ANNEX **5**

ANNEX **86**

EBC
Energy in Building and
Communities Programme

AIVC Technical Note 74
Smart Ventilation in Residential Buildings

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Wang, Y., Mortari, D., Plagmann, M., Mendes, N., & Guyot, G. (2024). Performance of smart ventilation in residential buildings: A literature review. The 44th AIVC Conference 'Retrofitting the Building Stock: Challenges and Opportunities for Indoor Environmental Quality'. https://www.aivc.org/resource/performance-smart-ventilation-residential-buildings-literature-review.

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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 86: Energy Efficient Indoor Air Quality Management in Residential Buildings

The goal of Annex 86 is to work in an international collaboration to create an integrated general assessment method to operationalize the air quality approach suggested by IEA EBC Annex 9, *Minimum Ventilation Rates*, to support the development, rating and implementation of innovative and highly energy efficient IAQ management strategies.

An IAQ management strategy is understood to be any coherent set of measures by a stakeholder in the building that aims to improve IAQ. The annex aims to improve the energy efficiency of the IAQ management strategies in operation and to improve their acceptability, control, installation quality and long-term reliability.

The scope of the annex is focused on residential buildings because they represent the largest section of the building stock. They are also understudied and have the broadest range of (non-specific) uses. Additionally, residential building projects often lack the funds for extensive bespoke engineering and therefore require robust cost-effective standardized solutions that can be implemented on a large scale. For the study of specific IAQ management strategies, this annex mainly concentrated on the use of smart materials (materials that have an ability to actively or passively influence IAQ in the space) and smart ventilation (as defined by AIVC VIP nr. 38), since these are strategies that have a high energy efficiency potential. Air cleaners are already studied in a separate Annex 78 and are therefore not studied in detail in this annex.

The annex has the following specific key objectives:

- To select metrics to assess energy performance and indoor environmental quality of an IAQ management strategy and study their aggregation;
- To improve the acceptability, control, installation quality and long-term reliability of IAQ management strategies by proposing specific metrics for these quality issues;
- To set up a coherent rating method for IAQ management strategy that takes into account the selected metrics;
- To identify or further develop the tools that will be needed to assist designers and managers of buildings in assessing the performance of an IAQ management strategy using the rating method;
- To gather existing or provide new standardized input data for the rating method;
- To study the potential use of smart materials as (an integral part of) an IAQ management strategy;
- To develop specific IAQ management solutions for retrofitting existing buildings;
- To benefit from recent advances in sensor technology and cloud-based data storage to systematically improve the quality of the implemented IAQ management strategies, ensure their operation and improve the quality of the rating method as well as the input data;
- To improve the availability of these data sources by exploring use cases for their providers;
- To disseminate about each of the above findings.

The Annex 86 was approved in June 2020 and operates from 2020 to 2025. The activities of the Annex 86 are a follow-up of the work undertaken by Annex 68 to develop a framework with specific metrics for energy efficiency and particulate matter, explicitly including moisture control and HVAC component modeling as well as creating a common methodology for IAQ data sharing among smart devices. Annex 86 supports 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. To fulfil the objectives, the work was divided into the following subtasks:

- Subtask 1 Metrics and development of an IAQ management strategy rating method;
- Subtask 2 Source characterization and typical exposure in residential buildings;
- Subtask 3 Smart materials as an IAQ management strategy;
- Subtask 4 Ensuring performance of smart ventilation;
- Subtask 5 Energy savings and IAQ: improvements and validation through cloud data and IoT connected devices;
- Subtask 6 Dissemination, management and interaction.

The participants undertake a co-ordinated effort, involving the sharing of activities within the Subtasks. The participating countries are:

Subtask 1 Metrics and development of an IAQ management strategy rating method
Subtask Leader: UK (U of Nottingham, Benjamin Jones)
Co-Lead: Denmark (DTU, Pawel Wargocki)
Partners involved: UoN (UK), PUC (Chile), BBRI (BE), UGent (BE), UoS (UK), ULR (FR), LU (UK), DTU (DK), AAU (DK)

Subtask 2 Source characterization and typical exposure in residential buildings
Subtask Leader: Austria (UASoS Salzburg, Gabriel Rojas)
Co-Lead: France (ULR, Marc Abadie)
Partners involved: UASoS (AT), ULR (FR), ULille (FR), LU (UK), NUIG (Ire), UoS (UK), UoN (UK), EPFL (CH), SU (USA), NJU (CN), TU (CN), BBRI (BE), CETIAT (FR), PUC (Chile), BRANZ (NZ), AAU (DK)

Subtask 3 Smart materials as an IAQ management strategy
Subtask Leader: Denmark (DTU, Menghao Qin)
Co-Lead: USA (SU, Jensen Zhang)
Partners involved: DTU (DK), SU (USA), UMD (USA), UPJV (FR), NJU (CN), BUCEA (CN), BBRI (BE)

Subtask 4 Ensuring performance of smart ventilation
Subtask Leader: France (Cerema, Gaëlle Guyot)
Co-Lead: Denmark (DTU, Jakub Kolarik)
Partners involved: Cerema (FR), DTU (DK), NUIG (IRe), ULille (FR), UGent (BE), KUL (BE), BBRI (BE), UoS (UK), CETIAT (FR), EPFL (CH), UAntwerp (BE), ULR (FR), BRANZ (NZ), UASoS (AT)

Subtask 5 Energy savings and IAQ: improvements and validation through cloud data and IoT connected devices
Subtask Leader: Belgium (UGent, Marc Delghust)
Co-Lead: France (ULille, Benjamin Hanoune)
Partners involved: UGent (BE), DTU (DK), LU (UK), ULille (FR), CETIAT (FR), AAU (DK)

Subtask 6 Dissemination, management and interaction
Subtask Leader: Denmark (DTU, Carsten Rode)
Co-Lead: Belgium (UGent, Jelle Laverge)

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/).

Moreover, there is a close interaction with several ventilation related annexes of IEA-EBC. This publication is the result of the collaboration between AIVC and Annex 86.

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

Table of content

Abbreviations

ACH	air changes per hour
AIVC	Air Infiltration and Ventilation Centre
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	carbon dioxide
constant MEV	constant flow mechanical extract ventilation system
constant MVHR	constant flow mechanical ventilation with heat recovery
DALYs	disability-adjusted life years
DCMEV	demand-controlled mechanical extract ventilation
DCV	demand-controlled ventilation
demand-controlled MVHR	demand-controlled mechanical ventilation with heat recovery
HCHO	formaldehyde
IAQ	indoor air quality
IEA	International Energy Agency
IEQ	indoor environmental quality
IoT	Internet of Things
M/M DCV	balanced mechanical with DCV supply and extract and a heat exchanger
M/M NBN	constant flow balanced mechanical
MEV	mechanical extract ventilation
MMV	mixed-mode ventilation
MVHR	mechanical ventilation with heat recovery
n/M NBN	natural supply/mechanical extract
NO_2	nitrogen dioxide
O_3	ozone
PACs	portable air cleaners
PM	particulate matter
PM_{10}	particles 10 µm or less in diameter
$PM_{2.5}$	particles 2.5 µm or less in diameter
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RE	relative exposure
RH	relative humidity
RH-MEV	RH-controlled mechanical extract ventilation
TVOCs	total volatile organic compounds
VOCs	volatile organic compounds

Definitions

While writing this technical note, the following definitions were considered by the authors:

Airing: Intentional opening of windows, doors, vents, etc. for increasing the ventilation in a room [EN 16798-1:2019, 3.4]. Note: Since airing is the air change by manually operating windows or other openings, it has to be observed that it cannot be considered to be the effect of a ventilation system.

Ventilation: Process of supplying or removing air by natural means or mechanical means to or from a space for the purpose of controlling air contaminant levels, humidity, odours or temperature within the space [ISO 16814:2008, 3.44]. Note: Prescriptive requirements or performance-based requirements on ventilation are not a matter for this definition. Ventilation can be combined with air treatment.

Natural ventilation: Ventilation whose operation is based solely on the effect of wind and the stack effect. Open windows can be used for natural ventilation if they are purposed-provided.

Mechanical ventilation: Ventilation system where air is supplied or extracted from the building or both by a fan using air terminal devices, ducts and roof/wall devices [EN 16798-1:2019, 3.18].

Hybrid ventilation: Ventilation whose operation is based on the combination or alternation of natural ventilation and mechanical ventilation.

Smart ventilation: "Smart ventilation is a process to continually adjust the ventilation system in time, and optionally by location, to provide the desired IAQ benefits while minimizing energy consumption, utility bills and other non-IAQ costs (such as thermal discomfort or noise). A smart ventilation system adjusts ventilation rates in time or by location in a building to be responsive to one or more of the following: occupancy, outdoor thermal and air quality conditions, electricity grid needs, direct sensing of contaminants, operation of other air moving and air cleaning systems" (Durier et al., 2018)**.**

Demand-controlled ventilation: DCV is a ventilation system where airflow rates are controlled automatically according to measured needs at room level [EN 16798-1:2019, 3.11]. DCV is considered a specific subset of smart ventilation.

Parameter: Pollutant or marker that is used in the expression of a requirement. Note 1: More than one parameter may be used at the same time and combined. Note 2: Relative humidity, odours, CO2 are examples of parameters [EN 15665:2009].

The definitions of airing, ventilation and natural ventilation are consistent with the ongoing revision work of the EN12792 in the TC156/WH1 (V. Leprince, June 26, 2024).

Regarding the occupant's bioeffluent and the emissions from the occupant's activities, we have adopted the "parameter" definitions provided by the EN 15665:2009.

Although we adopted these definitions, as this is a literature review, we preserved the definitions adopted by the authors when discussing their primary findings.

1. Introduction

An ideal ventilation system should be robust and capable of providing thermal comfort and good indoor air quality (IAQ) that safeguards occupant health while also minimising space conditioning costs and reducing auxiliary energy use for fans. Experts from the Air Infiltration and Ventilation Centre (AIVC) have defined smart ventilation as "a process to continually adjust the ventilation system in time, and optionally by location, to provide the desired IAQ benefits while minimising energy consumption, utility bills, and other non-IAQ costs, such as thermal discomfort or noise" (Durier et al., 2018, p. 38). The key concept of smart ventilation is to use controls to ventilate more when it provides either an energy or IAQ advantage or other non-IAQ cost and less when it provides a disadvantage. The fundamental goal of this concept is to reduce ventilation energy consumption while maintaining the same IAQ or achieving better IAQ in comparison to a continuously operating or constant airflow ventilation system. The parameters that smart ventilation systems can respond to include, but are not limited to, occupancy, indoor contaminants, outdoor temperature and humidity, outdoor air quality, electricity grid needs and the operation of other air moving or cleaning systems. Smart ventilation includes demand-controlled ventilation (DCV), which responds to the direct sensing of indoor contaminants.

The publications on residential smart ventilation systems between 1979 and 2016 were reviewed (Guyot et al., 2018), including the development of smart ventilation in the International Energy Agency (IEA) annexes, the types of commonly available smart ventilation systems and the challenges in the comparison of IAQ performance and energy savings resulting from the implementation of these smart ventilation systems. This previous review showed that up to 60 % of ventilation energy savings can be obtained without compromising IAQ.

Since 2016, there have been many new developments in residential smart ventilation. For example, formaldehyde (HCHO) and particulate matter (PM) have been used to develop control strategies (Johnston et al., 2020). The combination of ventilation and filtration controls has been used to maintain indoor $PM_{2.5}$ within an acceptable level and minimize energy consumption (Kim et al., 2020). The indicator of dynamic disability adjusted life years (DALYs) has been developed and applied to investigate the impact of IAQ in households with smart ventilation on occupants' health, as well as the energy consumption associated with the ventilation (De Jonge and Laverge, 2022). The impact of changing the number of occupants on non-occupant dependent pollutants exposure, i.e., volatile organic compounds (VOCs) when ventilation is controlled by occupants generated pollution, such as relative humidity (RH) and carbon dioxide (CO_2) has been investigated (De Jonge et al., 2023). Decentralized ventilation units are investigated to suit the apartment settings and retrofit the existing house to avoid the possible challenges due to the lack of space for the installation of ducts and air handling units (Carbonare et al., 2020, 2019; Filis et al., 2023). In conjunction with the IAQ performance and energy consumption by ventilation system, the potential for mold growth at the window surface has been investigated (Shin et al., 2018). The simulation of humidity-based DCV in the whole high-rise building, including 23 units, is also a new development (Sowa and Mijakowski, 2020). The data-driven approach has been used to develop control strategies (Han et al., 2022). The large-scale field performance analysis of the demand-controlled mechanical extract ventilation (DCMEV) systems has been published (De Maré et al., 2019).

Today, energy savings in the building sector are in high demand, as is the need to provide an acceptable IAQ, which means ventilation plays an even more critical role. Since residential buildings are often unoccupied or occupied at a lower level, the smart ventilation strategy is extremely important to achieve the high potential of energy savings and assure good IAQ.

In the context of the emergence of new developments in residential smart ventilation and high demand for energy savings and providing acceptable IAQ, this review is conducted with the aim of summarising the evidence of the benefits of implementing smart ventilation in residential homes. It focuses on ventilation strategies and their effectiveness, which consists of IAQ benefits, non-IAQ benefits (such as thermal comfort and noise), minimising energy consumption and minimising utility bills, and other advantages related to indoor environmental quality (IEQ).

This review seeks to answer two questions:

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

This study is within the scope of IEA Energy in Buildings and Community (IEA EBC), Annex 86: "Energy Efficient Indoor Air Quality Management in Residential Buildings" focused on subtask 4 "Ensuring performance of smart ventilation", which points to the necessity of reviewing existing smart ventilation strategies (IEA EBC, 2020, p. 86). It is important to highlight that the focus of this review is to analyse smart ventilation strategies applied in residences and their effectiveness in improving IEQ and reducing energy consumption. In this context, we included papers addressing these two pillars. Therefore, related topics such as sensor development and evaluation of ventilation system durability are out of the scope of this review. It is recognised that source control is the essential initial step towards attaining good IEQ. However, this aspect also falls beyond the scope of this review. The smart ventilation strategies presented in this review can contribute the further development of smart ventilation, reducing energy consumption and improving IEQ. In addition, the wide range of described systems can provide a technical reference framework for professionals involved in building new dwellings and renovation processes that are currently facing a lack of knowledge and decision tools to choose, design and install the most efficient and suitable systems in residential buildings.

2. Methodology

This review was performed according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) recommendations (Liberati et al., 2009). The electronic databases used were Web of Science, Scopus and AIVC collections. As a result, journal and conference papers have been included in the review. A search for literature available within these databases was conducted on August 3, 2023. This review includes articles published between January 2017 and August 2023, as a continuation of a previous review that covered publications on this topic up to 2016 (Guyot et al., 2018).

Based on the two research questions, the search terms cover three aspects: ventilation, IEQ and energy, as shown in Figure 1. Under each aspect, different terms were used.

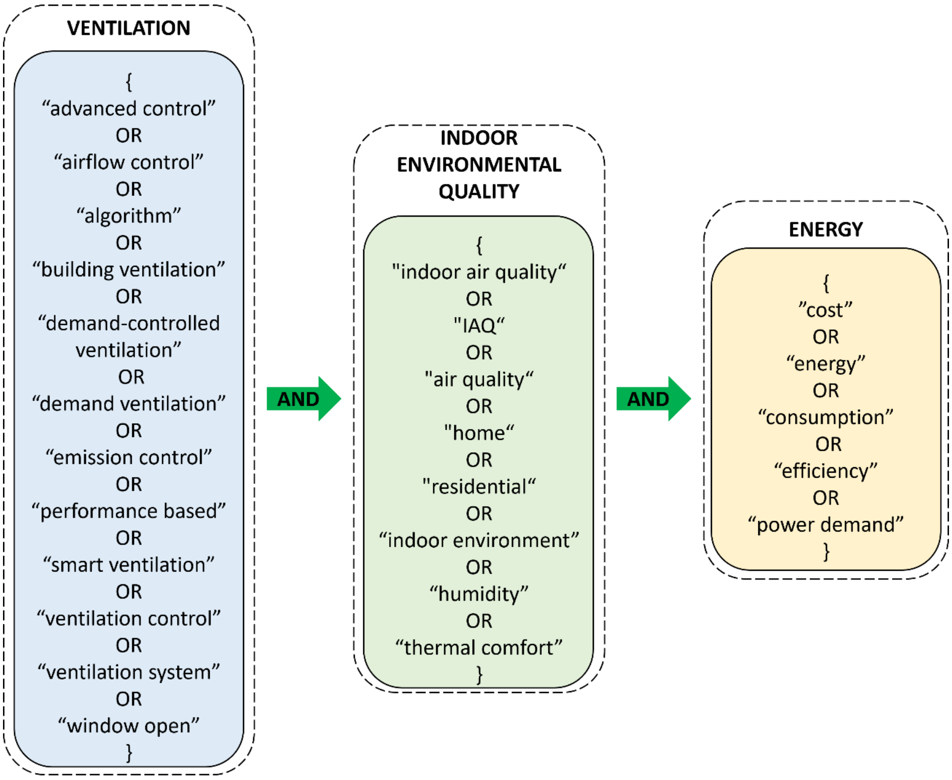


Figure 1: Combination of search terms.

This search string was permuted in both the Web of Science and Scopus databases, with an integrated search in the article title, abstract and keywords. The AIVC collections were searched using the string *{"control" or "demand" or "smart"}* in the article title. After performing the search, duplicated articles were removed, and inclusion and exclusion criteria were generated to guide the selection process. This process was carried out using the platform Rayyan, which is a free tool that enables authors to classify articles in a blind mode, reducing the risk of bias. The screening process undertaken to select the articles and the results of the process are detailed in Figure 2. Although we used the most relevant search string in commonly used databases, there remains a small possibility that some relevant studies were not captured. The limitations associated with the search process are discussed in Section 6.5 of this Technical Note.

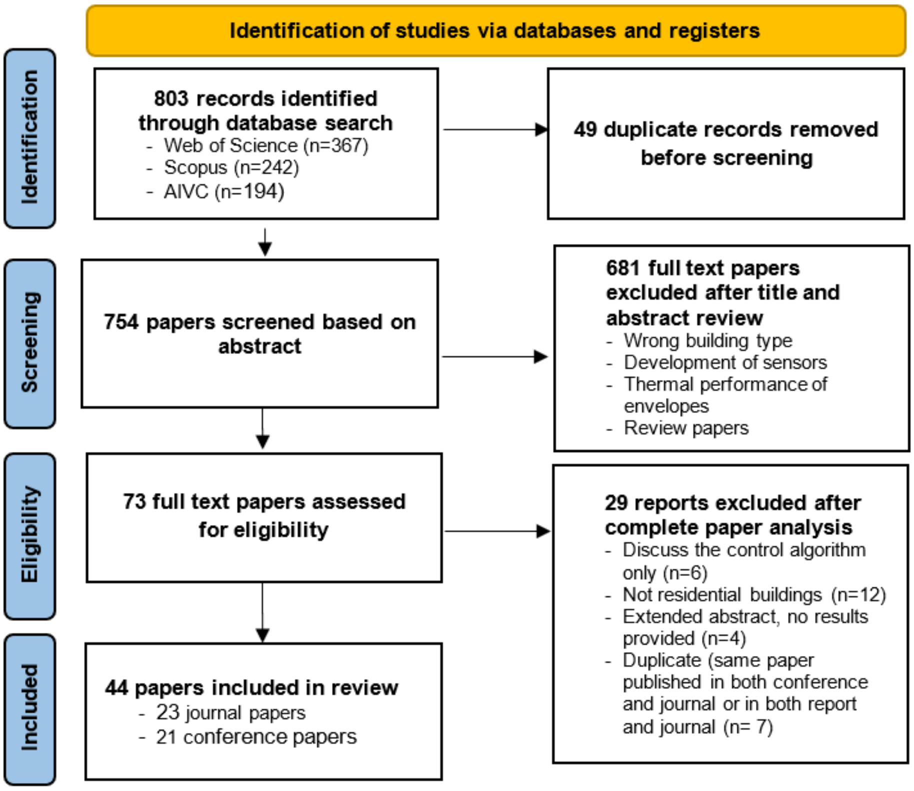


Figure 2: Diagram of the systematic review process performed.

A bibliometric analysis was performed to assess the development and trends of smart ventilation research. We investigated the evolution of smart ventilation publications by geographic location of the studies, by year in which the papers were published and by correlation among keywords.

The software VOSviewer was used to investigate the evolution in smart ventilation publications over the years by means of the papers' keywords co-occurrence from 2017 to 2023. Before exporting data in RIS format to VOSviewer, paper labels and authors' names were standardised, for example, the terms “indoor air quality”, “IAQ”, “Indoor air quality (IAQ)” and “Indoor Air Quality” were standardised to “Indoor air quality”.

3. Preliminary analysis of the literature

3.1. Summary of the reviewed studies

The search resulted in a total of 803 articles. After removing the duplicated articles and carrying out the screening process, 73 articles were reviewed in full. Of these, 44 articles discussed both IAQ and energy consumption and were found to be relevant and were included in the final review. The names of the journals in which the included papers were published, and the author's institutions are presented in Appendix 1.

Figure 3 shows the distribution of geographical locations of the studies included in this review. Belgium, France and the United States appear as the countries with the majority of the publications in this research topic, with 61 % of the included papers conducted in these three countries.

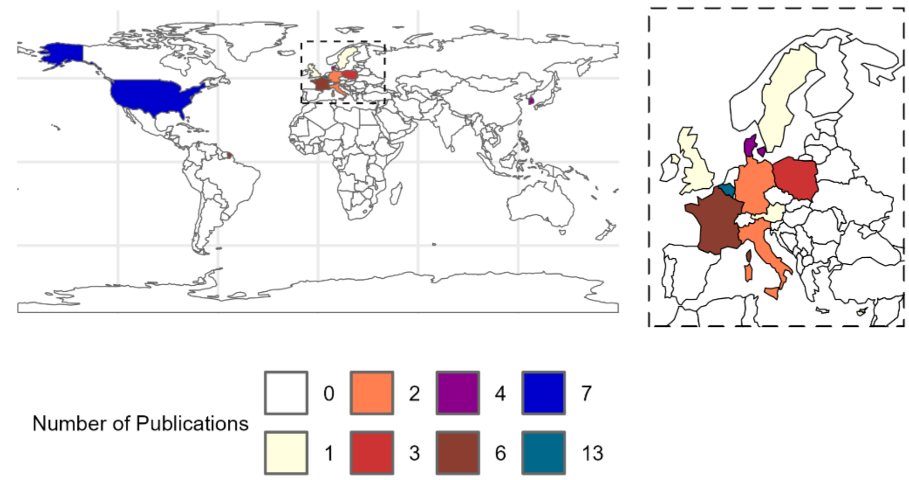


Figure 3: Distribution of the locations of the studies included.

It is evident that many studies on residential smart ventilation were carried out in Central Western Europe, which is mostly characterised by an oceanic and temperate climate, according to Köppen climate classification (Beck et al., 2018). The majority of studies from Midwest Europe and North America included in this review either focus solely on the winter season or consider the entire year but only account for heating demand in winter. Two studies concentrate on the cooling season/summer, one located in Cyprus (Cakyova et al., 2021) and the other in South Korea (Kim et al., 2017). Ventilation for cooling has started to be investigated in Midwest Europe, such as smart control hybrid ventilation.

In total, 44 studies are included in this review, consisting of 23 journal papers and 21 conference papers. Figure 4 shows the evolution of publication over the years. The first work on smart ventilation was published in the 1980s and reported by (Guyot et al., 2018). There has been a noticeable increase in the number of publications since 2003, peaking in 2022. However, in 2020 and 2021, there was a decrease in the publications, possibly due to the consequences of the COVID-19 pandemic. In 2022, the number of publications began to rise again. Regarding the conference papers included in this review, 90 % (19 of 21 papers) were published in the proceedings of AIVC conferences, and 54 % were published in 2018 and 2019. There was no AIVC conference held in 2020 or 2021 due to the COVID-19 pandemic. In 2023, the conference took place in October, and the publication date of conference papers fell outside the inclusion date of this review, which explains the low number of conference papers in 2020, 2021 and 2023. Given common practice where authors first submit preliminary research findings to conferences and subsequently submit more comprehensive versions to journals, the substantial number of conference papers in 2019 likely contributed to the increased number of journal papers in 2020.

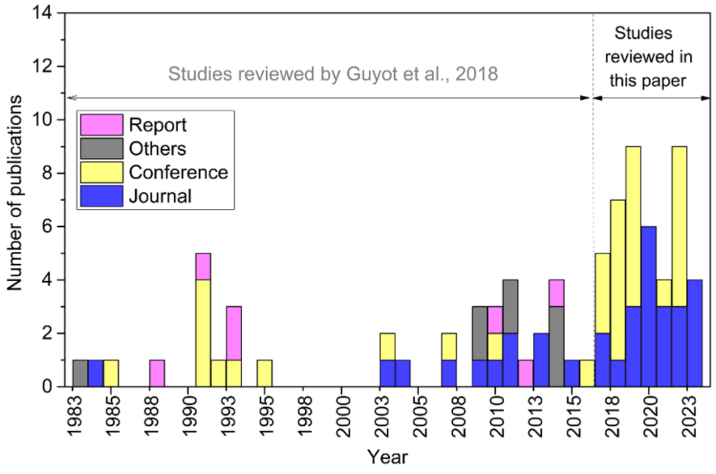


Figure 4: Evolution of publication over the years of this present research and of the research performed by (Guyot et al., 2018).

Figure 5 shows the results of the co-occurrence of keywords over the past 7 years. An evolution in smart ventilation publications over the last 7 years is evident. Between 2017 and 2019, research focused on themes such as CO_2-based control ventilation, humidity-based control, energy savings, emissions, smart buildings, airflow networks and building-generated pollution. Publications from 2022 to 2023 emphasise themes such as health, DALYs, VOCs, $PM_{2.5}$, performance-based assessment, room-based ventilation, data-driven methods and Internet of Things (IoT)

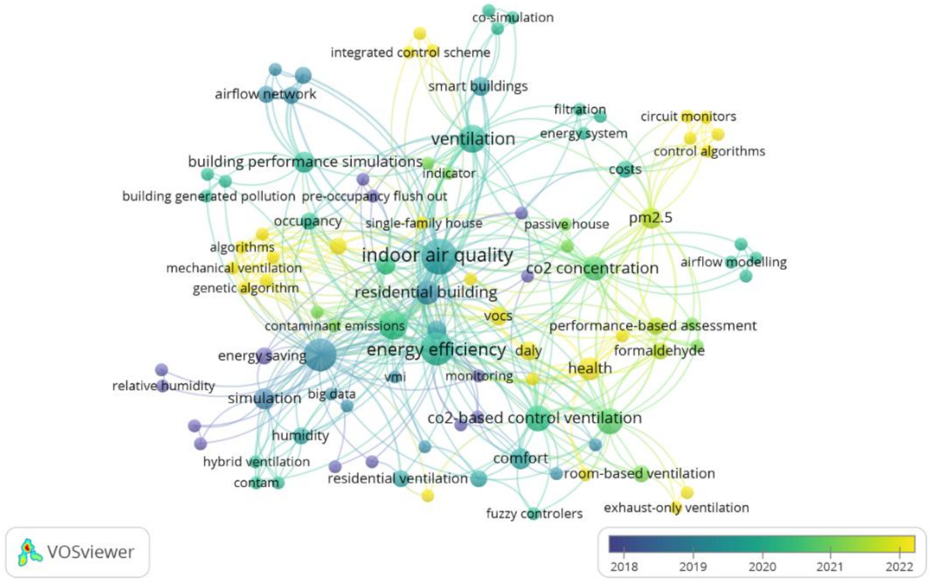


Figure 5: Co-occurrence of keywords from studies included in this review over the year.

3.2. Reviewed papers context

Among the total included papers, 77 % (34 studies) were conducted using simulation approach, 11 % (five studies) were experimental set-up studies and 11 % (five studies) were in-situ studies, as shown in Figure 6.

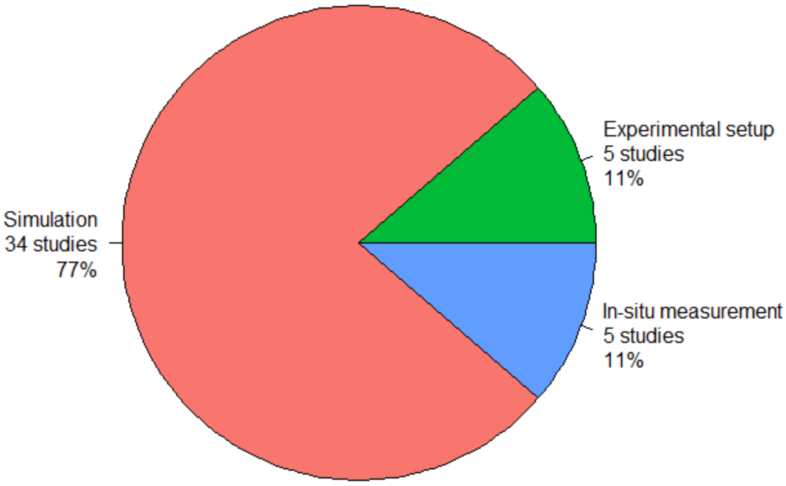


Figure 6: Distribution of studies based on the approach that studies were conducted.

Figure 7 shows the parameters that the ventilation control strategies responded to. Of the 44 included papers, 30 % (13 studies) focused on RH, CO_2 or both, 16 % (seven studies) assessed outdoor conditions-based strategies, 14 % (six studies) were based on indoor temperature along with other parameters such as RH, CO_2 and TVOCs and 11 % (five studies) centred on presence and other parameters such as RH, CO_2 or both. Three studies focused on occupancy-based strategies. Water vapour, $PM_{2.5}$, heating demand and absolute humidity were found to be used to control ventilation systems. One study developed a ventilation strategy based on HCHO levels.

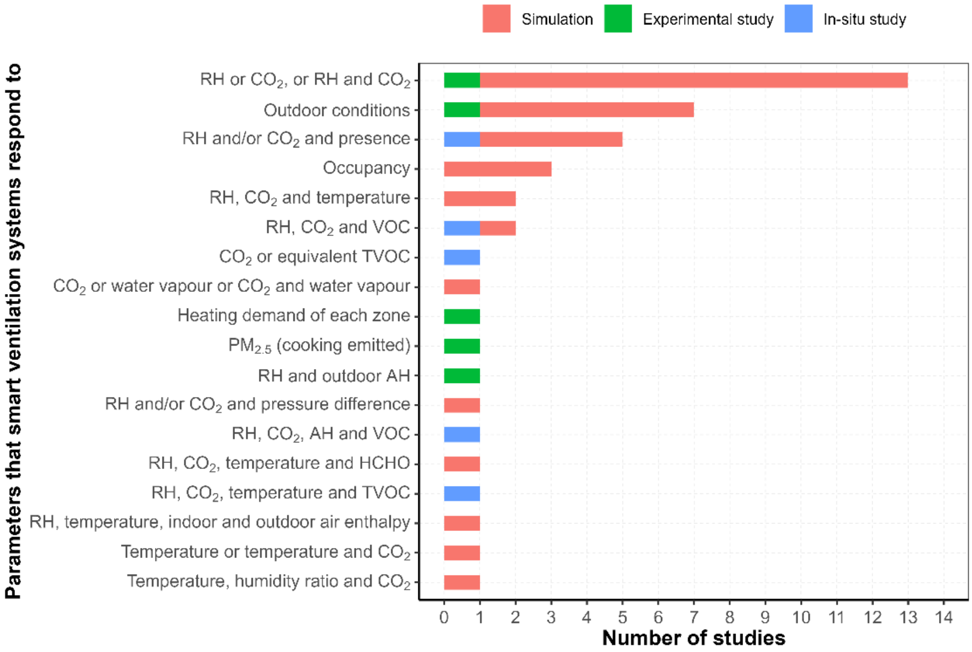


Figure 7: Distribution of the included studies based on parameters that ventilation control strategies responded to.

The distribution of study subjects is shown in Figure 8. Single-family detached house account for more than 40% of the study subjects, followed by the typical apartment unit, with a contribution of 32%.

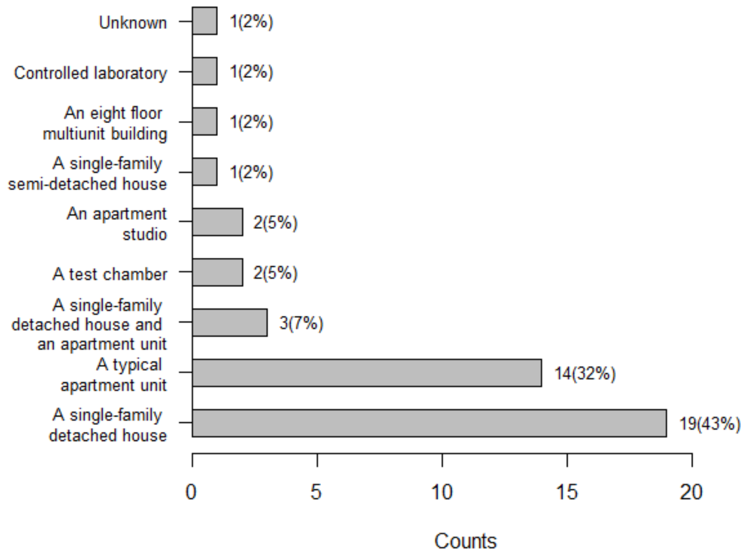


Figure 8: Types of buildings.

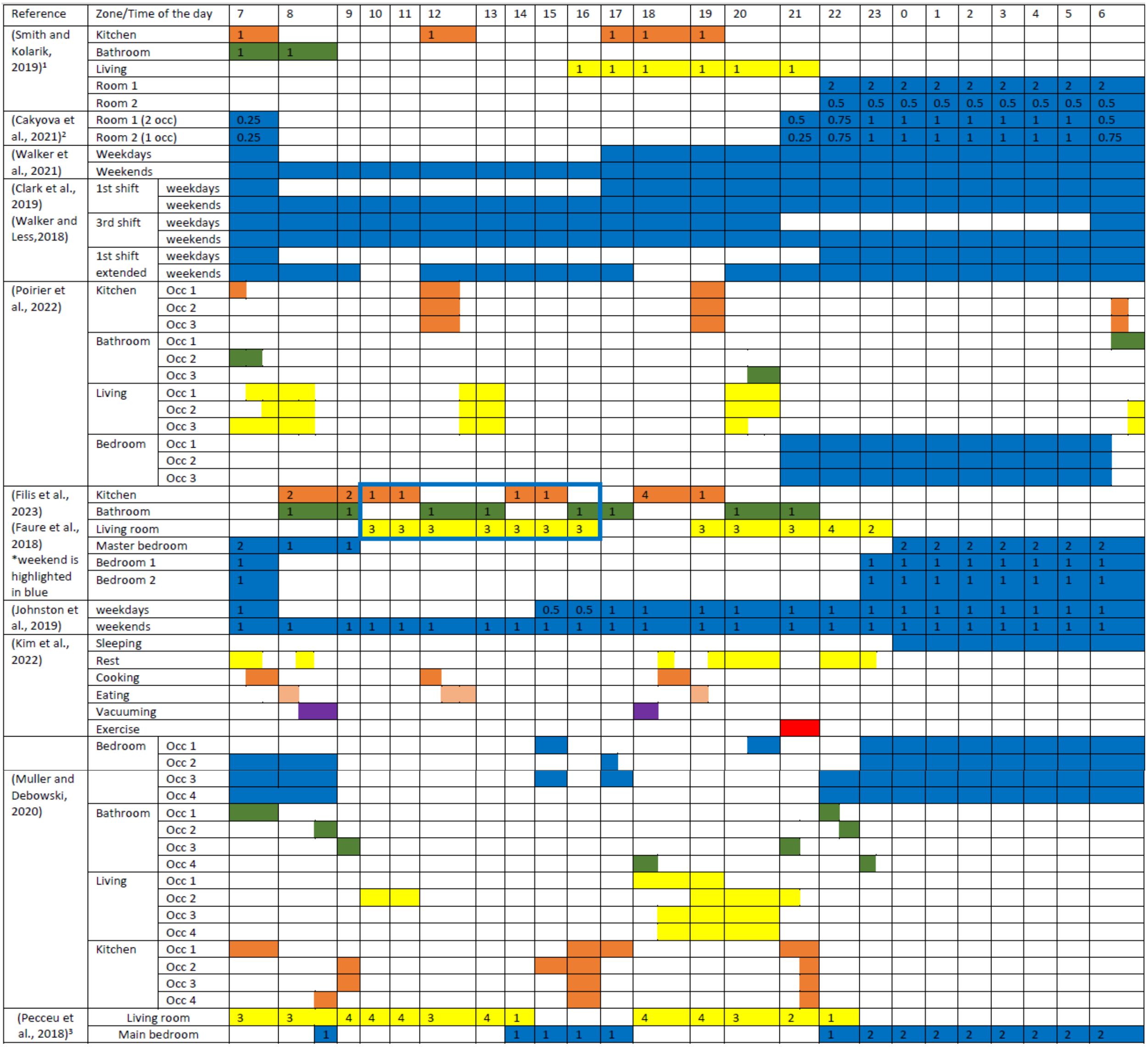
According to Figure 8, the 8-story multiunit building, including 23 units, is quite unique compared to all the other building typologies due to both the size and the complexity of the building. Overall, the single-family home received more research interest than the other building types.

3.3. Overview of the assessment methodologies

In every simulation type, the key to achieving an accurate and dependable predictive model lies in the availability of input data as well as the assumptions made. The occupancy pattern and pollutant generation rate are attributed to the simulation outcomes. The performance of ventilation systems or simulation outcomes are also affected by the control strategies implemented and assessment criteria used. Among the reviewed studies, the simulation duration ranged from one day in a winter, which represents the mean winter day according to the weather data (Van Gaever et al., 2017), to one heating season (Carbonare et al., 2020, 2019; Filis et al., 2023), and to an one year period (Müller and Dębowski, 2020).

3.3.1. Occupancy pattern

Occupancy patterns are essential for assessing ventilation performance due to their impact on various pollutant generation scenarios (such as bio effluents, CO_2, H_2O, and pollutants related to occupants' activities), as well as on performance indicators. Many efforts have been made to address occupant behavior in residential buildings, including monitoring occupancy, developing occupant behavior models, and applying those models in building performance simulations (Balvedi et al., 2018; Franceschini and Neves, 2022). (Nivetha et al., 2019) use the distance between the Wi-Fi device and the mobile device as an indicator of the occupant pattern through continuous tracking of mobile Wi-Fi devices. As shown in Figure 9, each individual simulation study uses unique occupancy pattern data. Table S1 in the supplementary material provides a database of the occupancy pattern data used in the reviewed simulation studies.



[1] weekends: living room occupied from 9:00 to 22:00h.

[2] Used the level of occupancy (%)

[3] Four occupants. Schedules represented just in the main bedroom (2 occupants) and living room (4 occupants – 2 adults and 2 kids).

Figure 9: Occupancy pattern data used in some of the reviewed simulation studies.

The primary distinction in the simulated patterns of occupancy lies in whether the occupants are at home throughout the day, representing the highest level of pollutants emissions and exposure (Van Gaever et al., 2017), or whether they are away at work (Müller and Dębowski, 2020; Walker and Less, 2018). There are many variations in the occupation schedule, e.g., (Smith and Kolarik, 2019) used in their simulation that the living room is occupied from 9:00 to 22:00 during the weekends. (Cakyova et al., 2021) used variations of occupants' entries in the rooms 2 hours before and after the sleep time. (Baptiste Poirier et al., 2021b; B. Poirier et al., 2021; Van Gaever et al., 2017) presented how long each occupant spends in each room, but they did not specify the timetable.

While some authors use information defined in standards (Carbonare et al., 2020, 2019), others use occupancy profiles derived from time-use survey data, as presented by (De Jonge and Laverge, 2022; Baptiste Poirier et al., 2021a). (De Jonge and Laverge, 2022) generated room-based occupancy schedules from a time-use survey data available at the Belgian National Institute for statistics, in which they applied four different occupant profiles: a working adult, an adult staying at home, a child going to school and a baby staying at home. In other studies, the same authors used several combinations of these occupants' profiles for different households (De Jonge et al., 2023; De Jonge and Laverge, 2022). (Baptiste Poirier et al., 2021a) utilized data from the national French survey, which was based on a representative sample of the population, encompassing 567 homes and 1612 occupants. The study revealed several key findings: 1) light differences between weekend days and weekdays; 2) no statistical difference between working periods and holidays; and 3) occupants are more likely to be at home between 12.00 p.m. and 2:00 p.m., as well as between 7:00 p.m. and 7:00 a.m.

The number of occupants varies according to the house size and type, as presented by (Walker et al., 2021). The authors considered three, four, and five occupants for a typical apartment unit, one-story and two-story prototypes, respectively. In addition, the schedules of occupant movement and routine activities between zones at different times of day are fixed, aiming to reflect reality (wake up, leave the bedroom, take a shower, prepare breakfast, leave the dwelling, return home, prepare dinner, etc.) (Walker et al., 2021).

In part of the analyzed studies, the occupancy schedule assumption appears only as a reference related to previous publications (Belmans et al., 2019a, 2019b; Rojas, 2022; Smith and Kolarik, 2019) and not in all cases are they accessible or detailed. (Grygierek and Ferdyn-Grygierek, 2022) used the schedule of occupied people based on the behavior of a traditional Polish family with two parents and two children, divided into working days and weekends. (Sowa and Mijakowski, 2020) used the schedules of occupancy defined in each room for each person, considering typical working days and the weekends, in which one adult and one child are out of the home during the day on workdays. In an experimental study, (Shin et al., 2018) used the occupancy schedule of a typical family with four members (two parents and two children) to simulate the CO_2 generation in a mock-up residential building. (Han et al., 2022) assumed that each of the observed days was divided into two periods: occupied and unoccupied. (Belmans et al., 2019b) showed an integrated semi-probabilistic occupant model for IAQ simulation based on previous work. In this model, every family person presents an age bin and an employment status. Seven household types, with different characteristics and behavioral patterns were included. Activities are assigned to each person associated to the probability of occurrence, which calculation is based on data from Belgian time-use surveys. The model limits the number of activities for a person to one at a time. For each activity that the user performs, there is a room related to that activity, such as cooking – in kitchen, bathing – in bathroom, etc.

In a general view, the only coincidence in the occupant's pattern among the reviewed studies is the time in the bedrooms from 00:00h to 6:00h.

3.3.2. Pollutant generation scenarios

The emission generation scenarios used in the simulation studies, including both the occupant-related emissions and the non-occupant-related emissions have been summarized in Table 1. A detailed pollutant generation table is presented in Appendix 2. The generation scenario of these parameters is either from a standard or from an in-situ measurement. As shown in Table 1, the generation scenario for each parameter varies in different simulations. The emission rate can be different for the same parameter. For example, the CO_2 generation rate for an awake-adult ranges from 14.4 $L.h^{-1}$ to 19 $L.h^{-1}$, and the units $L.h^{-1}$, $L.min^{-1}$ and $mg.s^{-1}$ were all used. The variation in pollutant generation scenarios lead to distinct outcomes in ventilation system performance, complicating the comparison of ventilation strategies among different studies. Notably, accurately quantifying the extent to which the pollutant generation scenario in the simulation study aligns with real-world conditions poses a significant challenge.

Table 1: Summary of emission generation scenarios in the reviewed studies.

Pollutants and contaminants		Emission rate	Reference
CO_2 (bio-effluent)	Adult awake	12 L.h^{-1}, 14.4 L.h^{-1}, 16 L.h^{-1}, 18 L.h^{-1}, 19 L.h^{-1}, 10 mg.s^{-1}, 8.5 mg.s^{-1}, 0.25 L.min^{-1} varying from1.86 e-4 m^{3}.s^{-1} to 9.69e-4 m^{3}.s^{-1} depending on the activity level, varying from 15 dm^{3}.h^{-1} to 35 dm^{3}.h^{-1} depending on the activity level	(Van Gaever, Laverge, and Caillou 2017) (Pecceu, Caillou, and Gaever 2018) (Poirier et al. 2021) (Walker et al. 2021) (Ghijsels, Jonge, and Laverge 2022) (De Jonge, Ghijsels, and Laverge 2022) (Carbonare et al. 2020) (Belmans et al. 2019) (Filis et al. 2023) (Kim, Kim, and Moon 2022) (Müller and Dębowski 2020) (Rojas 2022) (Shin et al. 2018)
	Adult asleep	10 L.h^{-1}, 15 L.h^{-1}, 6.5 mg.s^{-1}, 1.65e-4 m^{3}.s^{-1}, 10 dm^{3}.h^{-1}, 0.20 L.min^{-1}	
	Child awake	6.5 mg.s^{-1},12 L.h^{-1}, 12.6 L.h^{-1}, 9 L.h^{-1}	
	Child asleep	4 mg.s^{-1}, 8 L.h^{-1}	
H_2O (bio-effluent)	Adult awake	55 g.h^{-1}, 15 mg.s^{-1}, 45 g.h^{-1}, 40 – 45 g.h^{-1}	
	Adult asleep	40 g.h^{-1}, 9 mg.s^{-1}	
	child awake	10 mg.s^{-1}, 41.3 g.h^{-1}, 35 g.h^{-1}	
	child asleep	6 mg.s^{-1}	
H_2O (human activities)	cooking	1. morning and noon 0.5 L.s^{-1} (10min); evening 0.6 L.s^{-1} (10min) + 1 L.s^{-1} (10 min) + 1.5 L.s^{-1} (10min), 2. Breakfast 1512 g.h^{-1}, lunch 2268 g.h^{-1}, dinner 2844 g.h^{-1}, 3. 140 mg.s^{-1}, 4. 500 g.h^{-1}, 5. Breakfast 50 g/person, lunch 150 g/person, dinner 300 g/person, 6. 1.33·10^{-4} kg.s^{-1}	(Van Gaever et al. 2017) (Poirier et al. 2021) (Ghijsels et al. 2022) (De Jonge et al. 2022) (Carbonare et al. 2020) (Belmans et al. 2019) (Filis et al. 2023) (Johnston et al. 2020) (Kim et al. 2022)
	dishwashing	130 mg.s^{-1}, 200 g.h^{-1}	
	shower	0.5 L.s^{-1} per shower (10min), 1440 g.h^{-1}, 330 mg.s^{-1}, 500 g.h^{-1}, 300 g/shower/person, 7.22·10^{-4} kg.s^{-1}	
	Laundry room	0.06 L.s^{-1} (12h), 252 g.h^{-1}, 250 g.h^{-1}, Laundry + dry 136.8g/h, 200 g/laundry, 1000 g/drying	
H_2O plants		30 g.h^{-1}	
VOCs Proportional to the floor area		From 4.5 µg.h^{-1}m^{-2} to 23.6 µg.h^{-1}.m^{-2}	
$PM_{2.5}$ from cooking		1). 0.0208 mg.s^{-1}, 2). From 1.26 mg.min^{-1} to 2.55 mg.min^{-1}, 3). Per activitie: 70 µg.min^{-1} – vacuuming 10 µg.min^{-1} - oven 283 µg.min^{-1} – grilled, 1483 µg.min^{-1}- fried	
Generic contaminant		18 µg/m^{2}/h	(Walker et al. 2021)
Formaldehyde		3.06 µg.h^{-1}.m^{-2} for furniture (wood), 4.50 µg.h^{-1}.m^{-2} for doors (wood), 3.00 µg.h^{-1}.m^{-2} for cushion, 4.27 µg.h^{-1}.m^{-2} for carpet	(De Jonge and Laverge 2022)
Benzene		1.40 µg.h^{-1}.m^{-2} for furniture (wood), 2.00 µg.h^{-1}.m^{-2} for cushion, 0.21 µg.h^{-1}.m^{-2} for carpet	
Naphthalene		5.68 µg.h^{-1}.m^{-2} for furniture (wood) and 0.47 µg.h^{-1}.m^{-2} for carpet	
Toluene		11.00 µg.h^{-1}.m^{-2} for Cushions, 0.20 µg.h^{-1}.m^{-2} for carpet, 0.5 µg.h^{-1}.m^{-2} for gypsum	
Limonene		1912 µg.h^{-1}.m^{-2} for cleaning, 24.8 µg.h^{-1} for dishes1200 µg.h^{-1} for shower (soap/shampoo), 2000 µg/event for deodorant	
Naphthalene		3.76 µg.h^{-1} Shower (soap/shampoo)	

3.3.3. Performance indicators

The performance of the ventilation system included in this review was evaluated based on various aspects, which can be categorized into six groups, as summarized in Figure 10.

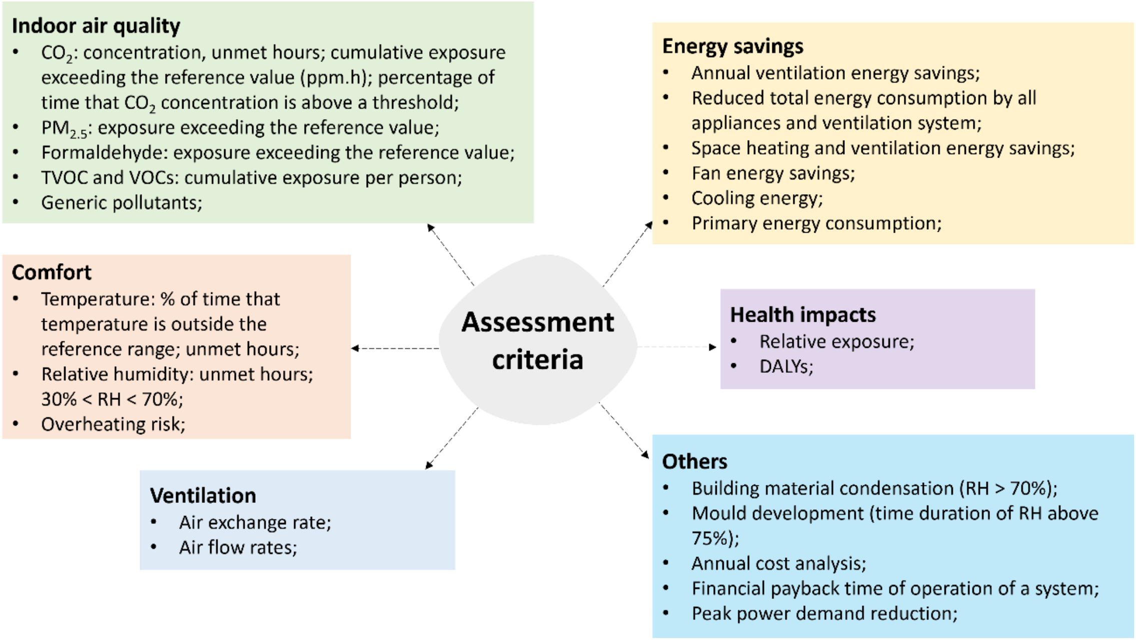


Figure 10: Performance indicator summarized from the reviewed simulation studies.

In addition to the widely used indicators for indoor air quality, energy savings, comfort and ventilation, there are some other aspects that are used to evaluate the ventilation system, for example, the water vapor-condensation in building materials, the annual cost analysis, including both the maintenance cost and operating costs, and the financial payback time of the operation of a system, etc.

The IAQ and comfort indicators are influenced by domestic activity, such as bathing, cooking, and the occupant's patterns. This underscores the significance of ensuring the quality and accuracy of input data in simulation models, particularly regarding occupancy pattern and pollutant generation scenarios.

As previously presented by (Guyot et al., 2018), CO_2 and RH are the parameters most frequently employed in evaluating smart ventilation performance. The trend is consistent with the findings of present review as depicted in Figure 11. In simulation studies, this preference primarily stems from the challenges associated with developing pollution emission scenarios from the building material, particularly for pollutants such as HCHO, PM and VOC. Similarly, in experimental studies, the reliance on CO_2 and RH is driven by the absence of accurate and cost-effective sensors for these pollutants.

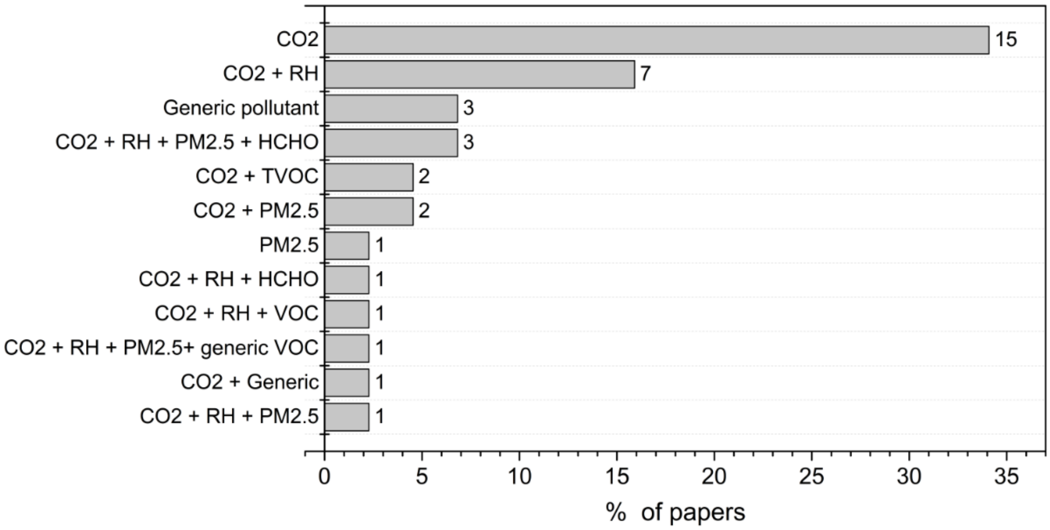


Figure 11: Parameters utilized by the authors to calculate the IAQ performance indicators.

Carbon dioxide (CO_2) is the most commonly used IAQ indicator. In this review, 15 papers (34%) used CO_2 as a parameter to assess the IAQ. The indicators using the CO_2 as a parameter are not only related to the health impact but can also represent the concentrations of bio-effluents and ventilation effectiveness (Guyot et al., 2018). This parameter is used in various ways as the surrogate of the IAQ, including, but not limited to, using CO_2 concentration (Faure et al., 2018; Kim et al., 2020), unmet hours (the sum of time that CO_2 concentrations in a zone fall outside the threshold values) (Belmans et al., 2019a, 2019b), the occupant cumulative exposure to CO_2 over a reference threshold with the unit of ppm.h (Jones et al., 2017) and the percentage of time when CO_2 concentration is above a reference threshold (Rojas, 2022). The reference threshold value ranges from 600 ppm (Müller and Dębowski, 2020) to 1000 ppm (Van Gaever et al., 2017), 1250 ppm (Carbonare et al., 2020), and 2000 ppm (Faure et al., 2018). Different thresholds for temperature and humidity are used as well. Annual cost analysis for ventilation systems (Müller and Dębowski, 2020) and financial payback time analysis (Evola et al., 2017) are relatively new concepts used to evaluate ventilation systems, which are beneficial to identifying the appropriate initial investment.

Among the used performance indicators, the concepts of relative exposure (RE) (Sherman et al., 2011) for assessing IAQ performance resulting from a ventilation system and dynamic DAILYs for assessing the health implications of exposure to indoor pollutants under a ventilation system are deployed. The theory of equivalent ventilation has been introduced to assess IAQ resulting from different ventilation systems. This theory assumes that a generic pollutant is emitted at a constant rate, outdoor air is adequate to remove indoor pollutants and there are no outdoor pollutant sources or other sources of air exchange. Based on these assumptions, the theory introduces the concept of RE to evaluate the IAQ performance of ventilation systems. It ensures that IAQ of a dwelling using a smart ventilation system is equivalent to that achieved by continuously operating fans, as required by ASHRAE Standard 62.2-2016 (ASHRAE, 2016). In some cases, the RE concept is also employed to control the ventilation system. To meet the equivalent ventilation requirements, the annual RE during occupied hours must be equal to or less than 1 and should not exceed 5 at any time to address acute exposure concerns. Dynamic ventilation control using the RE method is codified in ASHRAE Standard 62.2-2016, which governs residential ventilation. This equivalent ventilation theory is a key aspect of all Lawrence Berkeley National Laboratory smart ventilation studies included in the present review (Clark et al., 2019; Less et al., 2019; Walker et al., 2021; Young et al., 2020). The equations for RE, along with its advantages and limitations, are thoroughly discussed in the literature (Clark et al., 2019; Guyot et al., 2019; Less et al., 2019; Young et al., 2020).

DALYs, short for disability-adjusted life years, represents the combined total of years of life lost in a population because of illness or accident, plus the years lived with a disability, adjusted for the disability's severity. This measure considers both the duration and the impact of the disability on quality of life. Traditionally, two methods are employed to quantify the DALYs: the intake-DALY method, which relies on toxicological data, and the intake-incidence DALY method, which is based on epidemiological data. The latter incorporates concentration-response functions found from the literature to estimate the disease incidence, serving as an intermediate step in the DALYs calculation. The sum of DALYs reflects the harm caused by indoor air exposure to all pollutants considered over a population during the investigation timeframe. Typically, the population size is 100,000. The practical downside of these two methods is that they require the use of mean exposure concentration data as the input, and consequently, the calculated DALYs would be the mean values, which would lose information about when and where harm occurs to the occupants. (De Jonge and Laverge, 2022) developed the dynamic DALYs and applied this indicator to investigate the impact of IAQ in households with smart ventilation on occupants' health.

Comfort indicators in smart ventilation studies are often characterized by overheating risk and the percentage of time, as well as the unmet hours, where temperature and/or RH fall outside of a specified reference range. Comfort analysis in these studies adopts various definitions, including thermal comfort related solely to air temperature (Laffeter et al., 2019; Johnston et al., 2020; Cakyova et al., 2021; Grygierek and Ferdyn-Grygierek, 2022), air temperature and RH, and indoor comfort encompassing temperature, CO_2, and RH (De Maré et al., 2019; Carbonare et al.,2019; De Jonge et al., 2020).

Regarding thermal comfort, acceptable air temperature ranges from 15 to 27 °C have been reported (Belmans et al, 2019; De Maré et al., 2019; Johnston et al., 2020). As for RH, the setpoint for ventilation control varies, such as 35% < RH < 70% (K. De Jonge et al., 2022), 30% < RH < 70% (De Maré et al., 2019; Carbonare et al., 2020), 25% < RH < 70% (B. Belmans et al., 2019), 25% < RH < 60% (De Maré et al., 2019), and 20% < RH < 80% (Johnston et al., 2020). Some authors specify indoor comfort ranges according to standards like EN16798-1 (2019) (De Maré et al 2019) and NBN EN 15251 (Belmans et al., 2020).

The indicators for energy savings also vary significantly, particularly in terms of whether the electricity consumed by fans is included or not in the overall energy consumption calculations. While it is vital to account for both the space heating demand and the electricity consumed by the ventilation system in energy savings calculation, especially for systems with multiple fans and equipped with heat recovery mechanisms, there is one study that overlooks the energy consumed by fans in its calculation of energy savings (Filis et al., 2023). Primary energy reduction (Evola et al., 2017) and peak power demand reductions (Young et al., 2020) were also used as indicators of the energy performance of ventilation systems.

4. Results of simulation studies

In the previous review (Guyot et al., 2018), the control strategies have been summarised as being based on CO_2 or humidity or both, other pollutants, occupancy or outdoor pollutants. Despite the fact that these strategies continue to be used in smart ventilation controls, the set-up of these parameters has changed and new strategies have developed. This study presents the results of simulation studies based on the parameters to which these control strategies have responded. To avoid duplication, we have described studies that evaluate control strategies responding to different parameters only once under the most relevant subheadings.

These control strategies have been applied to various ventilation systems, including exhaust-only ventilation, decentralised and centralised balanced mechanical ventilation with heat recovery and hybrid ventilation systems. The objectives of smart control are diverse, including energy savings, peak power demand reduction and minimising exposure to pollutants, among other goals.

4.1. Occupancy based control strategies

To prevent occupants from experiencing high peaks of pollutant exposure upon re-entry and considering that both occupants and building materials are sources of indoor pollutants, several studies have explored occupancy-based ventilation control strategies. In this review, three papers focused on this issue in which all the studies applied equivalent ventilation theory and concept of relative exposure (RE).

(Clark et al., 2019) used the RE approach to assess IAQ and energy savings of three occupancy-based ventilation strategies for residential buildings located in four California climate zones, as defined by the California Energy Commission, and 15 climate zones across the United States, as defined by ASHRAE. This simulation study includes the continuously emitted contaminants from the building materials. Results showed that, when ventilation is completely turned off during the unoccupied period, occupants experience a peak in exposure to pollutants upon re-entering the environment due to the increased concentration of pollutants that accumulates during the off period. Furthermore, the energy consumption on ventilation to recover air quality makes this strategy impractical. In situations when the simulation used the time-varying natural infiltration rate instead of the constant annual average effective infiltration airflows, negative ventilation energy savings were observed for one-storey buildings. Specifically, one-storey buildings with an ACH_{50} of 5 in cold climates experienced up to a 24 % decrease in ventilation energy savings.

The need to rapidly reduce pollutant levels upon re-entry requires larger ventilation flow rates than for continuous operation. Reducing ventilation rates to 0.13 and 0.4 of the constant system during unoccupied periods, instead of turning off the ventilation system entirely, proves to be more efficient. The optimal approach is to reduce the ventilation rate to a continuous airflow at 0.35 times the baseline rate during unoccupied periods, which resulted in reduction in energy savings of 10 % or less except for two-storey buildings with an ACH_{50} of 5. More importantly, it also reduced the exposure to peak concentrations of pollutants upon re-entry. This lower concentration of pollutants required less airflow to recover IAQ (Clark et al., 2019). The addition of a preoccupancy flush period by turning on the ventilation 1–2 h prior to the occupants returning home proved to be the best strategy in terms of energy savings and less exposure to peak pollutants, which can result in up to 60 % energy savings for a two-storey building with an ACH_{50} of 5, according to simulations using a time-varying natural infiltration rate. One of the challenges to the implementation of occupancy-based ventilation control is accurately predicting occupancy schedules and related pollutant emissions (Clark et al., 2019).

Similar results were also obtained by (Walker and Less, 2018) who conducted a simulation study evaluating three occupancy patterns, two types of ventilation fans and two pollutant emissions scenarios. They found that median ventilation energy savings ranged 0–26 % across 15 ASHRAE climate zones, depending on the occupancy schedule, climate, ventilation type and emissions assumption. Results confirmed that turning off the ventilation system during unoccupied periods for the purpose of energy savings is not an acceptable strategy due to the increased exposure to pollutants upon re-entry (Walker and Less, 2018).

In another study, (Walker et al., 2021) developed 10 DCV strategies in three categories with the target of halving ventilation-related energy: 1) baseline and IAQ controls, in which the system tracks zone occupancy to control the zone air supplied; 2) outdoor temperature controls; and 3) zone occupancy controls, using 24-h averaged zone RE, personal RE or actual generic pollutant prediction. Energy use and IAQ performance of these strategies were evaluated for three California dwellings (one-storey and two-storey single-family prototype dwellings and a single apartment unit) in four different California Energy Commission-defined climate zones. IAQ performance was evaluated by personal contaminant concentration to three pollutants – $PM_{2.5}$, CO_2 and a generic pollutant (an unspecified, continuously emitted pollutant that can only be removed by ventilation). The emissions rate for this generic pollutant was set at 18 µg m^{-2} h^{-1}, proportional to the zone's area. The personal pollutant exposure was used to extend the equivalence concept to account for individual occupants, their movement between rooms and their absence from the building. Moisture exposure was also evaluated.

Results showed that, on average, the zonal ventilation marginally reduced personal concentration exposure to the generic pollutant and CO_2 while increasing $PM_{2.5}$ personal concentration exposure and zone hours with RH above 60 %. A less than 5 % exposure difference in personal concentration exposure was observed in the zoned ventilation compared to the unzoned ventilation. A large difference would be obtained if the unzoned ventilation served the dwelling unevenly, as in the two-storey dwelling (Walker et al., 2021).

The zonal control strategies achieved 10–30 % energy savings by reducing the outside airflow, while unzoned control strategies achieved approximately 7 % in energy savings. Optimal placement of supply and exhaust in zoned systems (such as supplying air to bedrooms and exhausting from the kitchen) can further improve efficiency. In general, exhaust-only ventilation consumed less energy than the supply-only ventilation system. Balanced mechanical ventilation systems had the highest energy use among these three types of ventilation. Most zoned systems saved more HVAC energy than unzoned controls (Walker et al., 2021).

4.2. Outdoor conditions-based strategies

Outdoor temperatures, outdoor pollutants and ambient air moisture content can be used to control the operation of ventilation systems. In this review, five papers focused on this aspect.

(Less et al., 2019) conducted a simulation study for two single-family dwellings located in four California climate zones to evaluate the energy-saving performance of six different outdoor temperature-based strategies. The control strategies included time-based lockout, measured temperature control and seasonal temperature control. Details of each control strategy are described (Less et al., 2019). In the simulation, the house was ventilated only by the mechanical system at the minimum acceptable airflow rates, with no natural ventilation used. This study was based on the RE concept and assumed the air in the house is well mixed and the outdoor air is suitable for dilution of indoor-generated pollutants. Simulation results showed that outdoor temperature-based strategies can save ventilation energy up to 33 % while maintaining the equivalent IAQ compared to constant flow ventilation systems as required by ASHRAE 62.2 (ASHRAE, 2016). Ambient temperature-based controlled ventilation is less effective in cold climate regions due to its lack of cooling season and low diurnal temperature swings. More energy savings are obtained from buildings located in regions with higher cooling demands and from buildings with less airtight envelopes, as observed across simulation cases with 1, 3 and 5 ACH_{50}.

One of the six outdoor temperature-based strategies assessed by (Less et al., 2019) was further investigated for its potential to temporarily curtail building ventilation systems and reduce peak power demand (Young et al., 2020). Simulation results showed that the outdoor temperature-based strategy achieved peak energy savings ranging from 0 to 30 % of the total building site power demand during the peak periods, while maintaining daily and annual RE of 1.0. The length of time that building ventilation systems can be temporarily curtailed was 12.9 h for one-storey and 13.5 h for two-storey single-family houses, while keeping the maximum RE to the generic pollutant less than 5, and 4.8 h for one-storey and 5.1 h for two-storey single-family houses, while keeping the maximum RE to the generic pollutant less than 2.5. The time-dependent valuation of ventilation energy savings, which varies over time, is contingent upon the climate. More energy savings are obtained in regions with a higher cooling demand. In regions with the highest cooling demand, the time-dependent valuation of ventilation energy savings reached its peak at 20 %. Conversely, no time-dependent valuation of ventilation energy savings was observed in the coldest climates. In general, residential buildings with a higher infiltration rate have less potential energy savings from smart ventilation systems. The level of peak power demand savings achieved by temporarily reducing building ventilation is similar to that achieved through other modifications such as adjusting building thermal control strategies and lighting systems.

In addition to outdoor temperature, outdoor moisture is also used to develop ventilation strategies. (Parker et al., 2018) evaluated a smart ventilation system controlled by outdoor temperature and moisture. The main principle is to ventilate less when the indoor-outdoor temperature and moisture differences are large and vice versa. The indoor target moisture level was set at 12 g m^{-3}, which corresponds to an RH of 55 % at 23.9 °C. The simulation is based on the RE concept and results showed that, depending on the maximum flow rate of the installed fan, this smart ventilation system reduced the cooling load by 59 W or 97 W and decreased moisture addition to the building by 0.14 kg or 0.04 kg, respectively, during the summer based on an hourly average. This simulation finding was validated by laboratory experiments conducted using two adjacent houses in Florida, USA, to demonstrate potential cooling energy savings. The experimental results showed that outdoor temperature and moisture controlled DCV achieved an average of 9.8 % air conditioning savings for the entire cooling season, with higher energy savings observed in May (12.4 %) compared to June (8.8 %) and July (8.7 %).

Another outdoor conditions-based simulation study was conducted in a typical Belgian apartment unit and assumes that the outdoor air quality is not always better than IAQ and consequently sometimes may not be suitable to be used to dilute indoor pollutants (K. De Jonge et al., 2022). Two ventilation control strategies were simulated and compared: one considered both the outdoor air quality (NO_2, O_3, $PM_{2.5}$ and PM_{10}) and IAQ (CO_2 and H_2O) and the other considered only IAQ (CO_2 and H_2O). Both strategies were evaluated based on DALYs, comfort and energy use. Compared with the control algorithm based only on indoor CO_2 and H_2O, the control algorithm taking into account both IAQ and outdoor air quality saved 44 % of energy use and reduced about 10 % of the total DALYs count. However, the trade-off was less comfort – an average CO_2 concentration difference of up to 50 ppm was observed, with the strategy considering outdoor air quality resulting in higher indoor CO_2 levels (K. De Jonge et al., 2022). This study indicates that considering outdoor air quality in ventilation strategies effectively reduces exposure to harmful pollutants and increases energy savings, despite a slight increase in CO_2 exposure levels.

Considering that the outdoor air in certain regions may contain pollutants at concentrations exceeding those found indoors (such as traffic-related particulates) and given that numerous ventilation systems intake ambient air into buildings directly to mitigate indoor pollutants, integration of filtration systems into these ventilation set-ups becomes imperative. (Kim et al., 2020) developed a ventilation and filtration control strategy aimed at ensuring indoor particulate matter (especially $PM_{2.5}$) concentrations meet regulatory standards and maintain acceptable IAQ while simultaneously minimising energy consumption. This strategy, known as condition zone control, is based on both the outdoor $PM_{2.5}$ concentration and the indoor $PM_{2.5}$ generating rate to determine the airflow volume from the ventilation system as well as whether the filtration system is activated or deactivated and the filter efficiency (0.65 or 0.95). A simulated comparison was conducted and showed that the conventional rule-based control strategy may lead to a high indoor $PM_{2.5}$ level when the outdoor $PM_{2.5}$ level is low but the indoor $PM_{2.5}$ generation rate is higher. This conditional-based strategy resulted in a 70 % reduction in power consumption compared to conventional rule-based ventilation while also maintaining both $PM_{2.5}$ and CO_2 levels within acceptable thresholds. This study considers only the ventilation fan energy consumption in the energy savings analysis, with space heating energy consumption excluded.

These studies show the necessity of considering outdoor conditions in ventilation control design to increase energy savings and improve IAQ.

4.3. CO_2, $PM_{2.5}$, wind speed, humidity and/or temperature-based control applied for data driven, hybrid and cooling approaches

Under this category, we only reviewed data-driven, hybrid and cooling smart ventilation studies if they included considerations for IAQ.

4.3.1. Data-driven approach for optimal ventilation operation schedule

In this review, two papers (Han et al., 2022; Kim et al., 2022) focused on data-driven approaches to optimise ventilation control schedules, aiming to improve IAQ and reduce energy consumption.

(Han et al., 2022) applied statistical methods (clustering and genetic algorithm) to build models based on real-time monitored data from an experimental house to identify indoor CO_2 patterns and estimate the fan energy consumption and then used mathematical modelling to control an existing smart ventilation system. The experimental house is situated in Sweden and is occupied by a family of two adults and two children. It features a Renson ventilation system (Renson Healthbox 3.0), which supplies fresh air to the dry rooms through self-regulating window ventilation grilles. The air flows to the wet rooms, where the air is exhausted. Continuous measurements of CO_2, RH, temperature, airflow rate, fan speed and fan voltage were conducted in seven rooms (zones) of the house at 1-h intervals. Data collection only focused workdays. During the data collection periods, the ventilation system operated in two modes: auto mode (running to a fixed schedule) and CO_2-based demand-controlled mode. The auto mode ran for 24 workdays, and the DCV mode ran for 101 workdays. In auto mode, the flow rate was maintained at a constant level of 77 % capacity of the ventilation system, with full capacity varying across different zones. In the DCV mode, the fan operated at 30 % capacity when CO_2 was below 800 ppm, at full capacity when CO_2 exceeded 950 ppm and linearly between 30 % and 100 % capacity when CO_2 levels were between 800 ppm and 950 ppm.

With the collected hourly CO_2 data from the experimental house, the elbow method was used to identify the optimal number of clusters for each hour of the day in various zones for the auto mode ventilation and the DCV mode ventilation. Living patterns across these workdays were placed into representative clusters to ensure development of an effective ventilation control strategy when the most typical days were considered. A model was also developed to estimate the energy consumption of the fan based on the airflow rate of the ventilation system. Indoor CO_2 concentration was estimated separately for occupied and unoccupied periods. Results showed that, in auto mode, the optimal number of clusters was four for the bathroom with the toilet and three for the living room/kitchen and the two bedrooms. However, in the DCV mode, the optimal number of clusters was four for one of the bedrooms and three for the other three zones: living room/kitchen, one bedroom and the bathroom with the toilet. Based on the cluster results, a genetic algorithm was proposed to control the ventilation system schedule. This proposed ventilation schedule achieved 37.8 % energy savings for the auto mode ventilation and 7.8 % energy savings for the CO_2-based DCV mode. These energy savings were estimated using a model with airflow rate as the input data.

The energy savings resulting from applying a data-driven approach to identify the optimal ventilation schedule has been demonstrated in another study (Kim et al., 2022) where the authors found that, compared to an on/off controlled balanced mechanical ventilation system, by employing the double deep Q-network, the data-driven ventilation schedule achieved 45.5 % energy savings in terms of total energy consumed. The on/off controlled system operated when indoor CO_2 concentration exceeded 1000 ppm, while all systems (ventilation system, air purifier and kitchen hood) were active when $PM_{2.5}$ was above 25 µg m^{-3}. The data-driven approach achieved slightly better IAQ, with improvements of 2.5 % in reducing exposure to $PM_{2.5}$ at a concentration of less than 25 µg m^{-3} and 0.6 % in reducing exposure to CO_2 levels below 1000 ppm (Kim et al., 2022).

While reports have indicated energy savings through the implementation of data-driven approaches to find optimal ventilation schedules, a significant limitation lies in the prerequisite availability of data before designing the ventilation system or scheduling its operation. Only two studies in this review have applied the data-driven approach, with one study relying on 5 days' training data (Kim et al., 2022). Consequently, further research is needed to explore the potential benefits of employing a data-driven approach to develop DCV strategies.

4.3.2. Hybrid ventilation for cooling and IAQ

We have included three studies related to hybrid ventilation – a system that combines or alternates natural ventilation and mechanical ventilation to achieve the best balance between IAQ, user comfort and energy efficiency, considering the constraints imposed by the buildings. This system can operate under favourable or unfavourable conditions without compromising IAQ – high wind speed, rain and low temperatures or high outdoor pollutants such as noise, VOCs and PM levels. Few studies have reported on hybrid ventilation due to the limited availability of tools for simulations, considering the complexity of hybrid systems and their control algorithms. Hybrid ventilation is also named mixed-mode ventilation (MMV) in some of the reviewed studies.

(Belmans et al., 2019b, 2019a) compared the performance of a generic MMV system with different ventilation strategies that are commonly used in residential ventilation contexts. The authors evaluated IAQ, energy demand for space heating, auxiliary fan electricity and average airflow rates for five ventilation systems in a typical Belgium residential apartment for seven different household types and 20 families per type during a year. The five ventilation strategies tested were: 1) natural supply/mechanical extract (n/M NBN); 2) constant flow balanced mechanical (M/M NBN) with a counter flow heat exchanger; 3) balanced mechanical with DCV supply and extract and a counter flow heat exchanger (M/M DCV); 4) mixed-mode ventilation (MMV) auto DCV; and 5) MMV manual DCV. The DCV systems are based on CO_2 and RH. The two evaluated mixed-mode DCVs consist of a fully natural mode by opening windows, mechanical exhaust ventilation and a balanced mechanical ventilation system with demand-controlled supply and extract flow rates with heat recovery. The MMV-auto DCV system can switch the mode automatically, while the MMV manual DCV system needs the occupant to switch the mode as per the system recommendation.

Simulation results, based on a weekly time schedule, showed that IAQ achieved and energy required for space heating were similar between the two types of MMV systems and the M/M DCV system. All performed better than the commonly used exhaust ventilation system. Compared to other dry rooms with supply outlets, the master bedroom CO_2 levels were high under the commonly used natural supply/exhaust ventilation system. This is because the exhaust terminals installed in the wet rooms experienced less resistance from other supply rooms than the bedroom, resulting in the bedroom becoming a dead zone with insufficient supply and exhaust air and fewer air changes. The average auxiliary energy use of fans by the M/M DCV was close to three times that of the MMV system. However, the energy demand for space heating by the M/M DCV was lower than that of the MMV systems. No significant difference was observed for IAQ and yearly average energy demand (including space heating demand and fan auxiliary energy use) among these three DCV systems (two types of MMV systems and the M/M DCV system). The demand-controlled MMV systems performed equally well as the M/M DCV system in winter in terms of the energy consumption and IAQ achieved. However, the demand-controlled MMV can minimise energy consumption in summer to achieve good thermal comfort as less mechanical ventilation is needed and more free cooling natural ventilation can be supplied. The mechanical flow rate in summer operation was less than 100 m^3 h^{-1} for the MMV system and in the range of 100–400 m^3 h^{-1} for the M/M DCV. Both the MMV auto DCV and MMV manual DCV systems have windows open for around 30 % of the year.

(Grygierek and Ferdyn-Grygierek, 2022) also combined natural with mechanical ventilation, evaluating different ventilation strategies in a Polish semi-detached house built in 2018. The purpose of this study was to investigate the benefits of using an earth-to-air heat exchanger (earth tube) in a ventilation system. The six strategies evaluated were: 1) natural ventilation through the automatic windows opening and closing, focusing solely on the thermal comfort of the residents; 2) natural ventilation through windows opening and closing to ensure both thermal comfort and adequate IAQ (low level of CO_2 concentration); 3) rooms equipped with supply fans to provide thermal comfort with low heating demand; 4) rooms equipped with supply fans to provide thermal comfort and mechanical ventilation for adequate IAQ (low level of CO_2 concentration); 5) earth tube strategy; and 6) earth tube CO_2 strategy, which is built on strategies 3 and 4 respectively but the ventilation airflow supplied to the rooms passes through the earth tube. The results obtained from these ventilation strategies were compared to a theoretical scenario of a building with only infiltration (reference case) in which there is no ventilation. In the reference case building, the heating demand, thermal discomfort hours, number of hours with CO_2 above 1200 ppm, maximum CO_2 and average CO_2 concentration in the living room, bedroom, children's room 1 and children's room 2 were simulated and verified. The aim of the reference case building was to minimise heating demand. However, this resulted in an extremely poor IAQ, with maximum CO_2 concentrations above 6000 ppm and CO_2 concentrations exceeding 1200 ppm for 98 % of the occupied time and overheating (temperatures exceeding 26 °C) occurring 20 % of the time. Most of the overheating occurred in the summer period.

Compared to the reference case, strategy 1 increased heating demand by 10 % but led to poor IAQ, with maximum CO_2 concentrations above 5000 ppm and average CO_2 concentrations of 2100 ppm. Strategy 2 was the least-effective strategy in terms of IAQ improvement, leading to the highest CO_2 concentration and heat demand, which was 2.2 times greater than the reference case. Strategies 3 and 5 increased heating demand by 57 % and 48 %, respectively, compared to the reference case. Although the fans in strategy 5 were activated 10 % longer than in strategy 3, the heating demand was 5 % lower due to the passive heating earth tube. Strategies 4 and 6 maintained similar maximum and average CO_2 levels. However, strategy 6 consumed 16 % less energy compared to strategy 4 due to the earth tube system. Overall, the natural ventilation system combined with automatic window opening resulted in the highest number of thermal discomfort hours. The passive heating earth tube method reduced the heat demand for the entire building by 15 % and its summer cooling effectiveness has been highlighted. This study suggests that, considering the installation cost of the earth tube and the energy savings achieved, such strategies may be not profitable at present.

4.3.3. Smart ventilation for cooling and IAQ

Ventilation for cooling has been applied in two different scenarios: in residential buildings located in hot climate regions and in residential buildings located in mild climate regions during the summer. In both situations, the occupants' behaviour regarding window opening patterns is crucial. The strategies developed for cooling purposes include natural ventilation and outdoor condition control. In this review, two papers focused on this subject.

(Cakyova et al., 2021) simulated three passive ventilation strategies in a single-family passive house in Cyprus to analyse indoor CO_2 concentration, thermal comfort (overheating risk) and energy consumption from May to September (summer season). The three ventilation strategies were: 1) original ventilation settings as a reference, which is a continuously operated summer bypass mechanical ventilation with heat recovery (MVHR), providing an ACH of 0.50 h^{-1} plus air infiltration of 0.03 h^{-1}; 2) summer bypass MVHR settings plus night mode, in which the MVHR was turned off from 22:10 to 07:50, and no windows opening during night; and 3) summer bypass MVHR settings plus night mode and smart window ventilation. Strategy 3 had two cases. Case A was open the window using an autonomous system if the maximum wind speed was less than 4 m s^{-1}, and Case B was open the windows if both the maximum wind speed was less than 4 m s^{-1} and outdoor temperatures were lower than 26 °C. In this study, comfort was defined as an indoor temperature in the range 20–26 °C.

Simulation results showed that, when the mechanical ventilation system was turned off (strategy 2) during night and without windows opening, CO_2 exceeded the normative limit of 1000 ppm for 46 % of the time and reached a maximum value of 3008 ppm. With the inclusion of window ventilation, in both cases A and B, CO_2 never exceeded the normative limit of 1000 ppm. However, given the outdoor temperatures ranged from 12 °C to 36 °C during the simulation period (May to September), overheating occurred in all scenarios more than 50 % of the time. It was more frequent for strategies 1 and 2 (60 % of the time), which had higher average indoor air temperatures (27.4 °C) compared to strategy 3 (26.6 °C for both cases A and B). Regarding energy demand, the window ventilation at night (strategy 3 case B) provided 28 % of the reduction in cooling demand compared to strategy 1, with features of 38.5 kWh.m^{-2} vs 53.6 kWh.m^{-2} (Cakyova et al., 2021).

(Kim et al., 2017) proposed an integrated comfort control strategy that integrates air conditioning (a variable refrigerant flow system), a humidifier and a ventilation system by considering the outdoor temperature and RH to ensure indoor thermal comfort and energy savings in buildings. The proposed strategy compares indoor and outdoor enthalpy to define whether ventilation is required and includes a ventilation system operating before the air conditioning system begins running. This strategy was compared to a temperature control strategy and a comfort control strategy in terms of comfort ratio (a ratio of the duration within the comfort zone to a reference time), time to reach the comfort range and energy consumption. The psychrometric charts evaluate the humidity levels in rooms, which is similar to the DC MEV to some extent. The thermal comfort zone in this simulation study was set to be dry bulb temperature in the range 24.4–26.5 °C and RH between 40 % and 55 %. The results showed that the integrated comfort control strategy presented a good result in terms of comfort ratio and reduced energy consumption by 13–37 %. The temperature control strategy took a longer time to reach the comfort range and also required higher energy consumption (Kim et al., 2017). A similar level of cooling energy savings from operating the outdoor temperature and humidity-controlled DCV has been reported by (Parker et al., 2018).

4.4. Temperature, humidity and/or CO_2-based control ventilation for decentralised systems

We reviewed four studies in this category, all focusing on decentralised systems. Apartment buildings and renovated residential buildings may not have the space to install a centralised ventilation unit and the associated ducting. For this reason, wall-integrated decentralised mechanical ventilation systems with demand-controlled controllers have been investigated. Room-based ventilation achieves IAQ and comfort in every zone according to the occupant's satisfaction. The simulation studies applying room-based ventilation system reviewed in this paper ranged from a winter week to a full-year period, all conducted under the European climate. Energy savings among these reviewed studies ranged from 3 % to 85 %.

(Carbonare et al., 2019) proposed and evaluated two comfort-oriented control strategies based on a façade integrated room-based ventilation unit. On average, 10 % energy savings were achieved from these two proposed strategies compared to the commonly used linear and step control strategies.

Another simulation study conducted by the same team evaluated four strategies for a façade integrated room-based ventilation unit – constant, steps comfort-oriented and fuzzy control (Carbonare et al., 2020). The fuzzy controlled strategy is defined by a mathematical model that is provided according to the interpretation of indoor RH and CO_2 concentration and fan speed is controlled based on instantaneous measurements of these two parameters. The proposed fuzzy controlled strategy aims to achieve a trade-off between energy efficiency (minimising ventilation system airflow), high humidity levels (avoiding high RH to protect building materials with RH less than 75 % to avoid mould growth), avoiding both high and low RH to protect occupants' health (RH below 20 % and 30 % is respectively regarded as unacceptable and undesirable) and indoor air quality (CO_2 as the indicator with CO_2 levels below 1250 ppm, assuming ambient CO_2 concentrations of 400 ppm). Simulation results showed the comfort-oriented controlled strategy achieved the best IAQ but around 3 % energy savings against the steps controller strategy. This highlights a discrepancy between results from different simulation studies: while 10 % energy savings were reported in (Carbonare et al., 2019), only 3 % energy savings were observed in (Carbonare et al., 2020), despite using the same control strategies. Occupants in the step-controlled DCV and fuzzy-controlled DCV environments experienced about 1.8 times poorer IAQ (using CO_2 levels below 1250 ppm as an indicator) compared to the comfort-oriented controlled strategy and 5.6 times poorer IAQ in the constant DCV environment compared to the comfort-oriented controlled strategy. A fuzzy DCV strategy achieved about 25 % energy savings compared to a constant airflow strategy and about 12 % energy savings compared to a step-controlled DCV (Carbonare et al., 2020).

In addition to the façade integrated room-based ventilation unit, (Smith and Kolarik, 2019) simulated (using IDA ICE) and assessed a manifold of fans connected to an apartment level air-handling unit to control the supply of airflow to each room in an apartment. The results showed that this system was effective in saving energy and maintaining IAQ targets related to CO_2, RH and temperature, with 74 % savings in fan energy consumption relative to the reference constant air volume system achieved and CO_2 only exceeding the limit in the bathroom, which did not have CO_2-based control. Meanwhile, according to the simulation, infiltration heat losses increased by 18 % during the winter season with closed doors despite the use of acoustic vents to assist overflow, which indicates that less-resisting overflow vents are needed in doorways to prevent infiltration heat loss when supplying bedrooms with greater airflow.

A study compared widely used mechanical extract ventilation (MEV) and room-based ventilation units under three French climatic conditions (Filis et al., 2023). The three ventilation systems evaluated were constant MEV, RH-controlled mechanical extract ventilation (RH-MEV) and constant flow balanced room ventilation units with heat recovery. These systems were compared in terms of the energy savings for space heating demand. The RH-MEV control for the exhaust fans in the bathroom and kitchen was running linearly when the RH was between 30 % and 70 %. When the RH was below 30 %, the exhaust fan was running at the minimum airflow rate, and when the RH was above 70 %, the exhaust was running at full speed. Simulation results showed that the inlet air temperature of MEV systems was below 16 °C for more than 88 % of the heating season, while in dwellings equipped with room ventilation units, the supply air temperature was above 16 °C for more than 93 % of the simulation time (a heating season). The simulation study demonstrates that, compared to constant MEV, the energy savings in space heating demand are between 61 % and 85 % for room ventilation units and between 44 % and 75 % for RH-MEV. Notwithstanding the impressive energy savings reported above, this simulation study did not take into account energy consumption by fans in terms of energy savings. Fan energy consumption for room ventilation units was higher compared to exhaust-only systems.

4.5. Humidity, CO_2, and/or HCHO, presence-based centralised ventilation systems

This category accounts for the highest number of studies, with 15 papers covering detached single-family houses, apartment buildings and multi-unit buildings in different European countries and climates.

(Pollet et al., 2017) compared IAQ and energy loss due to ventilation between three ventilation strategies in the Belgian and French contexts. The strategies evaluated were: 1) natural air supply in all habitable rooms (dry rooms) and demand-controlled mechanical extraction in wet rooms (conventional MEV); 2) natural air supply in all habitable rooms (dry rooms) and demand-controlled mechanical extraction in each room (both wet and habitable); and 3) natural air supply only in the bedrooms (night zone) and demand-controlled mechanical extraction in each room (both wet and habitable). The simulation results showed that adding extraction to bedrooms or to all habitable rooms resulted in better IAQ in the habitable rooms compared to conventional MEV. Ventilation heat losses are smaller for ventilation systems with only natural air supply to bedrooms and demand-controlled mechanical extraction in each room. However, for such a ventilation system, the extract volumes from the wet rooms should always be higher than the extract from the bedrooms to avoid a reverse airflow. Strategy 3 worked best in terms of both IAQ and energy consumption. Two weeks of in-situ measurements in a Belgian single-family house demonstrated that the bedrooms with natural air supply and mechanical extract ventilation consistently performed well, maintaining a CO_2 level consistently below 1200 ppm.

(Jones et al., 2017) simulated three DCV strategies for one detached house and one flat, which represent a large part of the United Kingdom housing stock. Each of the dwellings was simulated with envelope air leakage V_{50} of 0.6, 2.5, 5, 7.5 and 10 $m^3\ h^{-1}.m^{-2}$ at 50 Pa. The three ventilation strategies all used naturally supplied and mechanically extracted air, but the supply air was either naturally supplied without any control algorithm or controlled by the local RH, and the mechanically exhausted air was controlled either by RH or both CO_2 and RH at the local level. The simulation results revealed that all ventilation systems can achieve similar IAQ to the reference system (continuous MEV). Compared to the reference system, the average reduction factor for ventilation heat loss of the three proposed ventilation strategies across the two types of houses and five different air permeabilities was 0.83, and the average fan consumption reduction factor was 0.93. Among the three evaluated strategies, total energy consumption was reduced by 8 % to 23 %. The one with natural supply and local CO_2 and RH controlled mechanical extract achieved the highest reduction in both ventilation heat loss and fan electricity consumption. This was followed by the strategy with RH-controlled supply and RH-controlled mechanical exhaust air and then the strategy with natural supply and RH controlled mechanical exhaust air.

The control algorithm, location of sensors and number of sensors impact the performance of DCV systems. (Rojas, 2022) found that balanced MVHR, controlled by a single CO_2 sensor located in the common exhaust within the MVHR unit, did not outperform constant MVHR regarding IAQ, especially when the dwelling is not fully occupied, which was evaluated by the percentage of occupied time with the CO_2 exposure above 1000 ppm. In another study, (Faure et al., 2018) demonstrated how the distribution of leakage across the building envelope affects the performance of ventilation systems and highlighted the importance of a multiple sensor-based DCV strategy in mitigating the effects of uneven air leakage distribution to achieve the desired IAQ.

(Faure et al., 2018) did 100 simulations for two single-family houses located in France. Each house had a global building leakage value, q_{a4}, of 0.6 $m^3\ h^{-1}\ m^{-2}$ under a pressure difference of 4 Pa. This value represents the air leakage rate at 4 Pa divided by the loss surface area excluding the basement floor. The leakage was unevenly distributed across the building envelope for 50 simulations and evenly for another 50 simulations. Both houses were equipped with RH-based MEV. Simulation results showed that the impact of the distribution of building envelope leakage on energy consumption was within 2 % and negligible. However, its impact on IAQ, indicated by the cumulative hours of CO_2 above 2000 ppm, was not negligible, as 50 % of the simulations failed to meet the air quality requirements when the air leakage was unevenly distributed, while IAQ met the requirements when the air leakage was evenly distributed. Air leakage through internal partition walls in the transfer zone has a large impact on the overall IAQ of residential houses equipped with MEV. The findings of this study (Faure et al., 2018) suggest adopting a multiple sensor-based DCV strategy to mitigate the effects of uneven air leakage distribution in buildings to achieve the desired IAQ. This study also included experimental testing of two DCV systems: RH-controlled DCV and RH and CO_2-controlled DCV. The results showed that the maximum CO_2 level in the master bedroom for RH-controlled DCV was nearly double that of RH and CO_2-controlled DCV (3500 ppm vs 1800ppm).

(Pecceu et al., 2018) conducted simulation and onsite monitoring studies measuring CO_2, RH and temperature in living rooms and bedrooms at 5-min intervals over 2 years in 25 Belgian residential buildings. The types of ventilation systems used in the monitored dwellings were not specified. The monitoring data revealed that the correlation between moisture and CO_2 was not obvious or was even non-existent, with the yearly average correlation coefficients being 0.05 and 0.09 in the living room and bedroom, respectively. This indicates that RH alone is not an adequate control parameter for DCV in the living room. The simulation results showed that, in comparison to constant ventilation systems, DCV can achieve the equivalent IAQ with reduced airflow. However, DCV system with the control logic based on linear RH seems less efficient in maintaining IAQ compared to constant flow regulation especially when the occupancy changes, i.e. the dwelling is occupied by more people. In contrast, CO_2 and moving averaged (based on room occupancy) strategies required only 50–80 % of the airflow to achieve the same level of IAQ.

(Van Gaever et al., 2017) assessed four ventilation strategies in a one-storey detached Belgian dwelling and found that a local CO_2-controlled or CO_2 and water vapour-controlled ventilation system with air supply to the living rooms and bedrooms and air exhaust from wet rooms (kitchen, bathroom, toilet, and laundry) was the most effective ventilation strategy in terms of controlling CO_2 and RH exposure and to reduce the airflow rate. Compared to a ventilation system that involves air supply in the night zone (bedrooms), recirculation in the day zone (living room with additional outdoor air supply) and extraction in service spaces, the system of air supply to dry rooms and extract from wet rooms is easier to implement. Importantly, it does not involve the potentially polluted recirculated air. For each of the four assessed strategies, both manual control (ranging from 100 % to 30 % of the total airflow rate) and demand control were simulated.

(Baptiste Poirier et al., 2021b) evaluated three ventilation systems in a single-family house in the French context: 1) constant exhaust-only ventilation; 2) balanced constant ventilation; and 3) RH-based DCV (considered as a reference in France). The extracted airflows are the same for systems 1 and 2. Simulation results indicated that none of the three ventilation systems met all IAQ targets, which included five indicators: CO_2 cumulative exposure (thresholds of 1000 d ppm.h), humidity from the health perspective (percentage of time spent by an occupant with RH outside of the range 30–70 %), humidity from the condensation risk perspective (percentage of time with RH above 70 %), cumulative formaldehyde exposure (threshold of 9 d µg m^{-3}.h) and cumulative $PM_{2.5}$ exposure (threshold of 10 d µg m^{-3}.h), in which d is the simulation duration in hours (h). None of these three ventilation systems resulted in an IAQ that met the $PM_{2.5}$ targets. The balanced constant ventilation system provided the best IAQ in terms of CO_2, HCHO and condensation risk indicators. The RH-based DCV system provided slightly better IAQ in terms of humidity from the health perspective, reducing the 10 % exposure to RH outside of the range 30–70 %. The performance of the exhaust-only ventilation was comparable to the RH-based DCV in most aspects except for condensation risk. The exhaust-only ventilation was 67 % less efficient than the RH-based DCV ventilation in managing condensation risk. This result confirms that the RH-based DCV provided a clear advantage over constant exhaust-only ventilation, despite having lower airflows during periods of low humidity.

In another study conducted by (Poirier et al., 2022), five ventilation strategies were evaluated in a Danish apartment using the five IAQ indicators mentioned in the preceding paragraph: 1) constant exhaust-only ventilation; 2) RH-based exhaust-only ventilation; 3) constant balanced ventilation with heat recovery (constant MVHR); 4) RH-based balanced ventilation with heat recovery (RH-MVHR); and 5) RH and CO_2-based balanced ventilation with heat recovery. The simulation results indicate that DCV strategies can improve IAQ while decreasing airflows. For example, the HCHO exposure can be reduced 6–28 % for RH-based exhaust-only ventilation compared to constant balanced ventilation with heat recovery. The RH-MVHR system provided better IAQ regarding CO_2, HCHO and lower exposure to RH above 70 % than constant MVHR. However, constant MVHR saved 51 % energy consumption compared to the RH-MVHR system.

Formaldehyde as a control variable of a DCV system with heat recovery was assessed in Danish homes with the aim of investigating the impact of building-generated pollutants on the energy demand in homes (Johnston et al., 2020). An HCHO emissions model was developed based on measurement data in which temperature, humidity and ACH were included as predictor variables. The model is valid only for newly built or renovated houses (less than 5 years) and is coded to IDA ICE software in neutral model format. The authors simulated five different ventilation strategies for an apartment studio with a floor area of 20 m^2. A total of 161 scenarios were simulated with different combinations of ventilation control parameters. Simulation results showed that having a minimum ACH of 0.22 h^{-1} is necessary to protect the occupants from HCHO harm. In addition, a base ventilation rate of 0.3 L s^{-1} m^{-2} and DCV systems using HCHO as a control variable are able to prevent harmful levels of HCHO. The DCV systems with heat recovery improved IAQ and consumed 3 % less energy than constant MVHR.

The performance of DCV under the humid continental climate in Poland were explored (Müller and Dębowski, 2020; Sowa and Mijakowski, 2020). (Müller and Dębowski, 2020) estimated the difference in operating cost of achieving maximum CO_2 concentrations of 600 ppm, 700 ppm, 800 ppm and 1000 ppm in a Polish single-family house with a balanced ventilation system installed where the air is supplied to the dry rooms and exhausted from the wet rooms. The ventilation system operated in two modes: day mode from 07:00 to 23:00 for 16 h and night mode for the remaining 8 h. In each mode, the ventilation system either supplied or exhausted a constant volume of air to or from the rooms. Simulation results revealed that this control strategy effectively maintained the CO_2 level as required. The annual operating cost, which includes the running costs of the two fans and the energy required to heat the supply air to 20 °C, was found to be twice as high for keeping the maximum CO_2 below 600 ppm compared to maintaining the maximum CO_2 below 800 ppm. Significant annual operating savings of 22.1 % were observed when maintaining the maximum CO_2 at 1000 ppm compared to 800 ppm. This study highlights the importance of taking the operating cost into account when selecting a ventilation system.

(Sowa and Mijakowski, 2020) analysed a humidity-based DCV system that was installed in an eight-floor multi-unit residential building in Poland. This study is the only one included in this review that attempted to evaluate ventilation strategies for multiple units within a residential apartment building. The analysis evaluated the performance of the humidity-controlled ventilation system in terms of potential energy savings and improving IAQ. It also aimed to determine whether the system could reduce discrepancies in ventilation intensity across different floors and eliminate reverse flows in the ventilation ducts. Results showed minimal variation in ventilation performance among units on the same floor when different ventilation options were implemented. The efficiency of passive stack ventilation was influenced by outdoor temperature and wind conditions, leading to increased instances of unwanted backflows and significant airflow discrepancies between units on lower and higher floors of the building such as between the second and eighth floors. Humidity-controlled ventilation systems resulted in fewer backflows but less airflow into the building compared to passive stack ventilation systems and were unable to achieve the required ventilation rate. However, the difference in the airflows on different levels of the building was lower, and the airflow was not dependent on the ambient temperature. Compared with the humidity-controlled stack ventilation system, the performance of the ventilation system was better when exhaust fans were mounted on the roof above the individual exhaust ducts to support airflows induced by natural forces when needed, and no unwanted backflows occurred under this ventilation option. The average CO_2 concentrations under different ventilation options were 1146 ppm for passive stack ventilation, 1289 ppm for humidity-controlled stack ventilation and 1053 ppm for humidity-controlled ventilation with a roof-mounted exhaust fan. Using humidity-controlled ventilation with a roof-mounted exhaust fan resulted in a 21 % reduction in the energy needed to heat the ventilation air compared to passive stack ventilation.

(Evola et al., 2017) evaluated the energy (both final energy and primary energy) and financial convenience of five ventilation strategies in a residential apartment unit during the heating seasons in three Italian cities: Milan, Rome and Catania. The five ventilation strategies assessed were: 1) opening and closing windows; 2) constant MEV; 3) RH-controlled MEV; 4) constant MVHR; and 5) RH-controlled MVHR. Strategy 1 considered two scenarios: opening 25 % of the window's openable area and opening 10 % of the window's openable area. Simulation results showed that, compared to the final energy consumption associated with ventilation via opening 25 % of the window's openable area, final energy reductions were observed with the operation of mechanical ventilation. Specifically, final energy reductions were up to 70 % with constant MEV and up to 95 % with RH-controlled MVHR across these three cities. In colder climates, MEV systems provide lower energy savings compared to MVHR systems. The primary energy reductions were approximately 70 % for MEV systems and 90 % for MVHR systems across these three cities. Reductions in annual energy bills (including fan electricity consumption and heat demand for ventilation heat loss) ranged from 70 % (constant MEV) to 82 % (RH-controlled MVHR) in Rome. In addition, this study (Evola et al., 2017) revealed that MEV systems have a shorter payback time compared to MVHR systems. This is primarily attributed to the higher initial cost of MVHR systems and the additional electricity consumption required to operate the two fans. In cold climates, the payback period for MVHR systems is shorter because of the heat recovery benefits provided by the system, leading to greater reductions in annual energy bills. However, this benefit is less significant in warm climates where the outdoor conditions are mild in winter. For example, it would take 15 years and 6 years for the overall installation cost of MVHR to be paid back in Catania and Milan, respectively. The MEV configuration cost could be recovered within 6 years and 3 years in Catania and Milan, respectively. Heating system efficiency and initial cost of the ventilation system have more impact on payback time than the electricity price.

A recent novel development in the field of DCV is assessing ventilation performance through the health implications of exposure to different indoor pollutants under different ventilation strategies, expressed as DALYs. (De Jonge and Laverge, 2022) reformed the original DALYs calculation methods to incorporate time-resolved data in DALYs calculation, enabling the identification of when and where harm occurs to the occupants over a period of time when detailed pollutant exposure data is available. This dynamic DALYs concept has been used to examine the health implications of exposure to indoor VOC contaminants (HCHO, benzene, limonene, naphthalene and toluene) when the household is equipped with a continuous ventilation system and a DCV system that is controlled by presence, RH and CO_2 respectively. VOC contaminants are emitted from building materials and the occupants' activity in the household. Total dynamic DALYs during a year due to exposure to the five above-mentioned VOC contaminants for a working adult living in a typical Belgian apartment were 2.2 years when the household was ventilated by a constant mechanical ventilation system as required by Belgian ventilation regulation and 8.6 years when the dwelling was ventilated by the presence, RH and CO_2-based DCV system. This DCV was controlled by continuous measurements of presence, CO_2 and RH to optimise the airflow rate, varying from 30 % to 100 %. The energy consumed, including both space heating and fan electricity consumption, was 2307 kWh for constant mechanical ventilation and 1008 kWh for DCV. In other words, a 1300 kWh energy savings is a trade-off with a 6.3-year loss in DALYs. Two additional simulation studies (De Jonge et al., 2023; Klaas De Jonge et al., 2022) conducted by the same team of authors and based on the same Belgian apartment building discovered a similar result: while DCV results in significant energy savings, it also causes an increase in the sum of DALYs.

(Klaas De Jonge et al., 2022) examined the impacts of changing household sizes on individual exposure to individual pollutants for a RH, CO_2 and presence-based DCV system. The simulation studied 10 households of 2–6 occupants and showed that changing the number of occupants in a dwelling equipped with a presence, RH and CO_2-based DCV system (with heat recovery and an efficiency of 85 %) did not significantly affect the DALYs of a stay-at-home adult. The mean DALYs across the 10 households were 15.84 years (range: 14.75–17.72 years), while the mean energy use was 987 kWh (range: 731–1319 kWh).

To further investigate the impact of changing household numbers on individual exposure to pollutants, (De Jonge et al., 2023) assessed three control strategies based on mechanical ventilation systems with heat recovery (efficiency of 85 %) and compared their performance with a constant MVHR system. Ventilation was controlled by occupant-dependent parameters (CO_2, RH and presence in one of the three strategies). Pollutants included in the simulation were VOCs associated with both residents' activities and building materials and furniture. The simulation also studied 10 households with household sizes of 2–6 and found that, for a stay-at-home adult, the sum of DALYs ranged from 10.5 years (minimum) and 18 years (maximum) across all 30 simulated scenarios. Among these three control strategies, adjusting the airflow rates on a room-by-room basis resulted in the smallest DALYs, while the highest DALYs were observed from the ventilation system operated by day zone (living room) or night zone (bedroom) and adjusting the supply airflow rates based on the measurements of CO_2 in the two zones. The DALYs result for constant mechanical ventilation at 100 % of the nominal flow rate was about 3.5 years and did not fluctuate according to household size. This number was approximately five times lower than DCV, regardless of the control strategies used. The energy used (including space heating and the fan electricity consumption) for constant mechanical ventilation with heat recovery was about 2.5 times the energy used by the DCV systems – 25,000 kWh vs 10,000 kWh. The results highlight that DCV, which is controlled by pollutants that do not cause harm to occupants, might overlook the harm to occupants caused by pollutants that do cause harm.

The extent to which pollutant impacts most on total DALYs depends on which pollutants are considered in the model as pollutants of concern. For instance, in a simulation that considered seven pollutants of concern (benzene, HCHO, naphthalene, limonene, toluene, NO_2 and O_3), a minimum of 86.4 % of the harm was attributable to HCHO (Klaas De Jonge et al., 2022). However, this percentage increased to 97.7 % when NO_2 and O_3 were excluded from the pollutants considered in the model (De Jonge et al., 2023). The change in pollutants of concern influence the total DALYs of an individual in the household as well as the energy use of the household. These two studies (De Jonge et al., 2023; Klaas De Jonge et al., 2022) found that the absolute value of correlation coefficient between changing the number of occupants and DALYs of a stay-at-home adult was below 0.25. This indicates that the actual occupancy pattern of the other occupants is a more deciding factor than the number of the household occupants in terms of the exposure to non-occupant-dependent pollutants.

5. Results of experimental and *in-situ* studies

The settings of the experimental and in-situ studies encompassed four single-family detached houses, three typical apartment units, one apartment studio, one combination of single-family detached house and typical apartment unit, one controlled laboratory environment and one unknown setting. The duration of the studies ranged from 11 min (Pantelic et al., 2023) to a full year (Derycke et al., 2018). The studied ventilation systems include a decentralised ventilation system (room-based ventilation), classic MEV and modified DCV system. Six of the studies were conducted in Belgium and France. Although many simulation studies and laboratory experiment studies have shown the benefits of operating a DCV system, only a few have investigated their in-situ performance. All publications regarding DCV in-situ performance are peer-reviewed conference papers.

5.1. Experimental set-up studies

(Rahnama et al., 2023) designed a ventilation system that incorporated a heating system with the aim of eliminating the need for a separate system and being able to satisfy different room temperature requirements and airflow rates in each zone. The system is a balanced mechanical ventilation system with an air-handling unit and equipped with supply and exhaust fans, filters and a heat exchanger. In addition to these components, the novel component of this system is a manifold with a built-in heating coil and so-called heat values for each room with the supply duct regulating the temperature of the supply air. The airflow rate of the supply air is individually regulated at room level within the dwellings through adjustments in supply fan speed and a variable air volume damper. Negative pressure is maintained, with total exhaust airflow 5 % higher than total supply airflow. The control logic considers the heating demand of each zone, including indoor temperature and supply airflow rate. The developed system was tested in a controlled laboratory environment over a day and a half. During the test, the outdoor temperature varied between 2 °C and 16 °C, with indoor temperature set-points at 20 °C and 25 °C. The experimental results indicated the ability of the system to achieve and maintain individual room temperatures while ensuring the required airflow rate met IAQ requirements (based on minimum airflow rates per square metre) though not addressing the RH or CO_2 levels. The limitations of this study are that it was conducted in a controlled laboratory environment, no occupant activities were involved and there was no evaluation of the performance in terms of RH and CO_2 levels.

(Laffeter et al., 2019) tested a ventilation system called VMI in an occupied two-storey single-family house and compared data from a previous study investigating MEV. The VMI system incorporates a heat exchanger supplier with water from a reversible heat pump to preheat or precool the supply air. The conditioned supply air is blown into each of the dry rooms (living room, bedroom, mezzanine and office), circulates through the door's undercuts and is extracted from every wet room (kitchen, shower room, bathroom and toilet) through designed openings. The supply airflow rate varies according to the indoor RH and outdoor absolute humidity, with seven set-points ranging total airflow from 77 to 267 $m^3\ h^{-1}$. The exhausts consist of vents in the window frames in the ground-floor toilet, bathroom and shower room, a 5 $m^3\ h^{-1}$ mechanical extractor in the first-floor toilet and a vertical duct in the kitchen. Absolute humidity in the bathroom, window opening behaviour, indoor $PM_{2.5}$, and outdoor $PM_{2.5}$ were evaluated. Another evaluation parameter was the ICONE index, which shows the air stuffiness levels. The ICONE index scores range from 0 to 5, where 0 indicates excellent conditions with no stuffiness and 5 represents poor conditions with extreme stuffiness. This indicator is a logarithmic function of the percentage of exposure time spent in a room with a CO_2 concentration greater than 1000 ppm and 1700 ppm, providing greater weight to higher concentrations of CO_2 and neglecting concentrations below 1000 ppm (Ribéron et al., 2011; Rueda López et al., 2021).

(Laffeter et al., 2019) found that the use of the VMI system significantly improved air exchange rates, maintaining the ICONE's excellent value throughout the entire period from 01:00 to 05:00 in the bedroom while the VMI system was on. In contrast, without the VMI, the ICONE's excellent value was only achieved 43 % of the time. The median CO_2 was 508 ppm and 958 ppm when the VMI system was on and off, respectively. The absolute humidity in the bathroom of the house equipped with the VMI system was maintained below 13 g/kg for 95 % of the time, and the RH in bathroom was estimated below 75 % for 90 % of the time. Compared with data from a previous study investigating MEV, the absolute humidity in the bathroom in the house equipped with the VMI system was higher than in the house installed with the MEV system. The ratio of indoor to outdoor $PM_{2.5}$ during the period when the VMI was operated with the filter was close to 25 % of the ratio when the VMI was operated without the filter. This VMI increased the supplied air temperature by 10–25 °C above the outdoor air temperature (5–20 °C) and contributed to 25–40 % of the household total heating power demand during the heating season.

(Shin et al., 2018) investigated an energy recovery ventilation system with the aim of achieving acceptable night-time ventilation and mitigating the risk of condensation. This study consisted of two parts: a mock-up experiment to determine whether the CO_2 level in the living room or bedroom was more effective in controlling the ventilation system and an evaluation of the CO_2-controlled ventilation system. A CO_2-controlled ventilation system was modified to maintain CO_2 levels during night-time hours within acceptable levels, defined as the difference between outdoor and indoor CO_2 concentrations below 700 ppm. The effectiveness of this ventilation control strategy was tested through a mock-up experiment in a South Korean apartment unit. Results showed that the strategy was effective in preventing window surface condensation, assessed by comparing the window surface temperature in the main bedroom to the indoor air dew point temperature. Fan flow rates during the night were reduced to keep the noise level of the ventilation system below 40 dB and prevent occupant discomfort from fan noise. Additionally, results showed that a living room-based control can maintain the overall CO_2 concentration in the entire house at acceptable levels. The ventilation energy consumption would be reduced if the CO_2 were dispersed through keeping bedroom doors open.

(Pantelic et al., 2023) experimentally evaluated eight algorithms (seven tested strategies plus one reference strategy) in a fully furnished residential unit with a floor area of 32.6 m^2 to assess how IoT-enabled sensors can control cooking-emitted pollutants, specifically $PM_{2.5}$. The experimental cooking process lasted 11 min, including 1 min preheating the pan and 10 min cooking. The IoT sensors consisted of $PM_{2.5}$ sensors and a circuit monitor for tracking the stove's on/off status. The eight strategies ranged from a temperature-controlled constant air supply (reference) to various combinations of PM-activated stove hoods, PM-activated portable air cleaners (PACs), a circuit monitor-activated stove hood and a circuit monitor-activated stove hood and PACs. Details of each control strategy are described in (Pantelic et al., 2023). Results showed that single interventions such as PM-activated stove hoods or PACs significantly improved integrated $PM_{2.5}$ concentrations when properly sized. Source control with a stove hood was more effective than removing the particles using PACs. The seven control strategies achieved an average $PM_{2.5}$ concentration reduction of 81–94 % compared to the reference case (baseline). Accounting for a 10 % measurement uncertainty, the strategies fell into two groups: one with PM-activated PACs, which reduced $PM_{2.5}$ by 80 %, and another with stove hoods or combinations of stove hoods and other interventions, achieving a 90 % reduction. However, the difference between these groups was not statistically significant. This study also suggested that, during cooking, the hot plume with emitted particles first rose to the ceiling and then moved across the kitchen ceiling to the living room and dispersed into other parts of the kitchen opposite the stove. It highlighted the importance of sensor locations for the rapid detection of cooking-emitted $PM_{2.5}$ concentrations.

Another study based on IoT was conducted by (Chiesa et al., 2019) who developed and tested an IoT platform to monitor both the indoor and outdoor environments, including CO_2, TVOCs, temperature, and RH, and optimise ventilation to ensure an acceptable indoor environment. The ventilation system includes an extractor fan and an inlet with the same net opening areas. This system was tested in a custom-made prototype box with a net volume of approximately 0.4 m^3. Positive results were demonstrated over a test period of 1 h, showing that this ventilation system was able to maintain CO_2 levels below 1000 ppm and VOC levels below 0.087 ppm and kept RH within the range 40–70 %. However, the platform is not equipped with a heat recovery unit or a filter, so energy loss is inevitable and IAQ may deteriorate if it is used in areas where the outdoor air is polluted.

5.2. In-situ studies

Five in-situ studies all investigated the performance of DCMEV systems. Three studies assessed commercially available MEV systems from the manufacturer Renson: Healthbox® II (Derycke et al., 2018) and Healthbox® 3.0 (De Maré et al., 2019; Lokere et al., 2019). The remaining two studies did not specify the name of the ventilation system's manufacturer (Jardinier et al., 2018; Sutter et al., 2022). Healthbox® II and Healthbox® 3.0 systems supply fresh air to dry rooms via self-regulating window ventilation grilles. The air then moves to wet rooms through doors via door grilles, where it is extracted. Extraction rates are controlled based on factors such as the presence of people, humidity, CO_2 and VOCs. Both Healthbox® II and Healthbox® 3.0 incorporate SmartZone technology. The system is referred to as with SmartZone when it extracts air from both bedrooms and wet rooms and without SmartZone when it extracts air only from wet rooms.

(De Maré et al., 2019) conducted the first large-scale field data analysis of a DCMEV system. The data was collected from 350 Belgian dwellings over a winter period of 4 months from December 2018 to March 2019. Half of the buildings were single-family dwellings and the other half were apartments. All the dwellings were equipped with a Healthbox® 3.0 system – half with SmartZone and the other half without SmartZone. Air extraction was controlled locally based on absolute humidity and RH in the bathroom and utility room, CO_2 in the kitchen and bedrooms (for dwellings with SmartZone) and VOC in the toilet. Outdoor air was supplied through passive trickle vents located on top of the windows in dry rooms. The 4-month measurement data showed that, for at least 80 % of the time, typical RH in dry rooms fell within the ranges of 30–70 % or 25–60 %. In bedrooms with the extraction fan installed (dwellings with SmartZone),

CO_2 levels remained below 950 ppm for at least 90 % of the night (21:00 to 07:00). During the daytime (07:00 to 21:00), IAQ in the kitchen was assessed and CO_2 levels were below 950 ppm for 90 % of the daytime.

(Lokere et al., 2019) analysed real-time monitoring data collected by IoT-assisted sensors from 900 relatively new Belgian dwellings equipped with a Renson Healthbox® 3.0 system. The results showed that this DCV system effectively maintained indoor moisture levels within acceptable ranges, with the risk of mould growth remaining below 2.4 % across all rooms in the dwellings.

(Derycke et al., 2018) compared the results of 12-month in-situ measurements of two ventilation systems: Healthbox® II and MVHR. The MVHR system was reported to recover 80 % of energy based on laboratory test results. The houses investigated were constructed to passive house standards in Belgium. The monitoring campaign was carried out in three categories: general sensing in all dwellings; detailed monitoring in a subset of dwellings; and additional metering in a small sample for in-depth studies, including end-user comfort evaluations and performance assessments of the ventilation. All buildings were similar in terms of typology, architecture, building construction and orientation. The space heating demand was estimated by subtracting domestic hot water energy used from total heat use.

Results (Derycke et al., 2018) showed there was no significant difference in metered heat use for households equipped with DCMEV (Healthbox® II) and MVHR. This can be explained by the low airflow rates due to demand control, which reduces ventilation heat losses and thereby reduces heating demand. No significant difference in IAQ was observed for the houses with the two different ventilation systems. Monitored space heating demand for dwellings with DCMEV was approximately 30–85 % lower than the simulation results across nine dwellings. In contrast, monitored space heating demand for dwellings with MVHR was close to the simulation results, varying from 15 % higher to 30 % lower than the simulation results across six dwellings. In terms of fan electricity consumption, DCMEV consumed only one-third of the expected amount whereas MVHR consumed twice as much as expected. The average yearly fan electricity consumption of DCMEV was 15–25 % of the fan electricity consumption of MVHR. Overall, there was no significant difference in total energy consumption (combining space heating and fan electricity consumption) between DCMEV and MVHR. However, the total cost of the DCMEV system was about 30 % less than that of the MVHR system over a 15-year period. This cost difference, which considered initial investment, electricity consumption, space heating consumption and maintenance costs, was primarily due to the higher initial investment and maintenance costs associated with the MVHR system.

(Sutter et al., 2022) compared the performance of MEV when the extract ventilation outlet was controlled by CO_2 and TVOCs, respectively. The CO_2 and TVOCs control sensors were installed side by side on the kitchen and bedroom extraction dampers in 29 low-energy Belgian households. Each control was run for 2 weeks with three such cycles conducted, which corresponded to 12 weeks of in-situ measurement. Results showed that the average airflow rate under TVOCs-controlled ventilation was 50 % higher than it was under CO_2-controlled ventilation. On average, during 40 % of the operation time, the airflow rate under TVOCs-controlled ventilation was higher than that under CO_2-controlled ventilation. A weak correlation between CO_2 and TVOCs was observed. The result indicated that TVOCs-controlled ventilation works well when the occupant conducts activities that generate TVOCs, such as painting and cleaning.

While most of the in-situ studies were conducted in Belgium, (Jardinier et al., 2018) investigated the performance of RH-controlled MEV systems in 30 occupied apartment units in France after nearly 10 years of operation. Preliminary results showed that 80 % of the initially installed instruments were in working condition, and the drift of the hygroscopic devices (controlled by RH) were, on average, within the manufacturer's accuracy specification (±1.8 %). An absence of maintenance was observed – for example, 90 % of the batteries of the presence-based toilet exhaust fans were discharged. This finding highlights the importance of regular maintenance inspections for ventilation system.

6. Discussion of smart ventilation performances

This review evaluates 44 studies conducted internationally over the past 7 years (2017–2023) on smart ventilation in residential buildings and reveals that there is no standard approach for smart ventilation performance indicators, simulation input data or the results reporting. While comparisons are frequently made within the study or among studies, these often involve different simulation settings, reference ventilation systems and buildings. In this section, we discuss the performance results of smart ventilation on three main aspects – comfort, IAQ and energy savings. We also discuss the variations in simulation input data and results reporting at the end of this section.

6.1. Performance based on comfort indicators

Comfort performance indicators are not the same according to the studies (K. De Jonge et al., 2022; De Maré et al., 2019; Laffeter et al., 2019) and authors also used different thresholds (Belmans et al., 2019b; Carbonare et al., 2020; K. De Jonge et al., 2022; De Maré et al., 2019; Johnston et al., 2020). In some cases, the focus was on energy savings and IAQ, with comfort being considered as a secondary benefit. For example, a given strategy may have reduced energy consumption and improved or maintained IAQ while ensuring that comfort remained within the set standards.

Comfort has been directly investigated in eight of the studies included in this review. Generally, smart ventilation strategies based on comfort-oriented controls or outdoor temperature or designed for cooling or heating provide better comfort gains (Belmans et al., 2019b; Carbonare et al., 2019; Kim et al., 2017). These gains include a reduction in yearly unmet hours of temperatures above 28 °C from 423 to 0 (Belmans et al., 2019b, 2019a), a 98 % reduction in hours of thermal discomfort (Grygierek and Ferdyn-Grygierek, 2022), a 10 % reduction in the overheating period (Cakyova et al., 2021), a decrease in the time consumed to achieve the comfort zone (48 min compared to where the temperature was never reached without the smart ventilation strategy) (Kim et al., 2017), and a reduction in the air exchange rate when it was not needed, resulting in improved indoor temperature comfort without compromising IAQ (5 % worse at most) (Carbonare et al., 2020, 2019).

6.2. Performance based on indoor air quality indicators

When analysing the impact of ventilation strategies on IAQ, various approaches are used. This includes variability in the parameters used to develop performance indicators and evaluate IAQ. Some studies report a reduction (or, in some cases, an increase) in pollutant concentrations, a decrease in the number of hours pollutants exceed the set-up threshold (Jones et al., 2017; Van Gaever et al., 2017) and health impacts associated with exposure to indoor pollutants (De Jonge et al., 2023; De Jonge and Laverge, 2022). Some authors apply the equivalent ventilation theory to assess the performance of proposed strategies based on the energy savings (or, in some cases, reduced peak power demand) while maintaining the same IAQ levels as a continuous mechanical ventilation system or another reference system (Walker et al., 2021; Young et al., 2020).

Figure 12 summarises the IAQ results obtained through various smart ventilation strategies. Some strategies resulted in a deterioration in IAQ. Of the 17 comparisons presented in Figure 12, five show a negative effect on IAQ, which is highlighted in red.

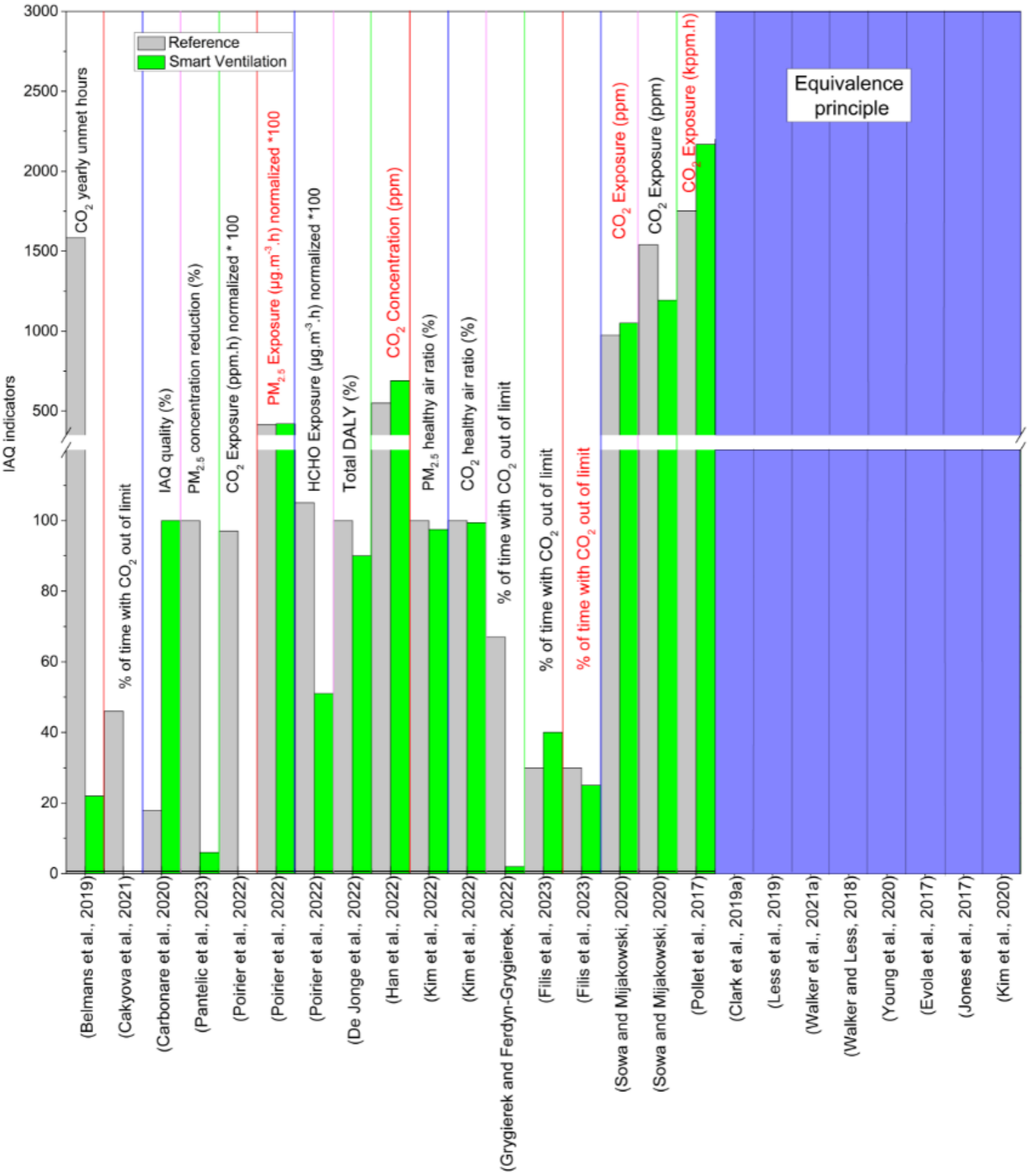


Figure 12: Indoor air quality results obtained through smart ventilation strategies compared to reference ventilation systems.

In general, the IAQ results presented in Figure 12 relate to pollutant concentrations or exposure in the master bedroom. When a study included multiple strategies, the graph only displays the strategy that achieved the best results compared to the reference system. In some cases, the same study is represented more than once, indicating that the authors analysed different indicators or applied the same strategy to different scenarios. For example, (Sowa and Mijakowski, 2020) implemented the same strategies for both the second and eighth floors of a building.

The smart ventilation strategy was not always compared to a constant air volume system. The reference systems varied and included the "opening and closing windows" ventilation strategy (Evola et al., 2017), constant air supply system (Pantelic et al., 2023), constant MEV (Jones et al., 2017) and constant MVHR (De Jonge et al., 2023; Johnston et al., 2020; Rojas, 2022). The CO_2 threshold varied across studies, ranging from 800 ppm (De Maré et al., 2019) to 1250 ppm (Carbonare et al., 2019). Additionally, IAQ was quantified in terms of health impact by means of DALYs, attributed to exposure to various pollutants such as VOCs, including benzene, formaldehyde, naphthalene, limonene, toluene, NO_2, O_3, $PM_{2.5}$ and PM_{10}. Since the introduction of methods to calculate DALYs given a population-wide exposure to a specific indoor air contaminant, these methods have been modified to calculate the time-resolved DALYs (De Jonge and Laverge, 2022).

Using DALYs to estimate the health impacts of different ventilation strategies is a relatively new concept. While smart ventilation systems are effective in saving energy, they may result in increased harm to occupants due to exposure to pollutants. For example, a year-long simulation study of a three-bedroom apartment in Belgium with four occupants using the time-resolve dynamic DALYs calculation shows that a 1300 kWh energy savings by the smart ventilation system is a trade-off with a 6.3-year loss in DALYs due to the exposure to formaldehyde, benzene, limonene, naphthalene and toluene (De Jonge and Laverge, 2022). The extent to which pollutants impact most on total DALYs depends on which pollutants are considered in the model as pollutants of concern. For instance, in a simulation that consider seven pollutants of concern (benzene, HCHO, naphthalene, limonene, toluene, NO_2 and O_3), a minimum of 86 % of the harm was attributable to HCHO (Klaas De Jonge et al., 2022). However, this percentage increased to 97 % when NO_2 and O_3 were excluded from the pollutants considered in the model (De Jonge et al., 2023). A recently published study showed that $PM_{2.5}$ accounts for approximately 94 % of DALYs among the investigated pollution, which include $PM_{2.5}$, PM_{10}, O_3, NO_2 and sulphur dioxide (Belias and Licina, 2024). The study also highlights that the overall health cost due to exposure to poor IAQ is higher than the energy costs (Belias and Licina, 2024).

In total, four studies (De Jonge et al., 2023; K. De Jonge et al., 2022; Klaas De Jonge et al., 2022; De Jonge and Laverge, 2022) included in this review have evaluated the impact of air quality achieved under different ventilation strategies on occupants' health, with outcomes illustrated by DALYs. These four studies were conducted by the same research team and focused on similar indoor pollutants, suggesting a need for further research into the impact of residential ventilation on both health and energy consumption. Future studies in this regard need to span aspects of both geographic and types of pollutants.

6.3. Performance based on energy savings

Figure 13 summarises energy savings and overconsumption results through the implementation of different ventilation strategies in different studies. Some studies report energy savings in a range among different strategies (represented by bars), while others present averaged results for each strategy individually (represented by points). Although most studies show average results, one study presents the median (Walker and Less, 2018). When a study includes multiple strategies, it either shows the range (min-max) of average ventilation energy savings among these strategies or the average savings for each strategy individually as shown in the study.

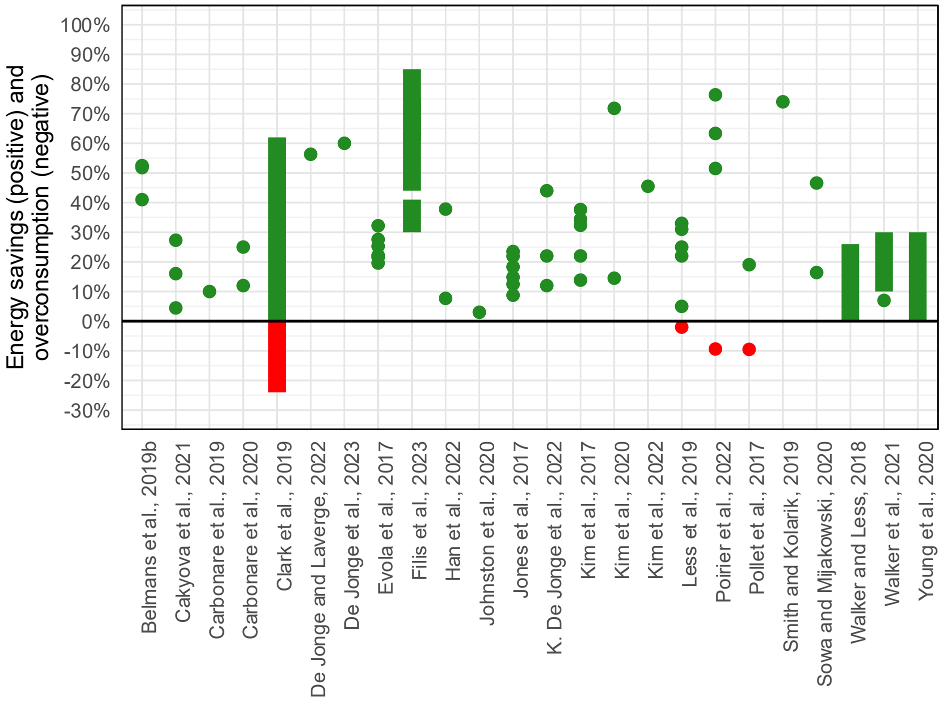


Figure 13: Summary of energy savings and overconsumption from different simulation studies.

Among the reviewed studies, energy savings of the investigated strategies ranged from -24 % to 85 %, with most studies reporting savings between 10 % and 40 %. A previous review study on residential DCV showed similar results: energy savings resulting from operating DCV ranged from -26 % to 60 % (Guyot et al., 2018). Due to variations in input data across simulation studies such as weather files, building characteristics, considered pollutants and occupant schedule, energy savings results are very difficult to compare among the different studies. For example, (Clark et al., 2019) found that, with the only changed parameter being air infiltration rate, energy savings ranged from -24 % (the highest energy overconsumption observed in this review) to 62 % with time-varying infiltration airflows but ranged from -5 % to 35 % with annual average effective infiltration airflows. (Klaas De Jonge et al., 2022) observed a 15 % relative standard deviation in energy use among 10 simulated cases when the only changed parameter was occupants (including both number and their activities). (Jones et al., 2017) observed a 2–4 % increase in energy savings when changing the building type from a flat to a detached house. The previous review study is also in agreement with our study and points out that the results from different studies were unable to be compared (Guyot et al., 2018).

Among the reviewed studies, the reference ventilation system varies. Some use constant mechanical ventilation, others use DCV and some use MVHR. These differences impact energy savings outcomes. (Johnston et al., 2020) found 3 % of annual energy savings from demand-controlled MVHR. This was a comparison result with constant flow MVHR rather than the common reference case without a heat recovery system. In contrast, energy savings of 51–76 % in the study conducted by (Poirier et al., 2022) were compared to those of demand-controlled MVHR and constant flow MEV without heat recovery.

When assessing the energy consumption of different ventilation systems, it is crucial to account for both space heating demand and auxiliary consumption of the ventilation system. Specifically, fan electricity consumption should be considered when comparing DCMEV with MVHR, as MVHR requires more electricity to run due to the running of two fans (supply and exhaust), high airflow resistance due to protective filters and narrow passages of the heat exchanger and the increased pressure drop (Derycke et al., 2018). The electricity consumed by fans in room-based ventilation systems needs to be considered as well, as more than one fan would be involved. However, (Filis et al., 2023) neglected to account for the energy consumed by the fans in the calculation of energy savings when comparing the performance of room-based ventilation units with other commonly used ventilation systems, which makes the maximum energy savings of 85 % less robust. (Kim et al., 2020) only calculated the energy consumed by the fan and did not consider space heating energy. (Young et al., 2020) showed the reduction in peak power demand. (K. De Jonge et al., 2022) used the relative change in average supply airflow rates to indicate changes in energy use.

The simulation studies summarised in Figure 13 indicate that energy savings of up to 85 % can be achieved with certain strategies. Interestingly, an in-situ measurement study found not much difference in total energy consumption or IAQ between houses using MVHR and DCMEV (Derycke et al., 2018). Regarding fan electricity use, DCMEV consumed only one-third of what was expected, while MVHR consumed two times more than the expected electricity use. The average yearly fan electricity consumption of DCMEV was 15–25 % of the fan electricity consumption of MVHR. This suggests that, while simulations show significant potential for energy savings, actual performance in real-world conditions may vary, highlighting the importance of validating simulation results with practical measurements. When considering the cost of initial investment, electricity consumption, space heating consumption and maintenance, the DCMEV system was about 30 % less than that of the MVHR system over a 15-year period (Derycke et al., 2018). Energy savings is only one indicator of ventilation system performance. Energy consumption, comfort achieved and IAQ are interconnected. In each ventilation case, a balance is needed between these factors to achieve optimal performance. Additionally, financial considerations (including initial costs and long-term operation and maintenance costs) are essential in selecting the ventilation strategy.

6.4. Identification of gaps and barriers

Throughout this paper, we have highlighted variability in simulation duration, the parameters used to develop performance indicators and ventilation reference systems. Additionally, there are other variations in simulation input data and results reporting such as emissions scenarios related to the building itself and residents' activities. Many authors have pointed out the lack of consistent emissions data and suggested the need for investigations into pollutants emissions rates during periods when homes are unoccupied.

Various occupancy schedules and behaviour models have been used in simulations. The only commonality among all reviewed studies regarding occupancy patterns is that time spent in bedrooms from midnight to early morning (06:00) is generally consistent. Some studies (De Jonge et al., 2023; Klaas De Jonge et al., 2022) have found that the actual occupancy pattern of the other occupants is a more deciding factor than the number of the household occupants in terms of the exposure to non-occupant-dependent pollutants in a household equipped with an occupant-dependent pollutants-controlled ventilation system. This raises questions about how to balance occupancy patterns and household numbers in the simulation study to minimise their impact on simulation outcomes.

Regarding simulation assumptions, some studies assume that the building is a well-mixed single zone, while others use multi-zone simulations. Outdoor air quality is often assumed to be better than IAQ, although some authors have highlighted the opposite. The assumption of building envelope airtightness is crucial to simulation outcomes (Clark et al., 2019; Faure et al., 2018). When simulations used a time-varying natural infiltration rate instead of the commonly used constant annual average effective infiltration airflows, the results for energy savings changed dramatically (Clark et al., 2019). When building air leakage was unevenly distributed, 50 % of the simulations failed to meet air quality requirements, whereas IAQ met the requirements when the air leakage was evenly distributed (Faure et al., 2018).

In some studies, the relative percentages of energy savings were calculated by dividing the energy savings from smart controls by the energy consumption of baseline ventilation (Clark et al., 2019; Less et al., 2019; Walker and Less, 2018), while in some other studies, the relative changes of the average ventilation flow rates compared to the reference cases were used to indicate the ventilation energy savings (K. De Jonge et al., 2022). Some studies report a range of energy savings, while others only provide the average or maximum savings. Additionally, energy savings are calculated in various ways, including only ventilation energy, space heating energy during heating months, cooling energy during cooling seasons and annual heating and cooling energy.

We found a contrast in results by using ‘warm’ or ‘cold’ to describe the climate within a certain country. To be specific, (Clark et al., 2019) found that the annual ventilation energy savings in US cities located in warm climates are higher than those in cities located in cold climates. However, (Evola et al., 2017) showed that more energy savings were obtained in the cold regions than in the hot regions from a study conducted in three Italian cities. This contrast could be avoided if a standard exists in terms of describing the climates around the world. We also find a discrepancy between results from different simulation studies, though the control strategies were the same (Carbonare et al., 2020, 2019).

In conclusion, the simulation duration ranged from one day in a winter, which represents the mean winter day according to the weather data (Van Gaever et al., 2017), to one heating season (Carbonare et al., 2020, 2019; Filis et al., 2023), and to a 1-year period (Müller and Dębowski, 2020). The control strategies, the objectives, the threshold of the expected air quality and the energy savings indicators are different in different studies, which subsequently leads to a different result and conclusion. Referring back to the review by (Guyot et al., 2018), it is evident that, despite advancements in ventilation technologies employing various strategies and performance indicators, the limitations highlighted by the authors in 2018 remain consistent with those outlined in this study.

6.5. Limitations

The limitations of this study are as follows.

- Although the search was conducted using as many combinations of the keywords as possible, different search results might be obtained with alternative search combinations such as using ‘moisture’ or ‘mould’ instead of ‘humidity’. However, it is not believed that changes in search string combinations would significantly affect the article search outcomes or the results of this review.
- It is worth noting that some studies consider both indoor and outdoor air parameters in developing ventilation strategies. In this case, the study could be considered in either category. There is no strict rule for categorising these strategies, and differences may exist when different researchers categorise them. These differences are generally considered to be very minor.
- The database search was conducted in August 2023. Since then, several publications on this topic have emerged. However, the emergence of new publications since then does not impact the relevance or comprehensiveness of the findings of this review as the overall trends and outcomes have remained consistent.

7. Conclusion and perspectives

This study reviewed the papers published from January 2017 to August 2023 as a continuation of the work by (Guyot et al., 2018) who reviewed the publications in this field up to 2016. The objective of this review is to answer two questions:

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

This review found that smart ventilation has increasingly been investigated in recent years. Single-family houses and apartment units are the most commonly investigated building types. Most ventilation strategies respond to RH or CO_2 or both. Outdoor conditions and occupancy are also used to develop ventilation strategies. The theory of equivalent ventilation is generally one of the key aspects of smart ventilation studies. Over the past 7 years, DCV concepts have been applied to some new areas such as ventilation for cooling and hybrid ventilation. The use of DALYs to estimate the health impact of exposure to indoor pollutants under various ventilation strategies is a new development. The DALYs approach to estimating the health impact highlights the importance of balancing energy savings and IAQ.

Among the total included studies, 77 % were conducted using a simulation approach. The energy savings of the simulation studies ranged from -24 % to 85 %. More than 70 % of studies showed a positive effect on indoor air quality with the use of smart ventilation. There are clear discrepancies in modelling input data, performance assessment criteria and results reporting, which makes cross-study comparisons impossible. Currently, there is no standard approach for assessing the performance of smart ventilation simulation, including input data, performance indicators or results reporting, and this issue has been considered during the IEA-EBC Annex 86.

Recent studies have integrated air purifiers into ventilation control systems, employed data-driven methods to develop control strategies and included financial analyses of these systems. Decentralised DCV is an emerging area, as it is beneficial to apartment renovations where space for centralised ventilation units is limited. It also addresses the individual ventilation needs of occupants in different zones within a building. A decentralised ventilation system has more important practical implications in terms of preventing the spread of pollution or viruses in the context of a pandemic. However, energy consumption by multiple fans in decentralised DCV system might be a shortcoming of this system.

Based on the findings of this review, the following areas for future research were identified:

- In-situ studies are needed to validate the performance of simulated ventilation strategies. Such studies would assess the practicality of these strategies, including validity of assumptions; impact of sensor location; number, accuracy and durability on ventilation performance; and performance of smart ventilation in different types and sizes of dwellings. Additionally, investigating the long-term performance and maintenance optimisation of smart ventilation system is also important.
- Research is needed to establish a standardised approach for assessing ventilation performance, ensuring consistency in simulation input data, performance indicators, assessment criteria and reporting outcomes, and to coordinate smart ventilation strategies according to climate conditions and building types, sharing data and technologies to improve the ventilation system performance.
- More studies are needed to investigate how smart ventilation could contribute to cooling demand. It would also be interesting to explore how smart ventilation systems can simultaneously achieve the goals of minimising carbon emissions, maximising cost benefits, increasing energy savings and improving indoor environmental quality. The sweet spot where occupants' health is not harmed while achieving these benefits needs to be discovered.
- Research on how urban heat islands and varying microclimatic conditions affect the efficiency and effectiveness of smart ventilation systems could also provide valuable insights for optimizing their performance in densely populated areas. This includes exploring how smart ventilation can mitigate adverse effects of urban microclimates on comfort, indoor air quality and energy consumption.

In conclusion, this review summarises the benefits of smart ventilation. It also identifies gaps in existing smart ventilation studies and highlights the research needed in the future. Addressing these gaps will advance the development of smart ventilation, contributing to both energy savings and improvements in indoor environmental quality. The findings of this review are significant for the selection of appropriate ventilation strategies and the design of ventilation systems. Implementing smart ventilation systems in both new and existing buildings will help reduce energy consumption in the building sector and promote more sustainable and healthy environments

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9. Supplementary information

Table S1: Summary of the occupancy pattern data in the reviewed simulation studies.

Reference	Zone/Time		7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6
(Smith and Kolarik, 2019)[1]	Kitchen		1					1					1	1	1											
	Bathroom		1	1																						
	Living											1	1	1	1	1	1									
	Room 1																	2	2	2	2	2	2	2	2	2
	Room 2																	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
(Cakyova et al., 2021)[2]	Room 1 (2 occ)		0.25														0.5	0.75	1	1	1	1	1	1	1	0.5
	Room 2 (1 occ)		0.25														0.25	0.75	1	1	1	1	1	1	1	0.75
(Walker et al., 2021)	Weekdays		🟦										🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Weekends		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
(Clark et al., 2019) (Walker and Less,2018)	1st shift	weekdays	🟦										🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
		weekends	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	3rd shift	weekdays	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦										🟦
		weekends	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	1st shift extended	weekdays	🟦															🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
		weekends	🟦	🟦	🟦			🟦	🟦	🟦	🟦	🟦	🟦			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
(Poirier et al., 2022)	Kitchen	Occ 1	🟧					🟧							🟧											
		Occ 2						🟧							🟧											🟧
		Occ 3						🟧							🟧											🟧
	Bathroom	Occ 1																								🟩
		Occ 2	🟩																							
		Occ 3														🟩										
	Living	Occ 1	🟨	🟨				🟨	🟨							🟨										
		Occ 2	🟨	🟨				🟨	🟨							🟨										🟨
		Occ 3	🟨	🟨				🟨	🟨							🟨										🟨
	Bedroom	Occ 1															🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
		Occ 2															🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
		Occ 3															🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
(Filis et al., 2023) (Faure et al., 2018) *weekend is highlighted in blue	Kitchen			2	2	1	1			1	1			4	1											
	Bathroom			1	1			1	1			1	1			1	1									
	Living room					3	3	3	3	3	3	3			3	3	3	4	2							
	Master bedroom		2	1	1															2	2	2	2	2	2	2
	Bedroom 1		1																1	1	1	1	1	1	1	1
	Bedroom 2		1																1	1	1	1	1	1	1	1
(Johnston et al., 2019)	weekdays		1								0.5	0.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	weekends		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
(Kim et al., 2022)	Sleeping																			🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Rest		🟨	🟨										🟨	🟨	🟨		🟨	🟨							
	Cooking		🟧					🟧						🟧												
	Eating			🟧				🟧							🟧											
	Vacuuming			🟪										🟪												
	Exercise																🟥									

(Muller and Debowski, 2020)	Bedroom	Occ 1									🟦					🟦			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
		Occ 2	🟦	🟦									🟦						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
		Occ 3	🟦	🟦							🟦		🟦					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
		Occ 4	🟦	🟦														🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Bathroom	Occ 1	🟩															🟩								
		Occ 2		🟩														🟩								
		Occ 3			🟩												🟩									
		Occ 4												🟩					🟩							
	Living	Occ 1												🟨	🟨											
		Occ 2				🟨	🟨								🟨	🟨	🟨									
		Occ 3												🟨	🟨	🟨										
		Occ 4												🟨	🟨	🟨										
	Kitchen	Occ 1	🟧									🟧	🟧				🟧									
		Occ 2			🟧						🟧	🟧					🟧									
		Occ 3			🟧							🟧					🟧									
		Occ 4		🟧								🟧					🟧									
(Pecceu et al., 2018)[3]	Living room		3	3	4	4	4	3	4	1				4	4	3	2	1								
	Main bedroom			1						1	1	1	1					1	2	2	2	2	2	2	2	2
(Poirier et al., 2021b) (Poirier et al., 2021c)[4]	Kitchen		2 h 40 min per day																							
	Bathroom		40 min per day																							
	Living room		2 h 50 min per day																							
	Bedroom		9 h 20 min per day																							
(Van Gaever et al., 2017)	Kitchen	Ad 1	0.75 h per day																							
		Ad 2	1.08 h per day																							
		Ch 1	0.25 h per day																							
		Ch 2	0.50 h per day																							
	Living	Ad 1	14.83 h per day																							
		Ad 2	8.33 h per day																							
		Ch 1	9.58 h per day																							
		Ch 2	8.00 h per day																							
	Laundry	Ad 2	0.25 h per day																							
	Hallways	Ad 2	0.25 h per day																							
	Bathroom	Ad 1	0.58 h per day																							
		Ad 2	0.83 h per day																							
		Ch 1	0.50 h per day																							
		Ch 2	0.75 h per day																							
	Bedroom 1	Ad 1	7.58 h per day																							
		Ad 2	12.25 h per day																							
	Bedroom 2	Ad 2	0.25 h per day																							
		Ch 1	13.42 h per day																							
	Bedroom 3	Ad 2	0.25 h per day																							
		Ch 2	14.50 h per day																							
	WC	Ad 1	0.25 h per day																							
		Ad 2	0.25 h per day																							
		Ch 1	0.25 h per day																							
		Ch 2	0.25 h per day																							

[1] weekends: living room occupied from 9:00 to 22:00h.

[2] Used the level of occupancy (%)

[3] Four occupants. Schedules represented just in the main bedroom (2 occupants) and living room (4 occupants – 2 adults and 2 kids).

[4] The number of occupants is assumed considering the size of the house.

10. Appendix 1

Table A1 presents the names of the journals in which the included papers were published, along with their impact factor and CiteScore. The Energy and Buildings and Journal of Building Engineering each published four papers, followed by Building and Environment and Energies, where each of them published three papers.

Table A1: Names of journals according to the number of studies published in this journal included in this review.

	Journal	Number of papers published in this Journal included in this review	Impact factor of the Journal*	CiteScore of the Journal*
1	Energy and Buildings	4	6.7	11.8
2	Journal of Building Engineering	4	6.4	8.3
3	Building and Environment	3	7.4	11.3
4	Energies	3	3.2	5.5
5	Science and Technology for the Built Environment	2	1.9	3.7
6	Atmosphere	1	2.9	4.1
7	sustainability	1	3.3	6.8
8	International Journal of Ventilation	1	1.5	3.4
9	Indoor Air	1	5.8	8.0
10	Building Simulation	1	5.5	7.7
11	Ecological Chemistry and Engineering S	1	1.9	3.3
12	Earth Systems and Environmental Sciences	1		

* Data were retrieved from the respective journal websites on April 3, 2024, except for the data from the sustainability journal, which were retrieved on May 26, 2025.

Regarding the conference papers included in this review, 90% of the total (19 out of 21 papers) were published in the proceedings of AIVC conferences. Two papers were published in the IOP Conference Series: Materials Science and Engineering.

Table A2 presents the rank of institutions with at least two publications. In instances of cross-institution collaborations, the same article was counted for each institution involved. For example, in a collaboration between Ghent University and Renson Ventilation, each institution is credited with one paper. Ghent University appears at the top of the list with 12 published papers. It is followed by Renson Ventilation with six published papers, and then by Lawrence Berkeley National Laboratory with five publications. Technical University of Denmark (DTU) and CEREMA from France each published 4 papers, followed by Université Savoie Mont Blanc and The Ohio State University with 3 papers. Twelve institutions appear with two publications each.

Table A2: Rank of institutions according to the number of articles.

Rank	Institution	Number of papers published
1	Ghent University	12
2	Renson Ventilation, Belgium	6
3	Lawrence Berkeley National Laboratory (LBNL)	5
4	Technical University of Denmark (DTU)	4
4	CEREMA, France	4
5	Université Savoie Mont Blanc	3
5	The Ohio State University	3
6	Belgian Building Research Institute (BBRI)	2
6	Karlsruhe Institute of Technology (KIT)	2
6	Fraunhofer Institute for Solar Energy systems (ISE)	2
6	AERECO SA France	2
6	Dankook University	2
6	Vrije Universiteit Brussel	2
6	Universiteit Antwerpen	2
6	Flemish Institute for Technical Research, Belgium	2
6	Daidalos Peutz Bouwfysisch Ingenieursbureau	2
6	National Institute of Standards and Technology, USA	2
6	Université Grenoble Alpes	2
6	Seoul National University	2

11. Appendix 2

Table A3: Emission generation scenarios in the reviewed studies

Parameters		Emission rate	Reference	Based on standard
CO_2	Adult awake	16 L.h^{-1}	(Van Gaever et al., 2017) (Pecceu et al., 2018)	CEN/TR 14788: 2006
CO_2 asleep	Adult asleep	10 L.h^{-1}		
H_2O	Adult awake	55 g.h^{-1}		
H_2O asleep	Adult asleep	40 g.h^{-1}		
H_2O kitchen	kitchen	morning and noon 0.5 L.s^{-1} (10min); evening 0.6 L.s^{-1} (10min) + 1 L.s^{-1} (10 min) + 1.5 L.s^{-1} (10min)	(Van Gaever et al., 2017)	
H_2O Bathroom	Bathroom	0.5 L.s^{-1} per shower (10min)		
Laundry room	Laundry room	0.06 L.s^{-1} (12h)		
VOC		Proportional to the floor area of each room (fixed emission rate) to represent the material emission in a simplified manner.		
CO_2	awake	18 L.h^{-1}	(Baptiste Poirier et al., 2021a)	CEN 2006
CO_2 asleep	asleep	15 L.h^{-1}		
H_2O	awake	55 g.h^{-1}		
H_2O asleep	asleep	40 g.h^{-1}		
H_2O laundry	laundry	laundry 252g.h^{-1}		
		Laundry + dry 136.8g.h^{-1}		
H_2O shower	shower	1440 g.h^{-1}		
H_2O cooking	cooking	Breakfast 1512 g.h^{-1}		
		Lunch 2268 g.h^{-1}		
		Dinner 2844 g.h^{-1}		
Formaldehyde/m^2 of floor area		High 23.6 µg.h^{-1} .m^{-2}		
		Medium 12 µg.h^{-1} .m^{-2}		
		Low 4.5 µg.h^{-1} .m^{-2}		
$PM_{2.5}$ from cooking		High 2.55 mg.min^{-1}		

		Medium 1.91 mg.min^{-1}		
		Low 1.26 mg.min^{-1}		
CO_2	Adults asleep	6.5 mg.s^{-1}	(Walker et al., 2021)	National Institute of Standards and Technology
	Child asleep	4 mg.s^{-1}		
CO_2	Adult awake	10 mg.s^{-1}		
	Child awake	6.5 mg.s^{-1}		
H_2O	adult awake	15 mg.s^{-1}		ASHRAE 160—2016
	adult asleep	9 mg.s^{-1}		
	child awake	10 mg.s^{-1}		
	child asleep	6 mg.s^{-1}		
	Dishwashing	130 mg.s^{-1}		
	Cooking	140 mg.s^{-1}		
	Showering	330 mg.s^{-1}		
	Background emission	20 mg.s^{-1}		
$PM_{2.5}$	cooking	0.0208 mg.s^{-1}		
	other	0.00007 mg.s^{-1}		
generic contaminant		18 µg.h^{-1} .m^{-2}		ASHRAE 62.2
CO_2 light activity	Adult	19 L.h^{-1} *	(Klaas De Jonge et al., 2022; Ghijsels et al., 2022)	*Norm CEN 14788
	Child	12.6 L.h^{-1}		
	Baby	6.7 L.h^{-1} *		
H_2O	Adult	55 g.h^{-1} *		
	Child	41.3 g.h^{-1}		
	Baby	18.3 g.h^{-1} *		
CO_2	Adult	14.4 L.h^{-1}	(Carbonare et al., 2020) (Belmans et al., 2019b)	(Persily and de Jonge, 2017)
	Child	9 L.h^{-1}		
H_2O	Adult	45 g.h^{-1}		(Firla̧g and Zawada 2013)
	Child	35 g.h^{-1}		
	Washing machine	250 g.h^{-1}		
	Dishwasher	200 g.h^{-1}		
	cooking	500 g.h^{-1}		

	shower	500 g.h^{-1}		
	Plants	30 g.h^{-1}		
CO_2	Activity level 1.0 MET	8.5 mg.s^{-1}	(Filis et al., 2023)	CCFAT, 2017
H_2O		40 – 45 g.h^{-1}		
	cooking	Breakfast 50 g/person		
		Lunch 150 g/person		
		Dinner 300 g/person		
	shower	300 g/shower/person		
	Laundry	200 g/laundry		
	Drying	1000 g/drying		
H_2O	Shower (15 min)	7.22·10−4 kg.s^{-1}	(Johnston et al., 2020)	(Tenwolde and Pilon 2007)
	Cooking (30 min)	1.33·10−4 kg.s^{-1}		
CO_2 (1 person)	Sleeping	1.65e-4 m^3.s^{-1}	(Kim et al., 2022)	ICATUS 2016 report (United Nations Statics Division, 2017) and the Time use survey 2019 (Statics Korea, 2020)
	Exercise	9.69e-4 m^3.s^{-1}		
	Vacuuming	8.25e-4 m^3.s^{-1}		
	Cooking	4.07e-4 m^3.s^{-1}		
	Eating	2.47 e-4 m^3.s^{-1}		
	Rest	1.86 e-4 m^3.s^{-1}		
	Work	2.68 e-4 m^3.s^{-1}		
$PM_{2.5}$	Vacuuming	70 µg.min^{-1}		
	Cooking	10 µg.min^{-1} - oven		
		283 µg.min^{-1} - grilled		
		1483 µg.min^{-1} - fried		
CO_2	Sleeping	10 dm^3.h^{-1}	(Müller and Dębowski, 2020)	
	Sitting person	15 dm^3.h^{-1}		
	Light work	20 dm^3.h^{-1}		
	Medium work	35 dm^3.h^{-1}		
CO_2	Adult awake	18 L.h^{-1}	(Rojas, 2022)	Månsson (Ed.), 2002)
	Adult asleep	12 L.h^{-1}		
	Child awake	12 L.h^{-1}		

	Child asleep	8 L.h^{-1}		
CO_2	One occupant in 'sleeping' and 'seated quiet' state	0.20 to 0.25 L.min^{-1}	(Shin et al., 2018)	
Formaldehyde#	Furniture (Wood)	3.06 $\mu g.h^{-1}.m^{-2}$	(De Jonge and Laverge, 2022)	(Ghijsels et al., 2022); *Norm CEN 14788 # Fixed furniture and building materials emission rates per unit of exposed surface area. ## Activity emission rates
	Doors (Wood)	4.50 $\mu g.h^{-1}.m^{-2}$		
	Cushions	3.00 $\mu g.h^{-1}.m^{-2}$		
	Carpet	4.27 $\mu g.h^{-1}.m^{-2}$		
Benzene#	Furniture (Wood)	1.40 $\mu g.h^{-1}.m^{-2}$		
	Cushions	2.00 $\mu g.h^{-1}.m^{-2}$		
	Carpet	0.21 $\mu g.h^{-1}.m^{-2}$		
Naphthalene#	Furniture (Wood)	5.68 $\mu g.h^{-1}.m^{-2}$		
	Carpet	0.47 $\mu g.h^{-1}.m^{-2}$		
Toluene#	Cushions	11.00 $\mu g.h^{-1}.m^{-2}$		
	Carpet	0.20 $\mu g.h^{-1}.m^{-2}$		
	Gypsum	0.5 $\mu g.h^{-1}.m^{-2}$		
Limonene##	Cleaning	1912 $\mu g.h^{-1}.m^{-2}$		
	Dishes	24.8 $\mu g.h^{-1}$		
	Shower (soap/shampoo)	1200 $\mu g.h^{-1}$		
	Deodorant	2000 μg per event		
Naphthalene##	Shower (soap/shampoo)	3.76 $\mu g.h^{-1}$		

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