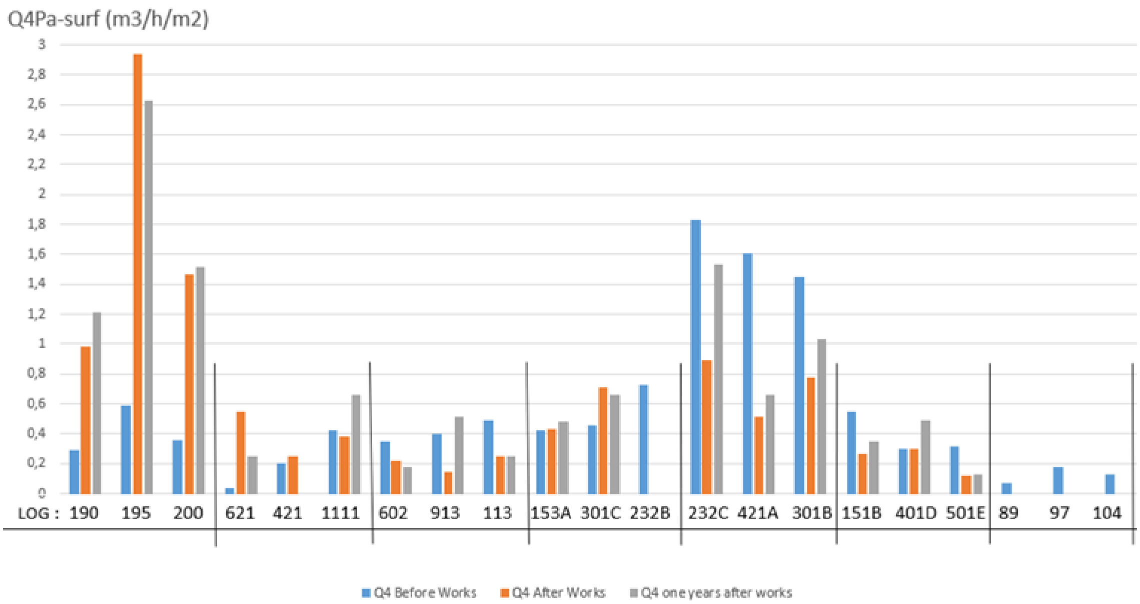

Figure 15: Comparison of air leakage rates (m3/h/m²) "before works"-BW (blue), "after works"-AW (orange) and "one year after works"-1yAW (grey) (Litvak & Handtschoewercker, 2024)

1.9. What is new in the EPBD recast 2024 with respect to indoor environmental quality and ventilation?

In the topical session **"**What is new in the EPBD recast 2024 with respect to indoor environmental quality and ventilation?", **Jaap Hogeling** (EPB Center) provided an overview of the EPBD recast's overall context (2024). This EPBD recast is an important legislative document as all EU member states have to transpose the requirements into national legislation.

CEN standards can play an important role in the implementation of the EPBD recast.

The EPBD recast gives increased attention to indoor environmental quality (IEQ) – thermal comfort, acoustics, visual comfort and indoor air quality. One of the requirements is the monitoring of IEQ in non-domestic buildings from May 2026 onwards (article 13.10). Bjarne Olesen (DTU Denmark) presented the activities related to CEN standards on IEQ (2024).

The EPBD recast also introduces requirements on inspection of ventilation systems in larger non-domestic buildings. Valerie Leprince (CEREMA France) elaborated on the CEN activities in relation to the inspection of ventilation systems (2024).

There are already countries with experiences about inspection of ventilation systems. Maarten De Strycker (BCCA – Belgium) presented the approach for residential buildings in the Flemish region whereby there is a systematic measurement of the air flow rates in new buildings (2024).

In the Netherlands, an overall approach for quality management is developed which also includes ventilation and IAQ related aspects. This was presented by **Wouter Borsboom** (TNO -Netherlands) (2024)

The implementation of the EPBD recast, particularly concerning IEQ and ventilation system inspections, presents challenges for many member states, whereby CEN standards can play an important role.

2. Airtightness & ventilation systems' inspection presentations

This chapter offers an overview of the main trends, ideas, and insights shared over the two-day conference, focusing particularly on building and ductwork airtightness as well as ventilation systems' inspection.

The "Airtightness" track at the conference was organised in 3 sessions, 1 of which was a topical session with a number of invited presentations:

1. Building airtightness
2. Durability of the building airtightness (Topical Session)
3. Ductwork & windows airtightness

The chapter is structured into four main themes:

1. Building & ductwork airtightness impact and guidelines
2. Durability of building airtightness
3. Building airtightness measuring methods
4. Inspection of ventilation systems.

2.1. Building & ductwork airtightness impact and guidelines

Roberts, Allinson, & Lomas (2024) examined the relationship between airtightness and infiltration, focusing on summertime conditions. Their study involved 34 blower door tests via depressurization (between January and March 2017) and 15 infiltration measurements taken throughout the summer using the CO_2 tracer gas decay method. The study revealed notable discrepancies between predicted infiltration rates (calculated using 11 different infiltration estimation methods) and actual summer infiltration rates (Figure 16). On average, the methods overpredicted measured infiltration rates by 64-208%. These findings highlight critical implications for the accuracy of overheating risk assessments, underscoring the need to account for these uncertainties in building design and modelling for summertime overheating resilience.

Using CONTAM simulations, **Roh, Lee, Lee, Lee, & Yeo** (2024) evaluated the impact of airtightness improvements—up to 80%—on pressure differentials and contaminant dispersion in temporary negative pressure isolation rooms (TNPI). The study found that elements like inter-room penetrations and ward doors significantly impacted pressure differentials, while exterior walls and inter-room penetrations were key factors in infection risk (Figure 17, Figure 18). Enhancing airtightness in critical areas, including inter-room penetrations, exterior walls, sliding doors, and ward ceilings, is recommended to improve performance in these temporary setups. The findings highlight the need for customized, project-specific interventions.

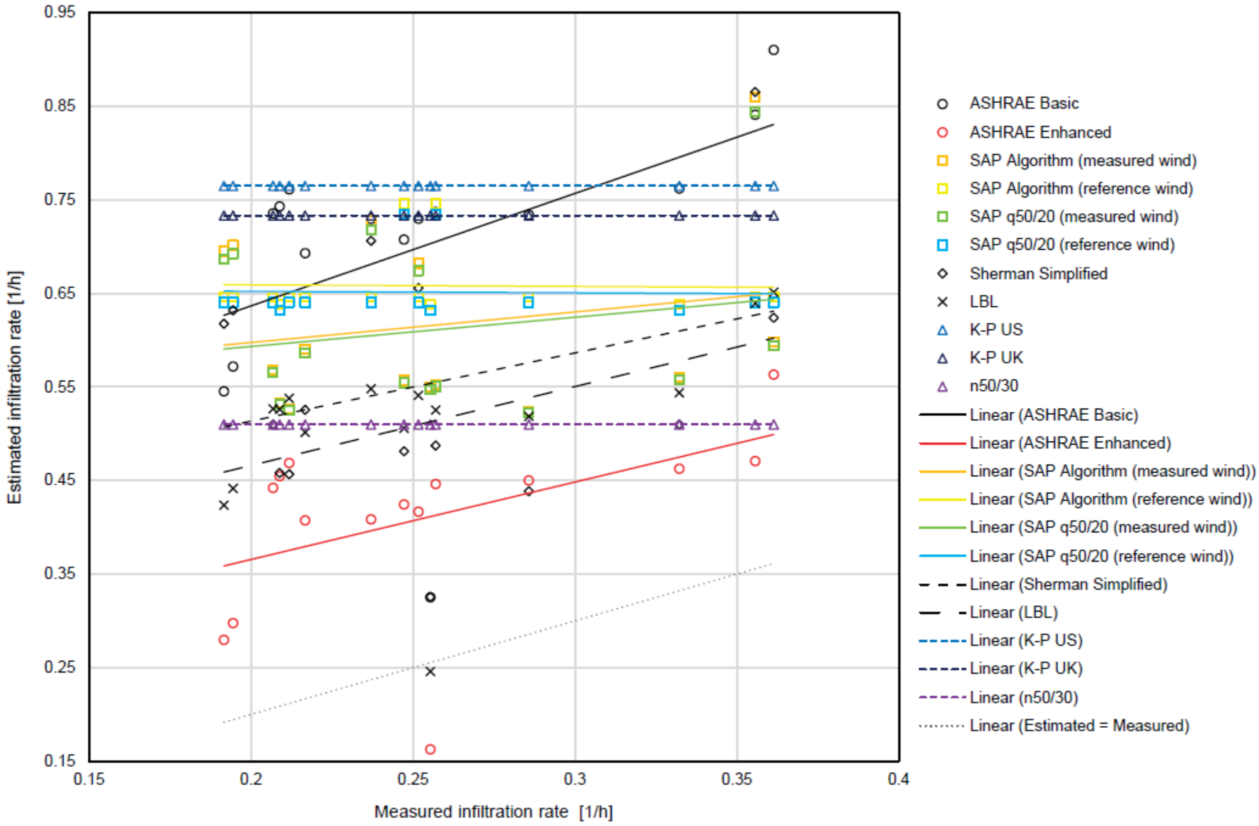

Figure 16: Measured infiltration rate plotted against estimated infiltration rate. Each data point represents one of the 15 tracer gas tests and the corresponding infiltration estimation method prediction (Roberts, Allinson, & Lomas, 2024)

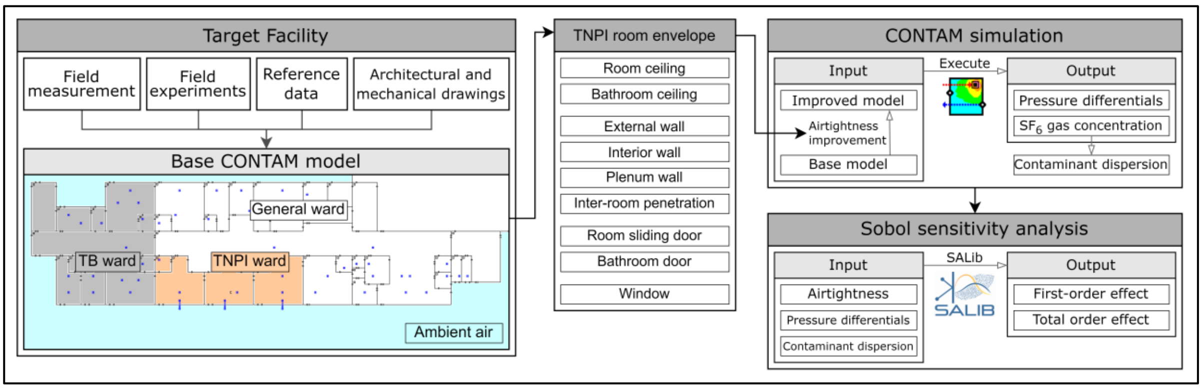

Figure 17: Schematic diagram depicting the methodology of the study (Roh, Lee, Lee, Lee, & Yeo, 2024)

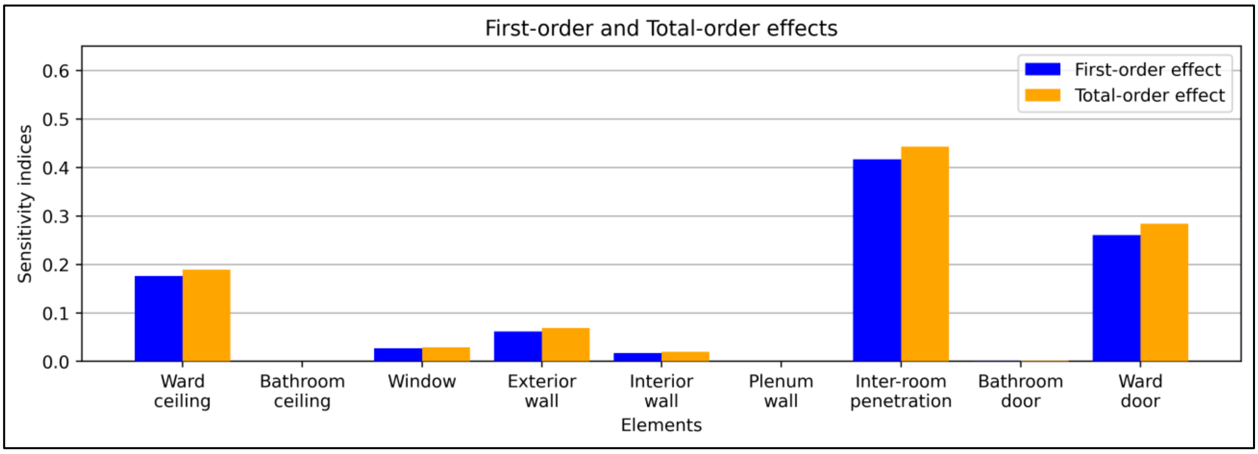

Figure 18: First-order and total-order effects of each element on the average pressure differentials of TNPI rooms (Roh, Lee, Lee, Lee, & Yeo, 2024)

Modera & Gord (2024) analysed energy and peak demand saving mechanisms across different types of duct systems, including exhaust, Constant Air Volume, and Variable Air Volume systems with different outdoor air (OA) controls (Figure 19)(Table 3). They examined savings mechanisms like fan power, OA conditioning, and peak power reduction, noting that savings from duct sealing vary significantly by application, with the largest factors being the operating hours of the system, the relief air fraction. Notably, substantial thermal conditioning savings (roughly 1/5 to 1/3 of savings) —independent of climate—are associated with the relief air fraction, especially beneficial in hospitals, where savings occur even when outdoor and relief airflows remain unchanged post-sealing.

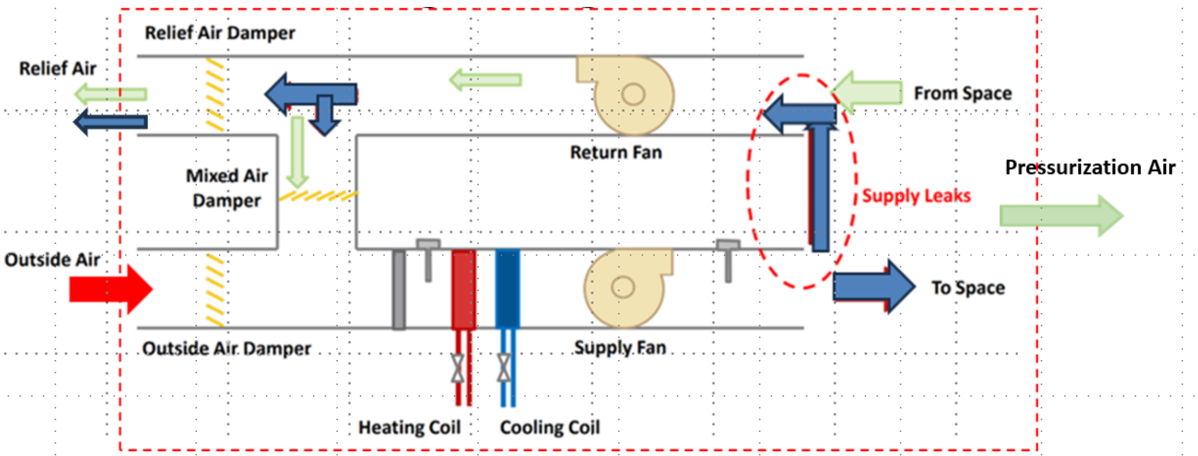

Figure 19: Schematic of Air Flow Pathways for CAV Supply System (Modera & Gord, 2024)

Table 3: Duct Sealing Impacts for Sealing 20% Supply Leakage for 23,600 l/s, 500 Pa system in NYC (Modera & Gord, 2024)

Application	Fan Power [kWh]	Fan-Heat Cooling [kWh]	Extra OA Cooling [kWh]	Total OA Cooling [kWh]	OA Heating [kWh]	Total Savings [kWh]
Office CAV Supply (fixed %OA)	33,638	10,659	1,702	3,938	47	49,984
Office CAV Supply (fixed OA, $\Delta P_{building}$)	33,638	10,659	0	2,236	0	46,533
Hospital CAV Supply (fixed OA, $\Delta P_{building}$)	133,942	31,273	0	53,426	0	218,641

The WTA (International Association for Science and Technology of Building Maintenance and Monuments Preservation) leaflet series, as presented by Rolfsmeier (2024) and scheduled for release by 2025, offers recommendations for achieving a defined quality of building airtightness when renovating existing buildings in Germany. These guidelines support planners, builders, and quality inspectors by (a) defining required airtightness levels for renovated buildings and building elements while establishing basic planning principles, (b) addressing planning details, sources of errors, construction options, and quality-check methods, and (c) focusing on suitable airtightness testing and leak detection methods, including guidance on building preparation and optimal testing timing.

2.2. Durability of building airtightness

During the topical session on “Building Airtightness Durability”, **Leprince** (2024)gave a brief introduction and presented key factors affecting the durability of building airtightness. According to the presenter, airtightness durability is influenced by several key factors, including product quality, where the resilience of sealants, tapes, and membranes is essential but can degrade over time due to aging, UV exposure, and moisture. Installation quality also plays a role, as e.g. inadequate use of sealing products can compromise durability. Environmental conditions during installation, such as temperature, humidity, and dust, may further impact airtightness durability. Additionally, occupancy effects, like regular use, the opening and closing of doors and windows, furniture installation, and retrofit activities, can affect airtightness over time. Finally, building/airtightness layer movement due to settlement or wind can reduce its long-term effectiveness.

As part of the **Durabilitair2 Project**, Litvak, Handschoewercker, Berthault, & Mathieu (2024) explored the impact of dust on adhesion surfaces which can degrade the performance of air sealing over time (Figure 20, Figure 21, Figure 22). Their research assessed the feasibility of an experimental weight measurement method to quantify dust levels on surfaces used for air sealing applications. While the method is suitable for quantifying floor dust, it is less effective for vertical surfaces due to higher uncertainties. Further investigation is needed to enhance reliability, with careful consideration of factors like adhesive properties and environmental conditions to address various uncertainties.

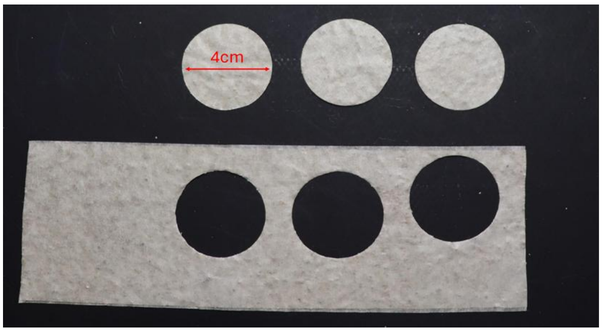

Figure 20: Preparation of samples taken on site (Litvak, Handschoewercker, Berthault, & Mathieu, 2024)

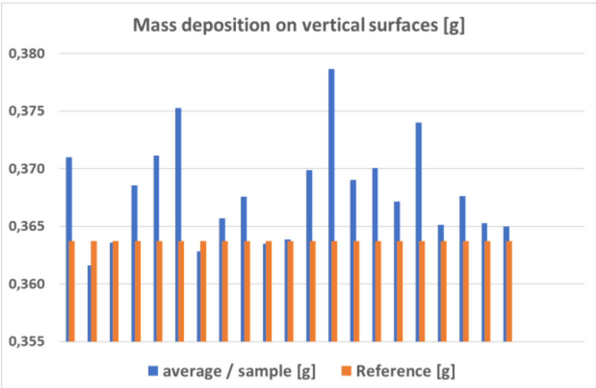

Figure 21: Mass deposition by samples on vertical surfaces (Litvak, Handschoewercker, Berthault, & Mathieu, 2024)

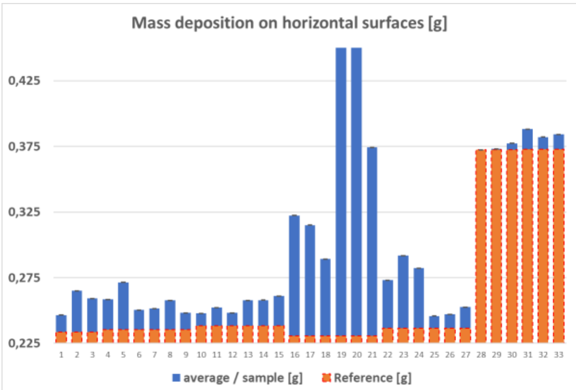

Figure 22: Mass deposition by samples on horizontal surfaces (Litvak, Handschoewercker, Berthault, & Mathieu, 2024)

Another presentation by **Prignon** (2024), focused on the HAMSTER bi-climatic chamber, installed in Brussels in 2022 and designed to assess the airtightness of building components in various conditions including, but not limited to, its durability (Figure 23). The HAMSTER chamber's dual climate zones-hot (simulates interior conditions) and cold (reproduces exterior climate)-enable precise replication of external and internal building environments, including also features to reproduce rain, pressure difference or infrared radiations. This setup allows measuring airtightness performances in specific climatic conditions and assessing the durability of building components through accelerated ageing.

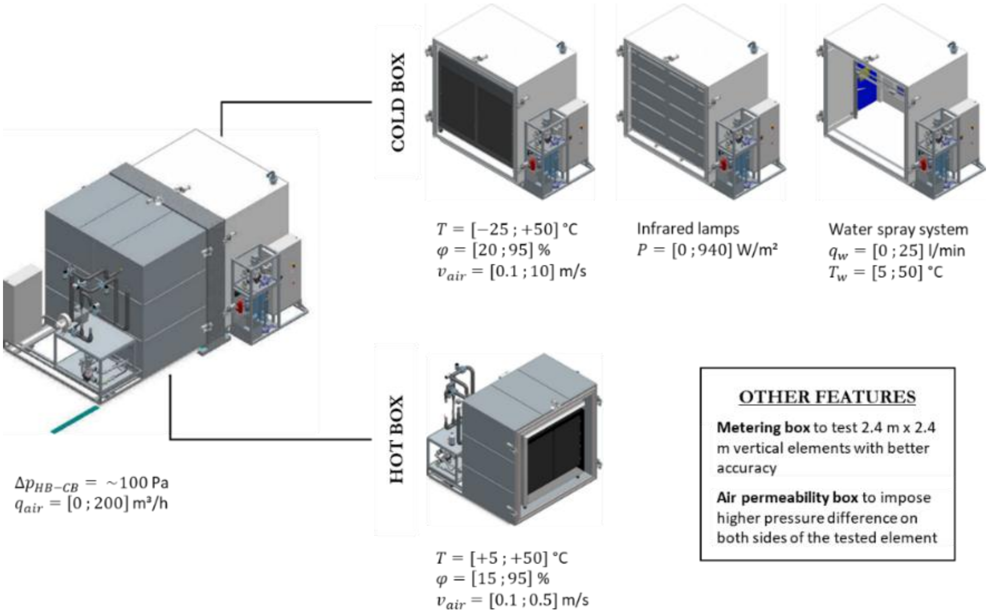

Figure 23: Features for HAMSTER equipment (Prignon, 2024)

The **TightEN project** carried out in the years 2019-2022, aimed to highlight and strengthen the research on adhesive tapes and develop test methods adequate in the cold climate conditions to ensure a proper durability of sealing solutions over time so that energy efficiency is maintained throughout buildings' lifetime (Kolstad Linløkken & Dorota Hrynyszy, 2024). A new testing methodology, addressing local Norwegian conditions, was proposed to evaluate the long-term performance of tape products and systems for air-sealing application in buildings with sufficient accuracy, reproducibility, and repeatability. This method measures air permeability using a Test Stand and assesses durability by comparing permeability rates before and after artificial aging (Figure 24). Unlike existing methods, it directly measures permeability, though results vary with the quality of specimen application. The approach effectively verifies whether tapes meet specific permeability thresholds.

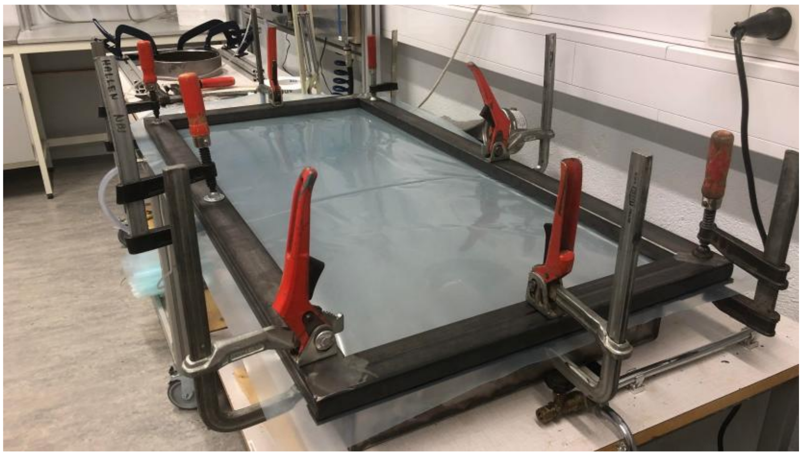

Figure 24: Test Stand leakage evaluation setup (Kolstad Linløkken & Dorota Hrynyszy, 2024)

A paper by **O'Brien & Artigas** (2024) reviewed research on the long-term durability of air barrier systems, with a focus on wall membranes and fenestration systems (Figure 25, Figure 26). Their study used energy modelling of a typical large building at various air leakage rates to assess potential impacts on energy use. Their results showed that current code requirements for air barrier systems performance are practical and achievable with today's materials and industry knowledge. Exceeding air leakage beyond these requirements appears to have a minimal impact on energy use; however, air barrier durability is crucial for condensation control and overall building enclosure performance. The authors recommend further research into accelerated material weathering, field studies, and over time comparisons of actual air leakage.

Figure 25: Breach in fluid-applied air barrier (O'Brien & Artigas, 2024)

Figure 26: Mold growth on interior wall and damaged carpet due to air and water leakage (O'Brien & Artigas, 2024)

2.3. Building airtightness measuring methods

Ordinary Least Squares (OLS) regression, the standard method recommended by ISO 9972 for building airtightness tests, faces reliability issues under fluctuating wind conditions. To address these challenges, **Kölsch & Leprince** (2024) proposed improvements to the regression method and uncertainty calculation. Their study evaluated three methods-OLS, Weighted Least Squares (WLS), and Weighted Line of Organic Correlation (WLOC)-using data from over 6,000 blower door tests across various house configurations (Figure 27, Figure 28, Figure 29, Figure 30). While all methods showed similar accuracy in predicting the airflow at 50 Pa, WLS and WLOC_2 outperformed OLS at 4 Pa under high wind speeds, with WLS offering the most reliable uncertainty estimates. These findings support incorporating weighted regression methods into airtightness testing standards.

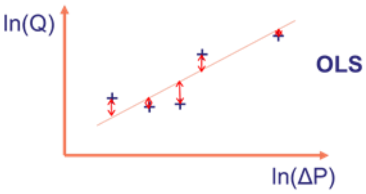

Figure 27: Schematic representation of regression techniques methodology for OLS (Kölsch & Leprince, 2024)

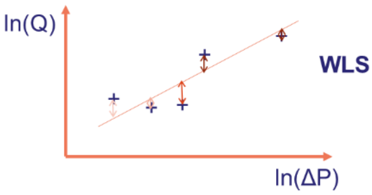

Figure 28: Schematic representation of regression techniques methodology for WLS (Kölsch & Leprince, 2024)

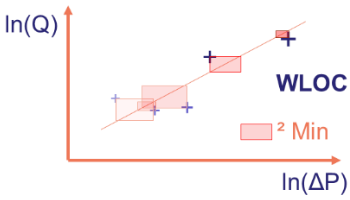

Figure 29: Schematic representation of regression techniques methodology for WLOC (Kölsch & Leprince, 2024)

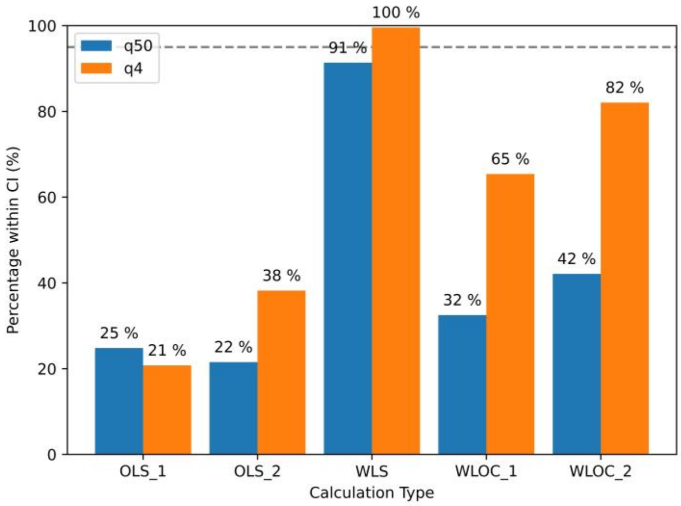

Figure 30: Total percentage per type of regression where mean values of calculated airflows at 50 Pa and 4 Pa fall into the 95% confidence interval (Kölsch & Leprince, 2024)

Prignon, Delmotte, & Kölsch (2024) investigated the uncertainty associated with estimating the zero-flow pressure difference in the fan pressurization method, a technique used to measure building airtightness according to the ISO 9972:2015 standard. This method assumes a constant zero-flow pressure difference throughout the test, with the value calculated as the average of pre- and post-test measurements; however, this assumption introduces some uncertainty. The authors used two different datasets to assess the reliability of an existing formula proposed in the literature for calculating this uncertainty, explored variations in the measurement protocol to reduce it, and evaluated the impact of this uncertainty source on the final result of the fan pressurization test. Their findings indicated that uncertainty, which can affect overall test accuracy, can be minimized by increasing the number of measurements or employing a multiple-estimator approach. Future research should aim to incorporate additional datasets to address certain limitations of this study and to develop alternative procedures that could further reduce this source of uncertainty.

A study by **Tountas** (2024) investigated the air permeability of windows and doors installed in buildings in Athens, Greece, highlighting discrepancies between the manufacturers' declared air permeability classifications and the classification measured on-site (Figure 31). Through testing 40 windows and doors across both new and retrofit projects, the study found that nearly 95% of installations performed below the manufacturer-stated airtightness classifications, primarily due to installation practices that fail to maintain factory standards. Results showed that the airtightness of frames often decreases by more than 50% once installed, significantly impacting energy efficiency and leading to energy losses contrary to the consumer's investment in high-performance products. The findings emphasize the need for updated regulations mandating airtightness checks during installation to ensure consistent energy savings and CO_2 reduction goals.

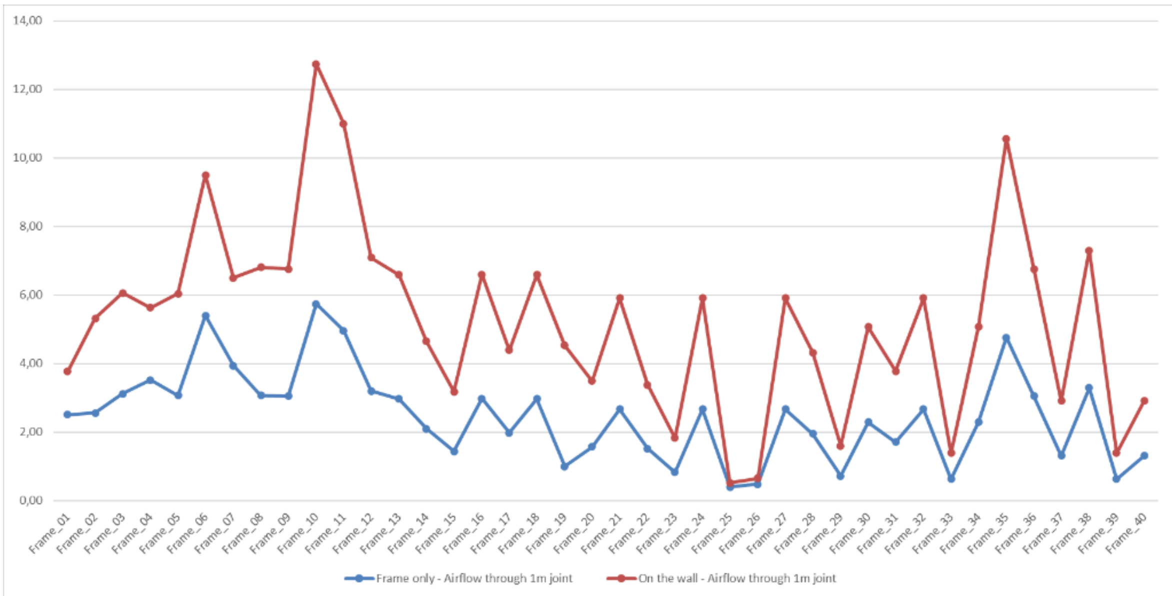

Figure 31: Airflow through 1m joint (Tountas, 2024)

A literature review by **Prignon** (2024) examined 43 studies -published between 1930 and the present- on window airtightness measurements to identify trends and gaps in current knowledge. The findings highlight the lack of standardized reporting, the limited number of reported results and the bad repartition among studies which make it difficult to draw solid conclusions, especially for in-situ measurements. Despite these limitations the review found that existing windows generally exhibit significant air leakage, with performance declining over time compared to newly installed windows. The study revealed that in-situ tests yield poorer airtightness results than laboratory tests, largely due to factors like the window-wall interface, the deterioration over time and the deterioration during installation. Additionally, sliding windows perform worse than other types of windows while windows with steel or aluminium frames exhibit poorer airtightness compared to wood-framed windows. Since the arrival of weather-stripped windows, there is no clear improvement of the windows airtightness over time, in either laboratory or in-situ settings. The study suggests acquiring data from further in-situ measurements on existing windows, with standardized measurements that account at least for variables such as window frame materials, opening mechanisms, the period of construction of windows and the year of testing.

Pedranzini (2024) proposed a revised model for estimating air leakage in HVAC systems, addressing limitations in current standards, which are based on one-point measurement with a fixed leakage exponent. The study highlighted issues with the Duct Air Leakage Test (DALT) model (widely used since the 80s), which inaccurately assumes a leakage exponent of 0.65, causing substantial errors in leakage and energy loss estimations among others (Figure 32). The author proposes an advanced model that uses multi-point measurements to better capture leakage behaviour. The findings highlight the need for updated standards that align with the capabilities of current technology and building requirements.

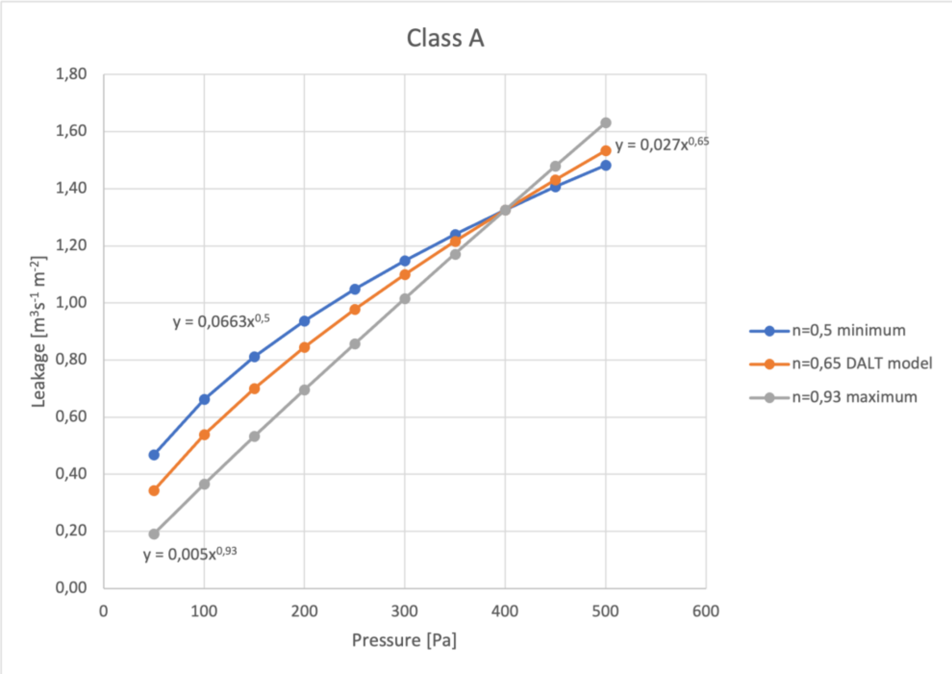

Figure 32: Comparison of systems with exponents other than n=0,65 (Pedranzini, 2024)

Diel, Schiricke, & Pernpeintner (2024) introduced a new test facility developed to improve the accuracy of acoustic and thermographic methods for detecting air leaks in building envelopes (Figure 33). Initial experiments showed that an acoustic camera could reliably locate leaks of varying hole sizes and measurement distances demonstrating a correlation between the maximum sound pressure level and the hole size. Meanwhile, thermographic imaging identified leaks smaller than the camera's pixel resolution, even at greater distances and shallower incidence angles. These findings support the feasibility of using both methods in detecting and quantifying leaks, with future work aimed at refining detection in more complex leak scenarios.

Figure 33: Test facility ATLAS equipped with its requisite measurement technology: Minneapolis DuctBlaster with Micro Leakage Meter (left), loudspeaker (inside), microphone array (right) and infrared camera (right) (Diel, Schiricke, & Pernpeintner, 2024)

An optimized methodology has been introduced for characterizing infiltration airflow in buildings through controlled air inlets using infrared (IR) thermography. Developed by **Tamayo-Alonso, Poza-Casado, Padilla-Marcos, Mercado, & Meiss** (2024), the method employs a three-dimensional matrix setup to capture a single IR thermal image, creating a 3D visualization of airflow and significantly reducing test time compared to traditional multi-image techniques (Figure 34, Figure 35, Figure 36, Figure 37). Conducted in a controlled environment, this approach minimizes potential errors from temperature or pressure fluctuations during measurements, as well as from camera location variation due to limited battery life. Results demonstrate the method's effectiveness for real-time applications, paving the way for further research in areas such as leakage quantification, in-situ evaluation of operating regime of ventilation grids, and validation of CFD systems.

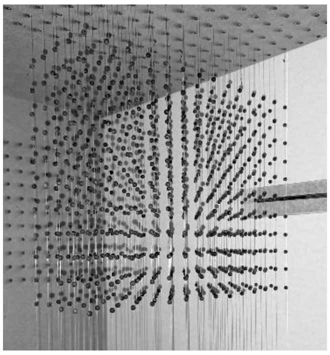

Figure 34: 3D Matrix (Tamayo-Alonso, Poza-Casado, Padilla-Marcos, Mercado, & Meiss, 2024)

Figure 35: Set-up of the experiment (Tamayo-Alonso, Poza-Casado, Padilla-Marcos, Mercado, & Meiss, 2024)

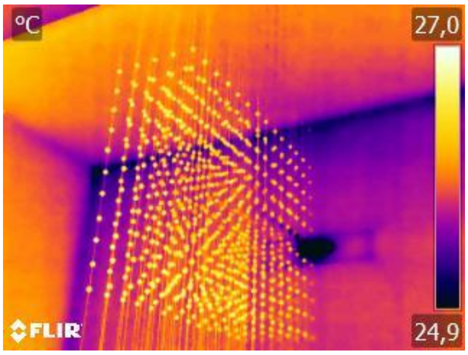

Figure 36: Thermal image of the airflow (Tamayo-Alonso, Poza-Casado, Padilla-Marcos, Mercado, & Meiss, 2024)

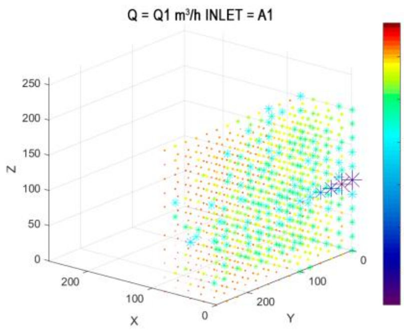

Figure 37: 3D representation of half the airflow (Tamayo-Alonso, Poza-Casado, Padilla-Marcos, Mercado, & Meiss, 2024)

Deprez, Verniers, Pollet, Bink, & Laverge (2024) investigated the variability of reference air pressure differences used to assess airtightness in 2 case studies in Belgium. Their study focused on a two-storey single-family home and a 14-storey student high-rise, applying various test methods to measure airtightness and differential pressure. The single-family home was tested using Blowerdoor, ACIN Air Tightness Tester, and Pulse methods, revealing greater variations in results at 50 Pa compared to 4 Pa, especially for the Pulse test. Additionally, simultaneous air pressure difference and wind measurements were conducted on both building façades. The study found that even with a mechanical extract only ventilation system the air may go out though inlets at 90% of the time (Figure 38, Table 4). Overall, the findings highlighted significant wind and stack effects on pressure distribution and demonstrated the need for pressure-regulated vents due to pressure variability.

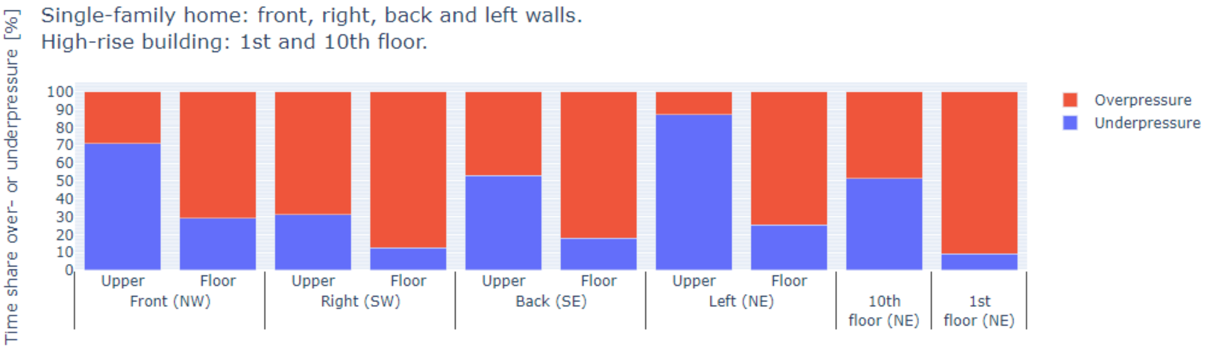

Figure 38: Time distribution between over- and under pressure conditions at each measurement point (Deprez, Verniers, Pollet, Bink, & Laverge, 2024)

Table 4: n50 and air leakage rates at 50 and 4 Pa for three airtightness test methods. Converted values in italics (Deprez, Verniers, Pollet, Bink, & Laverge, 2024)

Air tightness test method	Flow exponent n	Air leakage rate [m³/h] 50 Pa	4 Pa	n_{50} [1/h]
Blowerdoor (under- & overpressure)				
2019: underpressure	0.690	965	*169*	1.6
2019: overpressure	0.780	978	*136*	1.7
2019: average	0.735	972	*153*	1.7
2023: underpressure	0.615	1314	*278*	2.2
2023: overpressure	0.671	1333	*245*	2.3
2023: average	0.643	1324	*262*	2.3
ATT (underpressure): 2023				
Test 1 downstairs: $q_{extract}$ = 326 m³/h; Δp=5.1 Pa	0.660	*1471*	278	2.5
	0.615	*1327*	281	2.3
Test 2 downstairs: $q_{extract}$ = 326 m³/h; Δp=5.2 Pa	0.660	*1452*	274	2.5
	0.615	*1311*	277	2.2
Test 3 upstairs: $q_{extract}$ = 326 m³/h; Δp=6.1 Pa	0.660	*1307*	247	2.2
	0.615	*1189*	252	2.0
Test 4 upstairs: $q_{extract}$ = 326 m³/h; Δp=6.0 Pa	0.660	*1321*	249	2.3
	0.615	*1201*	254	2.0
Pulse (overpressure): 2024				
Test 1: downstairs		*1450*	265	2.5
Test 2: downstairs		*1712*	317	2.9
Test 3: downstairs		*1676*	310	2.9

2.4. Inspection of ventilation systems

The topical session on “Ventilation regulations in various countries” introduced the new series of Ventilation Information Papers by the AIVC focusing on trends in building ventilation requirements and inspection in Spain, Ireland, Belgium & France.

Linares-Alemparte, García-Ortega, & Feldman (2024), highlighted the evolution of Spain’s ventilation regulations over the past two decades, driven by greater focus on indoor air quality (IAQ), energy efficiency, and environmental policies. The main regulatory frameworks, CTE (Código Técnico de la Edificación) and RITE (Reglamento de Instalaciones Térmicas de los Edificios), mandate IAQ and ventilation standards for residential and non-residential buildings. While older dwellings predominantly used natural ventilation, all new constructions since 2006 require mechanical or hybrid systems, with hybrid systems being the most common, followed by single-flow mechanical systems, and, in advanced cases, double-flow systems with heat recovery. For non-residential buildings RITE sets mandatory requirements on ventilation establishing 5 different methods for the calculation of the needed outdoor rate: airflow per occupant indirect method, airflow per net floor area indirect method, perceived air quality direct method, CO_2 concentration direct method, and dilution method. According to a market analysis carried out by AFEC (Air Conditioning Equipment Manufacturers Association), from 2021 to 2022, the market for air distribution and diffusion rose by 19.7% and Air Handling Units and Ventilation Units by 10%. As regards the inspection of ventilation systems, RITE regulates initial and periodic assessments of ventilation systems covering all buildings with thermal installations to be carried out by authorised companies or inspection entities. HVAC systems should undergo inspections every four years, and thoroughly checked every fifteen years.

In Ireland, ventilation requirements for new constructions and major renovations are governed by the Building Regulations, Part F, last updated in 2019, to enhance energy performance and indoor air quality (**Coggins, McIntyre, Jones, & McGrath**, 2024). Section 1.2 of Technical Guidance Document (TGD) F deals with ventilation methods for new dwellings and extensions including continuous mechanical extract ventilation, mechanical ventilation with heat recovery and natural ventilation (no longer common). Section 1.3 of TGD F deals with ventilation methods for buildings other than dwellings, in particular, offices and car parks. Requirements for inspection of ventilation systems are mandatory (for residential dwellings) and are covered in the National Standards Authority of Ireland Ventilation Validation Registration Scheme.

Belgium's ventilation requirements for buildings are found in national ventilation standards & health regulations, as well as regional environmental & EPB regulations. Since 2006, it has been mandatory for all new and renovated residential and non-residential buildings needing a permit, to install a natural or mechanical ventilation system for acceptable indoor air quality. **Janssens, De Jonge, De Strycker, & Van Gelder** (2024), reviewed the present ventilation requirements, market trends, energy and inspection requirements, innovations, and COVID-19's impact (Figure 39, Figure 40, Figure 41). While national guidelines and standards exist, regional differences exist in building energy performance regulation, including ventilation requirements, i.e. Flanders, Brussels Capital, and Wallonia which have unique aspects, especially in inspections. The Regional decrees on EPB refer to Annexes which specify the residential & non-residential ventilation requirements according to the Belgian standard NBN D50-001 (1991) and NBN EN 13779 respectively. A mandatory quality framework with on-site performance checks has been implemented in Flanders since 2016 featuring ventilation pre-design before the start of construction, ventilation performance report after installation, measurements of mechanical ventilation flow rates, and, if possible, measurement of fan power. These tasks must be conducted by a qualified individual using appropriate measurement equipment and may be performed by someone involved in the project or an independent party. Additionally, a control body audits 10% of inspections during or soon after they are completed to ensure compliance.

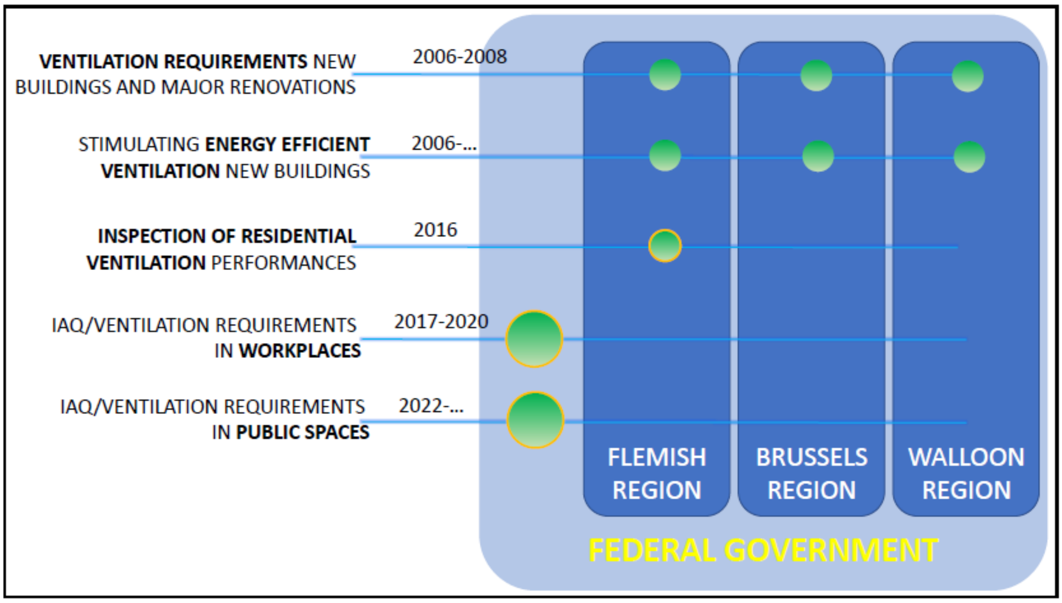

Figure 39: (Janssens, De Jonge, De Strycker, & Van Gelder, 2024)

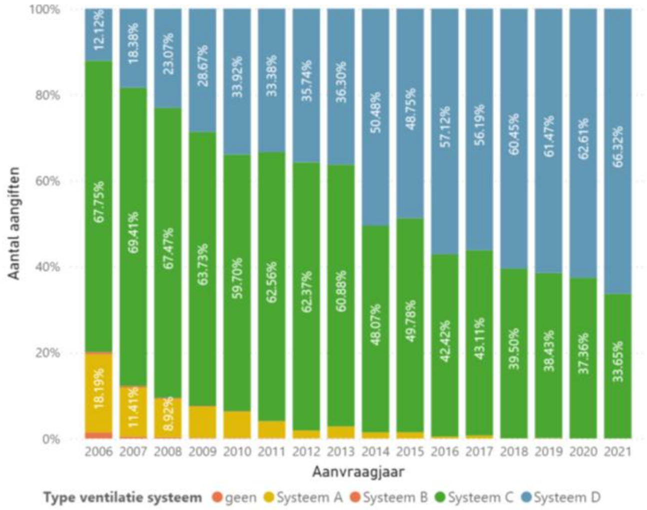

Figure 40: Evolution of the distribution of the type of ventilation systems in new dwellings in Flanders, Belgium between 2006 and 2021 (year of building permit), all dwellings combined (Janssens, De Jonge, De Strycker, & Van Gelder, 2024)

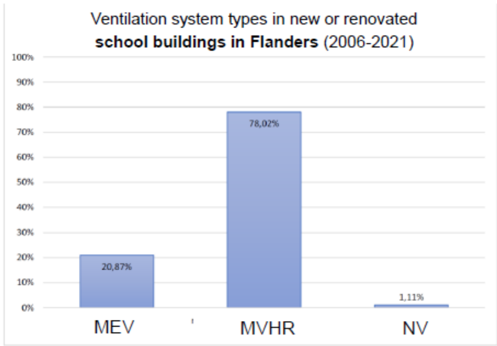

Figure 41: Ventilation system types in new or renovated school buildings in Flanders (Janssens, De Jonge, De Strycker, & Van Gelder, 2024)

French regulations for residential building ventilation have been in place since 1982, mandating mechanical ventilation systems to ensure continuous air renewal, adjustable air inlets, and air exhausts in key rooms among others (**Leprince, Guyot, & Mouradian**, 2024). Currently, around 95% of new residential buildings with exhaust-only ventilation are equipped with a humidity-based demand control system (Figure 42). Since January 2023, the RE2020 regulation requires mandatory inspections of the ventilation systems at commissioning for all new residential buildings, conducted by qualified testers and documented on an online platform. In contrast, regulations for non-residential buildings, dating back to 1979, do not impose the installation of ventilation systems as a prescriptive requirement; compliance is achieved if adequate air renewal is provided, which may involve a significant window area proportional to the floor area. However, inspections for non-residential buildings remain optional, even though more than half include some form of ventilation system.

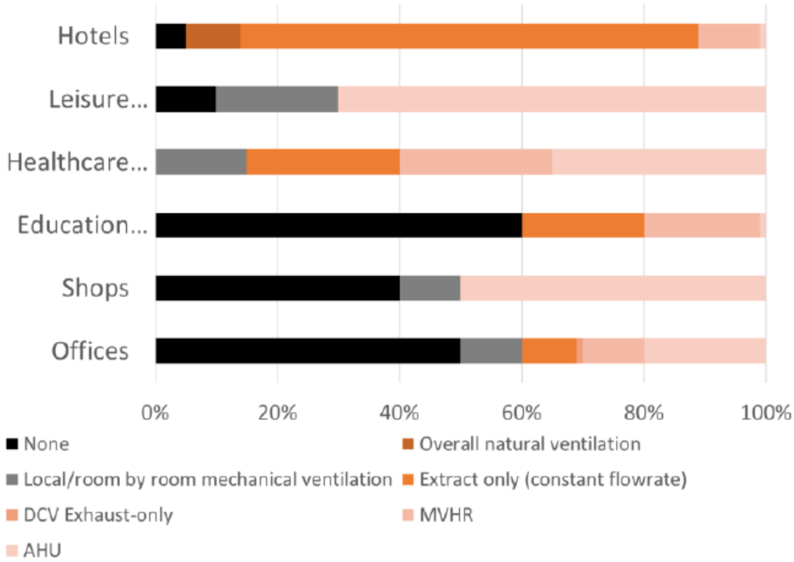

Figure 42: Ventilation Systems in the French Market for non-residential buildings (Leprince, Guyot, & Mouradian, 2024)

During the topical session: “What is new in the EPBD recast 2024 with respect to indoor environmental quality and ventilation?” **Leprince** (2024) presented the revised EPBD’s new requirements on the inspection of ventilation systems and highlighted existing gaps. Regarding the commissioning of smart systems, the presenter pointed out the need for a system-specific reception protocol to be designed concurrently with the system, as well as the importance of establishing maintenance protocols that take advantage of connected systems to trigger maintenance operations. For IAQ inspection they recommended a standardized commissioning measurement protocol, with clear specifications for the type of measurement, sensor position & specification, and measurement duration. Furthermore, they emphasized the value of continuous monitoring to assess the robustness and resilience of ventilation systems.

The discussions and research showcased at the conference highlighted significant advancements and ongoing challenges in building and ductwork airtightness, ventilation system inspections and more. We encourage participants to join our future conferences to stay informed and engaged with the latest developments in the fieldOutdoor conditions-based strategies.

3. Resilient ventilative cooling presentations

This chapter offers an overview of the main trends, ideas, and insights shared over the two-day conference, focusing particularly on resilient ventilative cooling.

The "Resilient Ventilative Cooling" track at the conference was organised in 7 sessions, 4 of which were topical sessions with a number of invited presentations:

1. Ventilative Cooling – latest and greatest. Importance of early design in the world of overheating mitigation using ventilative cooling (Topical Session)
2. Climate change resilience
3. Resilient Indoor Thermal Environments: Findings & Future Policy from an Irish National Study on Non-Residential Buildings (Topical Session)
4. Natural ventilation & cooling
5. ReCOver++: Improving resilience of buildings to overheating (Topical Session)
6. State of the art of Personalized Environmental Control Systems (PECS) (Topical Session)
7. Natural Ventilation analysis

The chapter is structured into four main themes:

1. Ventilative cooling & resilient cooling design
2. Thermal resilience assessment
3. Natural ventilation
4. Personal Environmental Control Systems

3.1. Ventilative cooling & resilient cooling design

During the topical session "Ventilative cooling – latest and greatest. Importance of early design in the world of overheating mitigation using ventilative cooling" **Plesner & Roth** (2024) presented the latest content of the upcoming European Technical Specification (CEN/TS) called "Ventilative cooling systems – Design". O'Sullivan (2024) and Frei (2024)contributed to the session by sharing insights on a ventilative cooling design process and "the cooling ladder".

This CEN/TS sets the framework for designing ventilative cooling systems able to cope with the set criteria, from the early feasibility phase to the actual design phase for both residential and non-residential buildings (Figure 43, Figure 44). Furthermore, the document is a "system design" document much like prEN15665 (under revision) and EN 16798-3 referencing existing EPBD standards e.g. thermal comfort criteria from EN 16798-1 or national regulations. The document serves as an important reference for prEN 16798-1-2 (thermal comfort) providing guidance on designing buildings without mechanical cooling while aligning with the chosen IEQ requirements; it is currently the only available document in Europe explaining how to design ventilative cooling systems. The core features of the document are:

8 design steps - to follow when designing free cooling systems

- ✓ Cooling ladder ethos – prioritising passive cooling solutions before moving to active cooling measures (Figure 45)
- ✓ Ventilative cooling potential method – that assesses outdoor air-cooling potential in the early design phase
- ✓ Flow diagram – enabling a simplified overview of the design steps and cooling ladder ethos including which choices to make
- ✓ Resilience checks – enabling checks to enhance readiness for future extreme weather events (probably the first standard to include this)
- ✓ Renewable energy for cooling calculations using ventilative cooling – as found in Renewable Energy Directive (RED II).

During the discussion part of the session, important conclusions were drawn such as the importance of correct formulas to quantify thermal mass, the significance of micro-climate considerations at different design stages, the significance of climate data to assess ventilative cooling properly etc.

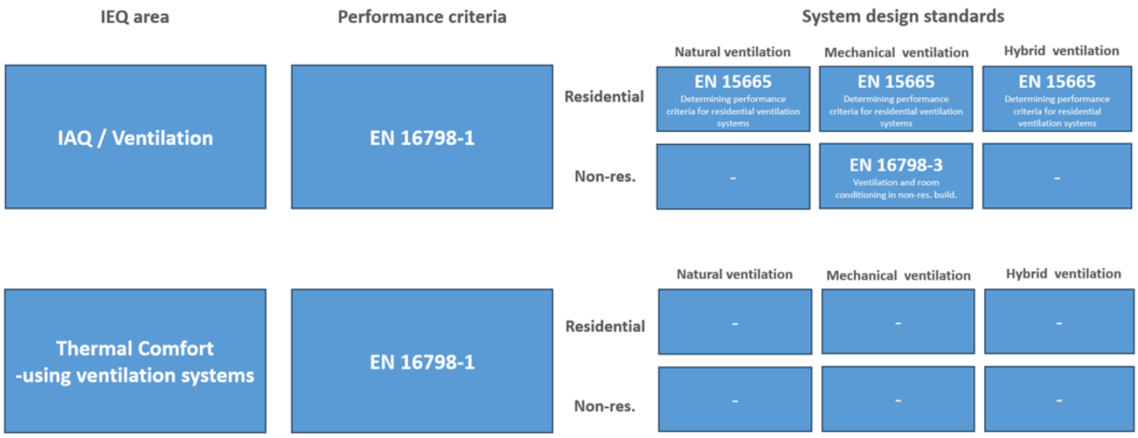

Figure 43: Lack of standards for system design of ventilative cooling (Plesner & Roth, 2024)

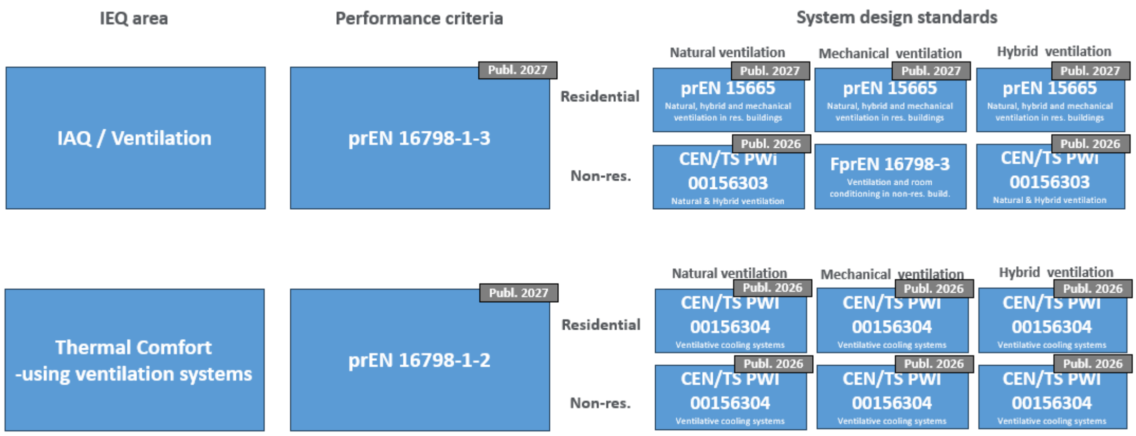

Figure 44: Upcoming standards for ventilative cooling (Plesner & Roth, 2024)

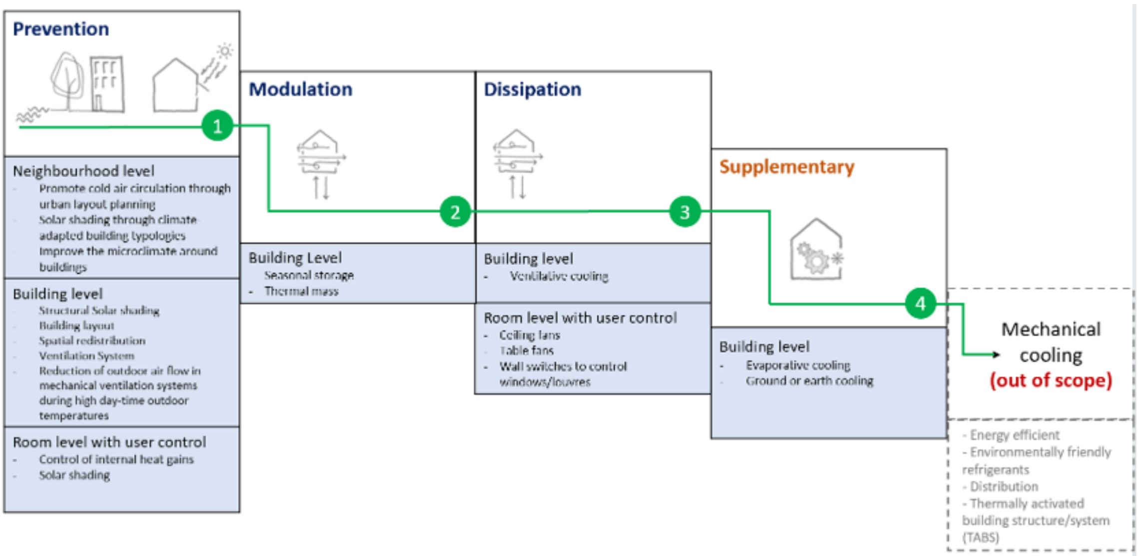

Figure 45: The Cooling Ladder: A design ethos for VC designers (O'Sullivan P. , 2024)

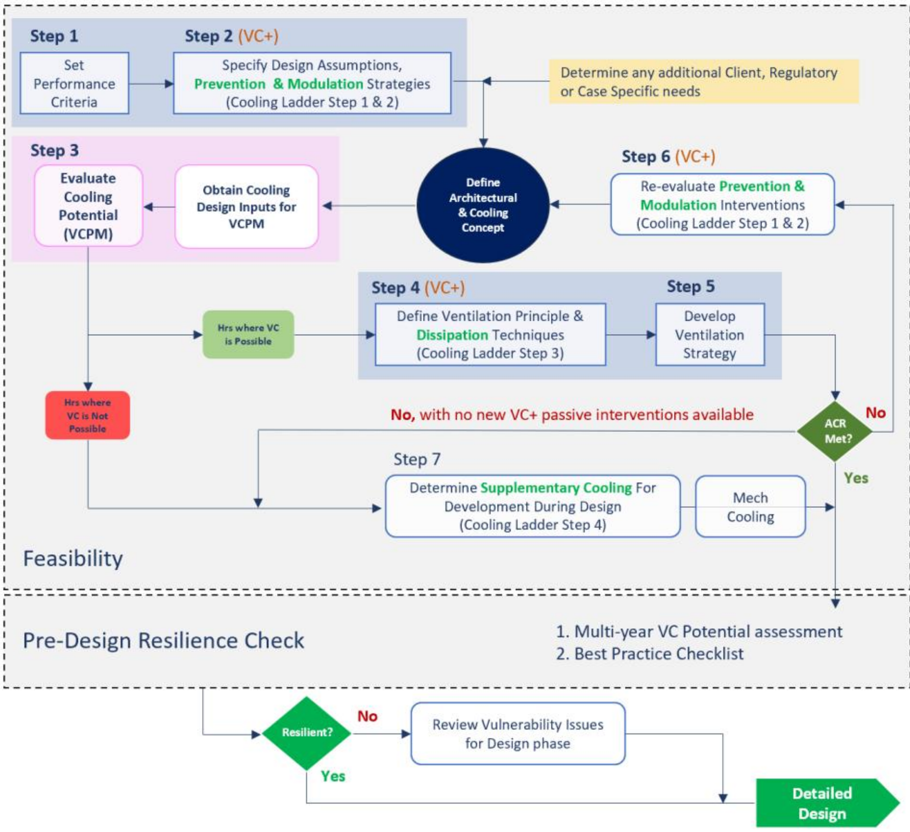

Figure 46: Early-stage design process for evaluation of ventilative cooling potential (O'Sullivan P. , 2024)

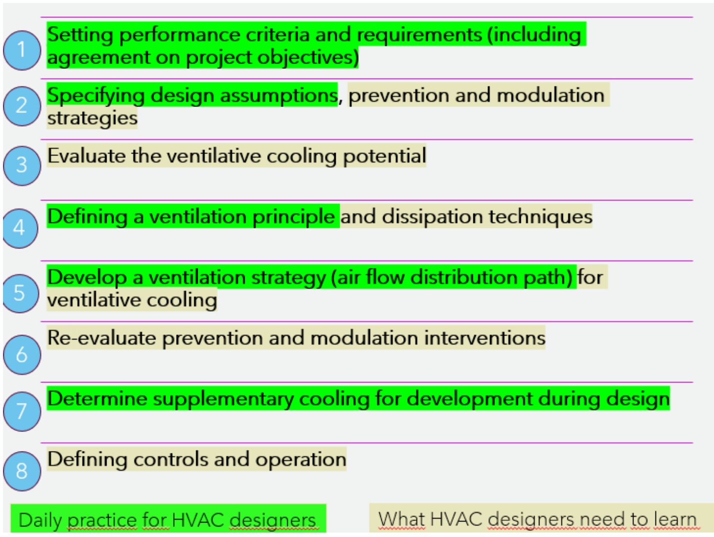

Figure 47: The eight-steps design process of ventilative cooling systems – Daily practice for HVAC designers/What HVAC designers need to learn (Frei, 2024)

The topical session "Resilient Indoor Thermal Environments: Findings & Future Policy from an Irish National Study on Non-Residential Buildings" discussed results from the three-year Project RESILIENCE, which investigated indoor thermal resilience and overheating risks in 33 high performance low-energy non-residential buildings in Ireland (schools, offices, and healthcare buildings) (**O' Sullivan,** 2024).

The session explored policy implications, building vulnerabilities, and the need for improved regulatory measures to enhance thermal resilience. Session discussions also focused on how thermal failure for indoor environments could be defined in practice as well as the role and responsibilities of the designer in mitigating future heat stress events in buildings as part of their designs. Initial findings from the project showed that while Irish schools appear resilient to future ambient warming, there are some warning signs that healthcare and offices are more vulnerable (**O' Donovan**, 2024).

Declercq & Holvoet (2024) investigated thermal resilience to overheating through climate-responsive architectural design, focusing on two real-life non-residential case studies modelled and simulated under future weather conditions, including shocks. They evaluated the impact of several architectural building features such as thermal mass, natural ventilative cooling strategies and different mechanical cooling strategies influencing the resilience to overheating under extreme conditions. Their findings, identified glazing ratio, shading, thermal mass, and ventilative cooling as key architectural factors, with shading and ventilative cooling proving highly effective, while thermal mass had a lesser impact during prolonged heatwaves. Overall, climate-responsive strategies, such as reducing glazing ratios, adding shading, and employing ventilative cooling, effectively reduce cooling energy demands and enhance resilience to heatwaves.

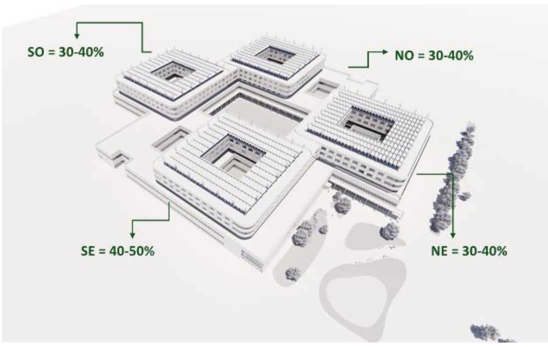

Figure 48: Solarloads on the facade (Declercq, 2024)

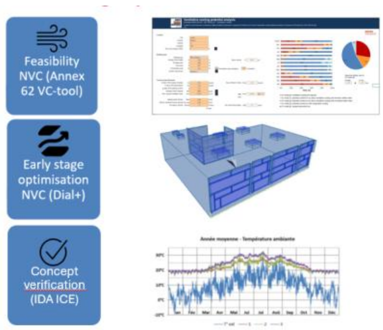

Figure 49: The design process (Declercq, 2024)

3.2. Thermal resilience assessment

Roccamena, et al. (2024) presented a method for assessing the resilience of social housing in Paris to current and future heat waves, considering the impact of climate change. Applied to 60,000 dwellings managed by RIVP (Régie Immobilière de la Ville de Paris), it quantifies the risk of heat-related health impacts for the tenants based on temperature thresholds (27°C at night, 30°C during the day) and projects their recurrence across different timelines (present, near future-2040, distant-future 2080). Dwellings are categorised into three groups based on how frequently the climatic conditions that deteriorate their thermal performance are exceeded within a given timeframe (Table 5): those where such conditions occur once every ten years or less, less than once annually, and more than once annually. The study underscores the significant advantages of window solar protection while highlighting the crucial role of nighttime ventilation in lowering indoor temperatures. However, despite the effectiveness of employing passive solutions, the findings reveal that maintaining nighttime temperature thresholds is still challenging due to heat evacuation difficulties, which are further intensified by increasing outdoor temperatures driven by global warming.

Table 5: Number of times each type of dwelling exceeds its outside limit required conditions in the present, near future, and distant future (Roccamena, et al., 2024)

	Outside limit required conditions				
	2006 - 1	**2017 - 1**	**2015 - 1**	**1983 - 2**	**2017 - 2**
Type and period of construction of the dwellings becoming faulty	"Vulnerable" dwellings before refurbishment: – before 1918 – 1918-1955 – 1960-1974 – 1975-1999 "Vulnerable" dwellings after refurbishment: - 1918-1955	"Typical" dwellings before refurbishment: – 1918-1955 – 1960-1974 – 1975-1999 "Vulnerable" dwellings after refurbishment: - 1960-1974 "Vulnerable" dwelling built after 2000	"Typical" dwellings after refurbishment: – before 1918 – 1918-1955 – 1960-1974 – 1975-1999 "Typical" dwelling built after 2000	"Typical" dwelling before refurbishment: – Before 1918	"Vulnerable" dwellings after refurbishment: – before 1918 – 1975-1999
Number of times the climatic sequences are exceeded in the present	**More than once a year**	**Once every 3 years**	**Once every 10 years**	**Once every 2 years**	**More than once every 2 years**
Number of times the climatic sequences are exceeded in the near future	**More than twice a year**	**More than 4 times every 7 years**	**More than 4 times every 10 years**	**More than once a year**	**More than once a year**
Number of times the climatic sequences are exceeded in the distant future	**More than three times a year**	**Twice a year or more**	**Once a year or more**	**More than twice a year**	**More than twice a year**

A study by **Sengupta, et al.** (2024) introduced a novel thermal resilience indicator providing architects and HVAC engineers with a practical tool to evaluate and enhance buildings' resilience to overheating. They assessed resilience across different building types (mid-sized offices, schools, apartments) and heatwave intensities (severe, intense and long) using simulations and global sensitivity analysis to identify the most influential design parameters affecting shock impact on heat stress of occupants. Key factors influencing thermal resilience, such as window-to-wall ratio, cooling capacity, solar shading, and natural night ventilation, were identified as twice as impactful as other design parameters (i.e. building orientation, envelope and glazing properties, occupancy pattern, airtightness, and cooling set-point). The study developed regression models/thermal resilience indicators based on the results of the sensitivity analysis to predict Standard Effective Temperature Degree hours (SET-Dh) for each type of building during 3 increasing shocks. The indicator incorporates the most influential design parameters and the health impacts of overheating during heatwaves, tested on office and residential buildings in two heatwave scenarios. This approach aims to guide architects, engineers, and policymakers in designing more resilient buildings under future climate scenarios.

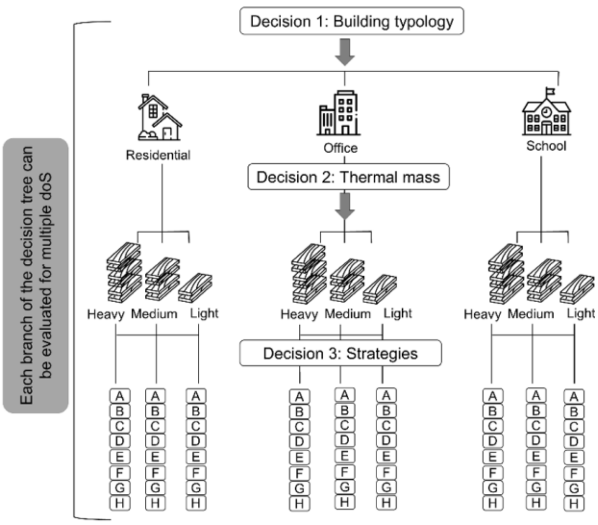

Figure 50: Decision tree for the development of thermal resilience indicators for different building types, thermal mass and operation of resilient cooling strategies (Sengupta, Al Assaad, Breesch, & Steeman, 2024)

3.3. Natural Ventilation

Kolokotroni, et al. (2024) conducted an intervention study using a climate correlation model to guide occupants of low-technology, naturally ventilated buildings in optimizing thermal comfort and indoor air quality (IAQ), to open the windows. The model, developed in the framework of the PRELUDE H2020 project, uses simplified linear correlations between external climatic variables and internal environmental variables derived from EnergyPlus simulations. Tested in three European buildings (in Greece, Switzerland, and Poland), the model provided occupants with daily guidance on window operation and shading via email or text. The results demonstrate the feasibility of using a single thermal study and associated correlation equations to inform occupants on the best way to control their internal environment based on prevailing external conditions in low-tech buildings without advanced sensors or actuators.

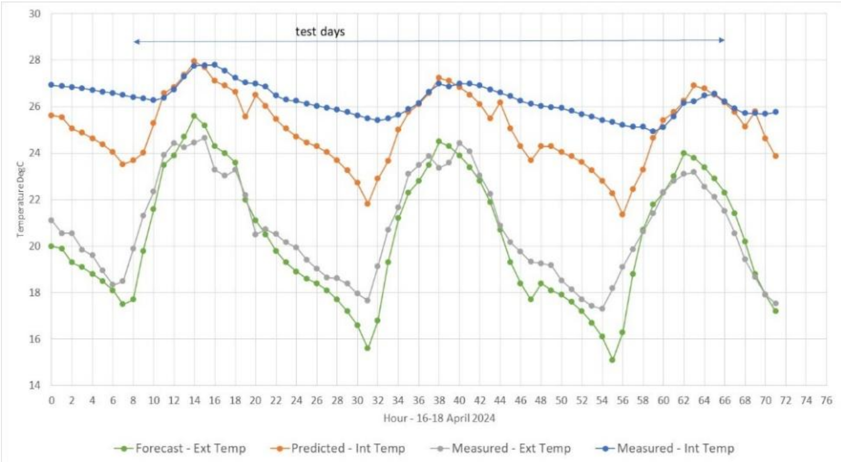

Figure 51: Athens: Thermal comfort predictions and measurements during the test period (Kolokotroni M. , et al., 2024)

Tuesday 16 April and Wednesday 17 April

- *Close the window at 8 in the morning*
- *Open the window at 3 for one hour*
- *Open the window at 8 pm and leave it open during the night (and then close it at 8 in the morning).*
- *The window does not need to be completely open, just ajar for example 10cm of opening (whatever is convenient – it does not matter how much it is open as long as it is open).*
- *If it is too cold at night, then they should close it and just tell us.*
- *Curtains should be closed between 3 pm and 6 pm.*

Figure 52: Instructions on window operation (Kolokotroni M. , et al., 2024)

The impact of night ventilation through motorized windows on the energy and thermal performance of office buildings was investigated by **Zinzi, et al**. (2024) using a living lab in Rome, Italy, as the test site. Their study explored various motorized windows to optimize ventilative cooling and reduce cooling energy demand. These windows (Figure 53), measuring 200 cm by 160 cm, feature two sashes: a manually operated one (130 cm wide) and a motorized sash (67.5 cm wide) controlled by a 30 cm developing chain, allowing a maximum opening angle of 30°. Using a TRNSYS calibrated model of the living lab based on field measurements, the research demonstrated that increasing the aperture size significantly enhances airflow and cooling performance, achieving up to 70% energy savings during the cooling season (Table 6).

Figure 53: Front view of the new window, left, with the push-button indicated on the right sash; detail of the motorized chain to open/close the sash on the right. (Zinzi, Botticelli, Romano, & Agnoli, 2024)

Table 6: Window aperture geometry and energy performance for the identified configurations (Zinzi, Botticelli, Romano, & Agnoli, 2024)

Chain length [m]	Aperture area [m²]	Aperture to floor area ratio [%]	Energy [kWh]	Energy intensity [kWh/m²]
0.00	0.00	0.0	4558	37.4
0.26	0.35	2.1	1983	16.3
0.31	0.43	2.5	1762	14.5
0.36	0.51	3.0	1613	13.2
0.41	0.59	3.5	1510	12.4
0.46	0.66	3.9	1445	11.9
0.51	0.74	4.4	1386	11.4

A study, by **Kubota, et al**. (2024) evaluated a novel design for a double apartment building incorporating a closed vertical void to enhance natural cross ventilation, particularly for leeward units (Figure 54). Using a full-scale experimental house in Tegal, Indonesia, the research examined wind velocity and volumetric flow rates (VFR) through field measurements and a tracer gas decay method. The proposed design includes a pilot at the ground floor and a closed-vertical void with a slit-shaped wind fin on the leeward side to create a positive pressure region by leveraging the venturi effect. While the venturi effect was clearly observed at the pilot, increased wind did not sufficiently reach the upper floors of leeward units, even with larger fins. Window and door opening conditions significantly influenced wind velocity distribution in and around the void. Sufficient levels of VFR were achieved even in the upper floor of leeward units due to the increased static pressure inside the closed void (Figure 55). The study concluded that this system could provide effective cross-ventilation for double apartment buildings, even mid-rise structures, by increased static pressure.

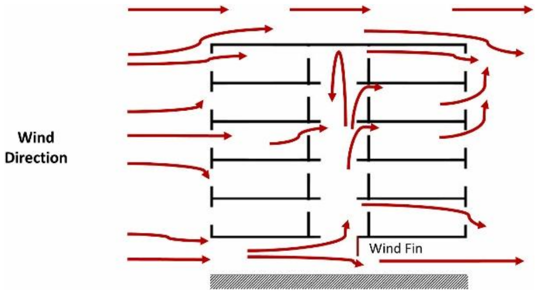

Figure 54: Natural ventilation concept of the proposed apartment building with a closed-vertical void (Kubota, et al., 2024)

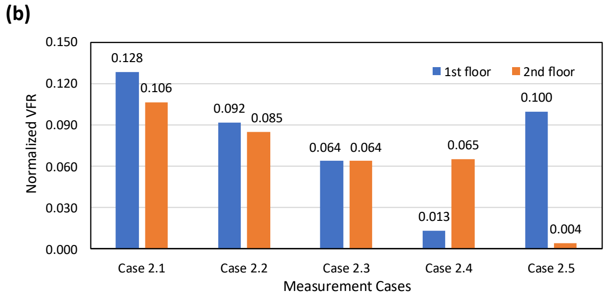

Figure 55: Normalized volumetric flow rates in leeward loft units (Kubota, et al., 2024)

Wang, et al. (2024) explored the energy-saving potential of a dynamic façade system integrating natural ventilation and shading in an office building (Figure 56). Using a validated simulation model, the researchers optimized façade operation strategies based on local solar radiation indexes and seasonal variations, achieving a 14.9% reduction in energy demand compared to a model without natural ventilation. The study revealed that natural ventilation contributed significantly to energy savings. Furthermore, a wider range of heating and cooling setpoints had a significant energy saving effect. Additionally, since occupants in naturally ventilated spaces can adapt to a wider range of indoor temperatures, the researchers recommend a wider thermal comfort adaptive temperature range for building operations to save energy. Overall, the study confirms the substantial energy-saving potential of dynamic façade systems that combine natural ventilation and shading strategies.

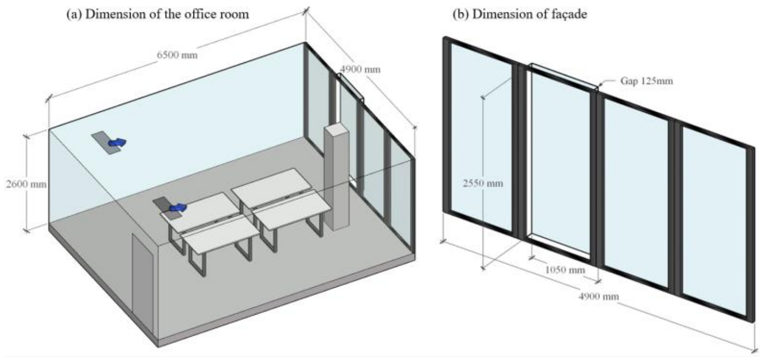

Figure 56: Geometry of the office room and façade system (Wang, Hajdukiewicz, Hoes, & Loomans, 2024)

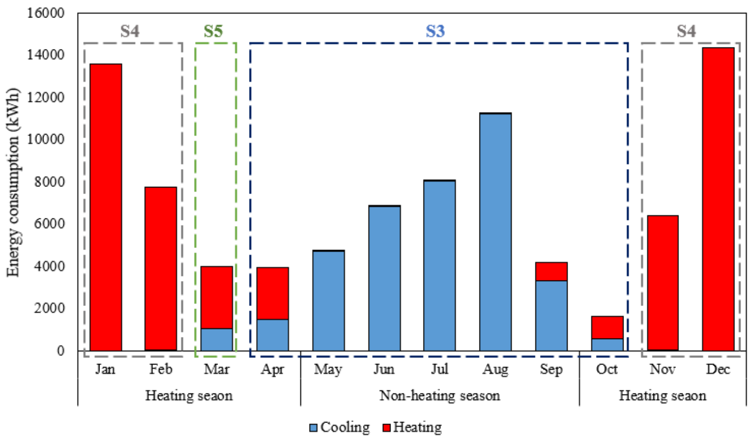

Figure 57: Combined strategy with monthly minimized energy demand (Wang, Hajdukiewicz, Hoes, & Loomans, 2024)

3.4. Personal Environmental Control Systems

The IEA-EBC Annex 87, "Energy and Indoor Environmental Quality Performance of Personalized Environmental Control Systems," hosted a topical session focused on an extensive literature review. After a brief introduction to Annex 87, four presentations were delivered, each covering findings from four of its five subtasks (**Bivolarova, Khovalyg, & Olesen**, 2024), (**Rewitz, Kim, Nabilou, Bayode, & Müller**, 2024) , **(Al Assaad & Pigliautile**, 2024) , (**Rawal, Olesen, Berk Kazanci, & Melikov**, 2024).

Comprehensive literature reviews were conducted for each subtask and presented during the session (Olesen, 2024), (Bivolarova & Shinoda, 2024), (Rewitz & Al Assad, 2024). The session concluded with a discussion on the work and insights of Annex 87.

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