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Evaluation of the overall performance of smart ventilation in low-energy housing

Baptiste Poirier

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THÈSE

Pour obtenir le grade de

DOCTEUR DE L'UNIVERSITÉ SAVOIE MONT BLANC

Spécialité : Génie Civil et Sciences de l'Habitat

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préparée au sein du **LOCIE**
dans l'**École Doctorale SIE**

Evaluation of the overall performance of smart ventilation in low-energy housing **Évaluation de la performance globale de la ventilation intelligente en logement basse consommation**

Thèse soutenue publiquement le **30 Mars 2023**
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A mini

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RÉSUMÉ

Les économies d'énergies et la réduction de l'empreinte carbone dans le secteur du bâtiment sont cruciales pour atteindre les objectifs climatiques. Pour soutenir la transition énergétique dans ce secteur, des objectifs européens ambitieux visent à généraliser les bâtiments à haute efficacité énergétique. Dans ces bâtiments, la ventilation pour le renouvellement de l'air intérieur reste une source de consommation d'énergie. Or, le renouvellement de l'air est essentiel, car la pollution de l'air intérieur des bâtiments est bien souvent pire que celle de l'air extérieur. Sachant qu'un européen passe en moyenne 60 à 90% de son temps à l'intérieur d'un bâtiment, les systèmes de ventilation jouent un rôle clé pour répondre aux enjeux de santé publique par l'évacuation et la dilution des polluants.

Dans ce contexte, les systèmes de ventilation dit « intelligents », en plein essor, présentent un grand potentiel pour répondre aux besoins de QAI et améliorer la performance énergétique de la ventilation. Les réglementations actuelles sur la ventilation proposent une approche prescriptive préconisant, par exemple en France, des débits d'air extraits à respecter. Dans ce travail, nous proposons une approche performancielle incluant la qualité de l'air intérieur (QAI) et la performance énergétique regroupées sous la notion de "performance globale".

Les principaux objectifs de ce travail de thèse sont de proposer une méthode améliorée d'évaluation de la performance globale (MOPA) des systèmes de ventilation au stade de la conception, avec une incertitude quantifiée, et de tester le potentiel de la MOPA comme outil d'aide à la décision pour les systèmes de ventilation dans la conception des bâtiments. Pour cela, nous avons cherché à répondre aux questions de recherches orientées sur les indicateurs de performance globale, les sources et les scénarios d'émission de polluants et les méthodes d'incertitude et de robustesse de la méthode.

Ce travail de thèse contient quatre articles publiés et un soumis, qui sont complétés par des résultats et des explications supplémentaires. La MOPA développée est basée sur des simulations aérauliques, réalisées avec CONTAM. En complément, des simulations énergétiques ont été réalisées afin de questionner l'utilisation de températures constantes dans CONTAM. De plus, un travail exploratoire de co-simulation en collaboration avec l'Université PUCPR (Brésil) a permis d'initier le couplage thermo-aéraulique.

Nous avons défini dans deux articles de revue de la littérature un ensemble pertinent d'indicateurs de performance de la QAI (ICO₂, IHCHO, IPM₂₅, IRH₇₀, IRH_{30_70}) avec leurs scénarios d'émission de polluants et leurs horaires d'occupation associés. L'humidité relative, le CO₂, le formaldéhyde et les PM_{2.5} ayant été identifiés comme des paramètres clés de l'air intérieur. En complément, un indicateur de performance énergétique IE_{wh} basé sur le calcul des déperditions thermiques liées à la ventilation est proposé.

A travers deux articles de conférence, nous avons appliqué la MOPA dans différents contextes (français et danois lors d'une mobilité au DTU Danemark) et sur plusieurs systèmes de ventilation. Nous avons modélisé une maison individuelle basse consommation et un appartement. Ces applications ont mis en évidence l'importance de prendre en compte d'autres paramètres de QAI que le CO₂ et l'humidité, pour une meilleure prise en compte de la QAI dans le bâtiment.

Enfin, nous avons réalisé une analyse d'incertitude en appliquant la méthode d'analyse de sensibilité RBD-FAST et proposé une approche de la robustesse pour le classement des systèmes. Une synthèse de la MOPA développée regroupe tous les apprentissages de ce travail et une application finale illustre les améliorations de la méthode, confirmant le potentiel de la ventilation intelligente pour assurer une bonne QAI couplée à des économies d'énergie.

Comme ce travail a été impliqué dans plusieurs collaborations internationales et pour prétendre au Label européen, le manuscrit a été rédigé en anglais. Toutefois, un résumé étendu en français de 25 pages, du travail effectué est fourni, conformément au règlement de l'école doctorale.

ABSTRACT

Energy consumption and carbon reduction in building sector is crucial to achieve sustainable development goals regarding the climate change. To support the energy transition in this sector, ambitious European objectives (EPBD Directive, 2003:2010.) aim to generalise nearly zero-energy buildings. However, ventilation systems for the renewal of indoor air are still a source of heat loss and of energy consumption. But the air renewal is essential, as indoor air quality (IAQ) in buildings could be worse than outdoor air environments. Given that the average European spends 60% to 90% of his or her time inside a building, ventilation systems play a key role in the evacuation and dilution of pollutants to meet corresponding public health challenges.

In this context, smart ventilation systems, which are booming in practice present a great potential to meet the IAQ needs and improve energy performance of ventilation system. Such performance benefits need to be assessed, indeed the current regulations on ventilation propose a prescriptive approach advocating. For example in France (JOFR , 1982), exhausted airflow rates must be respected whatever their impacts on energy and IAQ. In this work, we focus on an “overall performance-based” approach, including indoor air quality and energy performance with the aim to avoid conflicts between them. We introduce the notion of “overall performance assessment” (named OPA) for ventilation systems.

The mains objectives of this PhD work is to propose an improved method for overall performance assessment (named MOPA) of ventilation systems at design stage, with quantified uncertainty and to test the potential of this MOPA as a decision-making tool for ventilation systems at building design. We oriented this work to answer to the research questions on overall performance indicators, pollutants emission sources and scenarios, as well as uncertainty and robustness of the performance assessment method.

This PhD work includes 4 published and 1 submitted articles, which are complemented by additional results and explanations. The developed MOPA is based on airflows simulations, performed with CONTAM. In addition, several energy simulations were performed based on DOMUS to question the use of constant temperatures in CONTAM and energy simulations. Moreover, a co-simulation exploratory work in collaboration with the the LST in the University PUCPR, Brasil has allowed to initiate the coupling between DOMUS and CONTAM.

ABSTRACT

We defined in two literature review articles a relevant set of IAQ performance indicators, with their associated pollutants emission scenarios and occupancy schedules. The relative humidity, CO₂, formaldehyde and PM_{2.5} were selected as the restrained key indoor air parameters to be studied. Resulting in five IAQ performance indicators: I_{CO_2} , I_{HCHO} , $I_{PM_{2.5}}$, $I_{RH_{70}}$, $I_{RH_{30_70}}$ and one energy performance indicator $I_{E_{wh}}$ based on heat loss calculation from ventilation airflows.

Through two conference papers, we tested the applicability of the MOPA in different contexts (French and Danish within the framework of an international mobility at DTU Denmark) and for a diversity of ventilation systems (6 ventilation systems). We modelled, a low energy detached single-family house and an apartment in a multi-family building. These applications highlighted the importance of taking into account other IAQ parameters than the traditional CO₂ and humidity, for a better consideration of IAQ in buildings.

Lastly, we performed an uncertainty analysis by applying the RBD-FAST sensitivity analysis method and proposed a method for a robust design score calculation and a ranking of the systems. A synthesis of the developed MOPA regrouped all the learnings from these four chapters and a final application illustrated the method improvements; confirming the potential of smart ventilation for providing acceptable IAQ performance coupled with energy savings.

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ABBREVIATIONS

ACH: Air Change Rate

AIVC : Air Infiltration and Ventilation Center

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

AT: acceptable threshold

ATD: Air Terminal Device

BV : balanced constant airflow ventilation system (BV)

CEN: European Committee for Standardization

Cep: Primary energy coefficient in kWh/(m² of reference surface)

CO: Carbone Monoxide

CumExp_i (kg.m⁻³.h): cumulative exposure

DALY : disability-adjusted life years

DCV : Demand controlled ventilation.

ELA: equivalent leakage area

ELV: exposure limit value

EP: energy performance

EV : exhaust-only constant ventilation system

FMI: Functional Mock-up Interface

FMU : Functional Mockup Unit

HCHO : Formaldehyde

H_{thi}: the thermal heat losses from exhausted air in kWh,

IAQ : Indoor Air Quality

IEA-EBC: International Energy Agency- - Energy in Buildings and Communities Programme

LHS : Latin Hypercube Sampling

MEV : Mechanical (exhaust) Ventilation

MEV-cav : Mechanical exhaust-only ventilation with constant air volume

MEV-rb : Mechanical exhaust-only ventilation and CO₂ & humidity control at the room level

MEV-rh : Mechanical exhaust-only ventilation and humidity control

MOPA : Method for Overall Performance Assessment

MVHR : Mechanical balanced ventilation with heat recovery

MVHR-cav : Mechanical balanced ventilation with heat recovery and constant air volume

MVHR-rb : mechanical balanced ventilation with heat recovery and CO₂ & humidity control at the room level

MVHR-rh : Mechanical balanced ventilation with heat recovery and humidity control

NO₂ : Nitrogen dioxide

OPA : Overall Performance Assessment

PM_{2.5} : Fine Particles Matters < 2.5 μm

RE2020: French current energy performance buildings regulation

RH : Relative Humidity

SHS : Second-hand smoke

VOC: Volatile organic compound

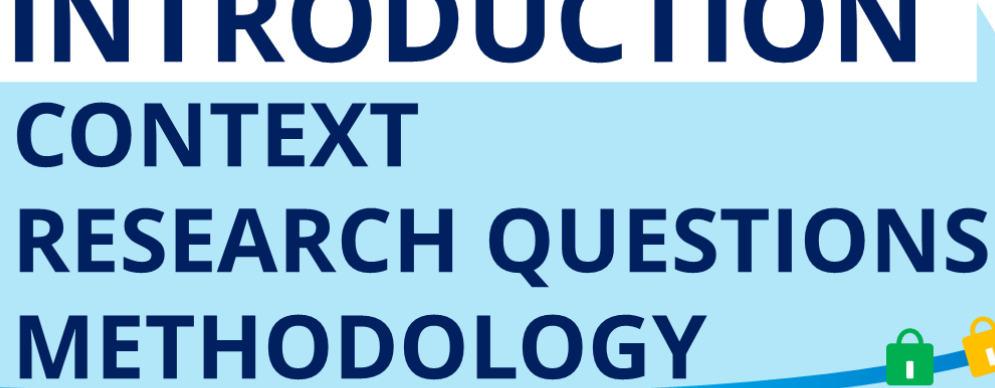
WHO : World Health Organization

INTRODUCTION

CONTEXT

RESEARCH QUESTIONS

METHODOLOGY



This manuscript gathers the research work produced during this PhD work in a compilation of published or submitted articles, which are complemented by additional results and explanations to make them consistent with the scientific objectives. Because this work has been performed in several international collaborations and to apply for the European label, the manuscript has been written in English. However, a 25 page-extended abstract is provided in French in accordance with the requirements of the doctoral school. The international collaborations have been:

- *The collaboration with Pr Nathan Mendes and his laboratory LST, PUCPR University, Brazil. A common project already existed with the LOCIE laboratory: CAPES-COFECUB project ("Mathematical models and numerical methods for the improvement of building simulation tools" Ma 899/18). An extensive collaboration with PR Nathan, Mendes, Dr Julien Berger (Univ. La Rochelle), Dr Walter Mazuroski (LOCIE-LST) allowed to work on the co-simulation between CONTAM and DOMUS. The secondment in Brazil has been cancelled because of the pandemic crisis and has been replaced by two mobilities of 2 weeks in La Rochelle University.*
- *The collaboration with Dr Jakub Kolarik, DTU, Denmark, through a secondment of 3 months in 2021.*
- *The active involvement in the IEA-EBC Annex 86 - Energy Efficient Indoor Air Quality Management in Residential Buildings. In this annex, the task "Smart ventilation" is co-leaded by G. Guyot and J. Kolarik.*

In this introduction, the context of overall performance assessment for smart ventilation in low energy houses is introduced, based on a short context literature review. Indeed, more comprehensive literature reviews are detailed by topic across the published journal articles and sections with additional results. Then, the research questions with objectives of this thesis work are formulated. Finally, the general methodology developed to answer the research questions and to achieve the objectives is detailed step by step, by presenting the articulations of the different parts of this thesis.

CONTEXT

INDOOR AIR QUALITY AND ENERGY PERFORMANCE

The residential sector represents 28% of the total final energy consumption in the European Union countries (Directorate-General for Energy (European Commission), 2022). Moreover, in 2019 in France, the building sector was responsible for 25% of the national's carbon emissions (RE2020 dossier de presse, 2021). As a consequence, the building sector is a promising sector for carbon reduction and energy conservation. To support the energy transition in this sector, ambitious European objectives (EPBD Directive, 2003:2010.) aim to generalise highly energy-efficient buildings. In France, the new thermal regulation RE2020 pursues the objectives of reducing the energy consumption of buildings by decreasing by 30% the bioclimatic needs Bbio compared to the previous thermal regulation (RT2012) (Bbio, is an indicator translating the energy needs of the building in the RE2020 regulation). (RE2020 : Arrêté du 4 août 2021 - Légifrance; RE2020, 2021).

To reach this level of energy performance, improvements have been made on the airtightness and insulation of the buildings to reduce heat losses during the use phase. These gains in thermal performance reduce the energy needs in a building for heating or air conditioning. However, ventilation systems for the renewal of indoor air are still a source of heat losses and of energy consumption. With the advent of new, low energy buildings, the ventilation systems take then an increasing indoor share of the overall building consumption (Walker et al., 2014).

Indoor air is an environment in which we find a greater number of pollutants than in outdoor air and at higher concentrations. Given that the average European spends 60% to 90% of his/her time inside a building, the daily exposure to these pollutants is then important and has a strong impact on health. The poor indoor air quality (IAQ) is responsible for 30 000 deaths and represents a socioeconomic cost estimated at more than 19 billion€ per year for France (Bayeux et al., n.d.). Ventilation systems play a key role in the evacuation and dilution of pollutants to meet corresponding public health challenges.

The air vector is therefore at the crossroads between the energy issues of buildings and public health. For energy aspects, ventilation performance is often integrated in energy calculations required by the thermal regulations. However, ventilation performance criteria are still being developed for the indoor air quality aspects. Thus, the assessment of ventilation performance must be developed as an *overall performance approach* combining energy and IAQ performance to meet these two issues.

SMART VENTILATION SYSTEMS

In this context, smart ventilation systems, which are booming in practice but are still only little discussed in the scientific literature, are designed to meet this need for the overall performance. Indeed, smart ventilation systems are characterised by variable operating airflow rates that can be adapted to indoor pollution conditions, to occupation scenarios, or even to outdoor pollution peaks. This flexibility gives the possibility to optimise air renewal periods to reduce heat losses, improve IAQ and limit the energy consumption of the systems. A recent definition is given by the AIVC (Durier et al., 2018) :

“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) [...]”

Thus, the continuous adjustment of ventilation rate is the essential characteristic of smart ventilation system, that ensures the others features of a smart system, such as improved IAQ, minimized energy consumption, reduced noise, or lower operating cost (Figure 1). To provide these functionalities, a smart ventilation system responds to several parameters and becomes sensitive to the indoor environment, such as occupancy or contaminant level, as well as to the outdoor environment, such as weather conditions or electricity grid needs.

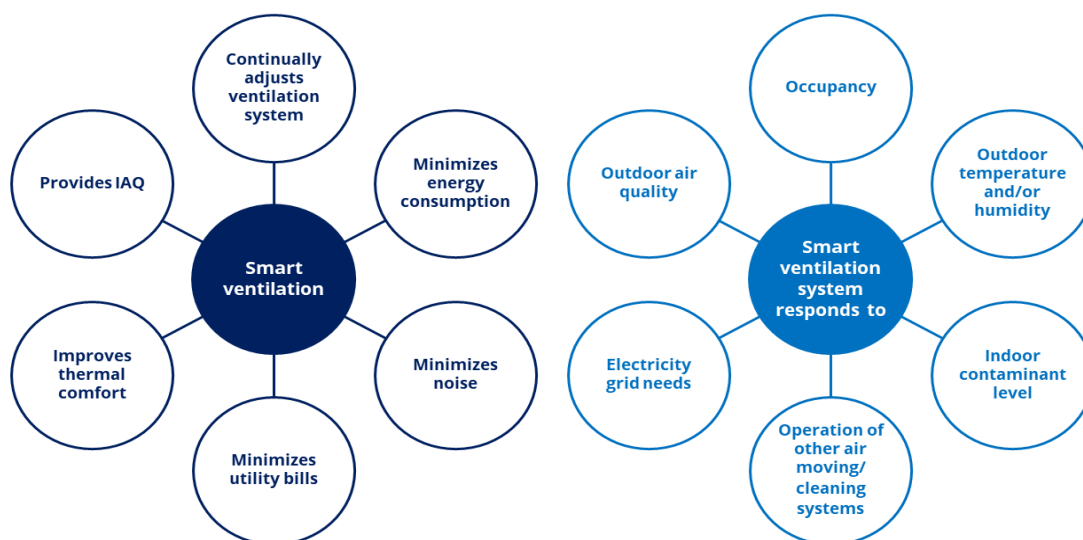


FIGURE 1 : MAIN FEATURES AND PARAMETERS TO WHICH A SMART VENTILATION SYSTEM CAN RESPOND (DURIER ET AL,2018)

Humidity-controlled ventilation is a type of controlled mechanical ventilation system that continuously adjusts its airflows according to the indoor air humidity. Consequently, humidity-controlled ventilation can be considered as a smart ventilation system. More generally, a ventilation system, which continuously adjusts its flow rates to meet one or more functions while being sensitive to its environment, is a smart ventilation system.

Based on this logic, the smart ventilation systems discussed in the scientific literature are essentially systems sensitive to humidity or carbon dioxide. These two technologies are the most spread throughout the world. In France for example, the humidity-controlled systems are very popular and have been commonly installed in dwellings for the past thirty years.

However, performance gains in energy or IAQ can also be achieved with other types of control strategies. A study of a demand-controlled ventilation system using occupancy estimation based on CO₂ showed that control by occupation allows energy savings (Han et al., 2019). This ventilation system evaluates the number of occupants in a shopping centre using an algorithm exploiting the level of CO₂. With this occupant-based ventilation control, the airflow rate was reduced to 7.3 L.s⁻¹ per person, in comparison with 14.7 L.s⁻¹ per person for the reference ventilation during opening hours. This reduced by two the ventilation rates, while maintaining equal performance in terms of IAQ. Nevertheless, these gains could be even greater by improving the management strategy (Han et al., 2019). Moreover, a study on PM_{2.5} air filtration for IAQ and energy optimization in a theoretical office building, shows the potential of variable airflows based on outdoor pollutant concentration (Belias and Licina, 2022). In the modelled case, ventilation bypass activation for outdoor PM_{2.5} concentration lower than 10 µg/m³ achieved on average between 4% and 14% fan energy saving without compromising indoor air quality.

Another study on the performance of a single-family home with occupancy-based ventilation system showed that energy consumption can on the contrary increase with this system. In fact, when the occupants are away, pollutant concentrations increase because the ventilation is turned off and, in the end, pollutants concentrations are higher. It requires more energy to ventilate when the occupants return compared to a conventional system that maintains constant flow rates (Clark et al., 2019). Here, to improve the performance without degrading the IAQ, it is also suggested to refine the adopted strategies for controlling the variable airflow rates.

In addition, the conclusions of a study reviewing 38 publications dealing with smart ventilation confirm the energy gains achieved and the potential for improving IAQ. But this study also highlighted the lack of data in the published literature concerning the description of the ventilation strategies used and the measurements of pollutants present in the indoor environment (Guyot et al., 2018).

These studies from 2018 and 2022 show the potential of innovative control strategies for IAQ improvements and energy savings but a method is still needed to assess their effective performance in comparison with traditional constant airflow strategies.

THE NEED FOR AN OVERALL PERFORMANCE-BASED APPROACH

In contrast to the development of advanced technologies, the national regulations for ventilation systems in residential buildings have changed little over the last 30 years. The current regulations on ventilation propose generally a *prescriptive approach* advocating, for example in France (JOFR, 1982), exhausted airflow rates to be respected according to the size of the house and the type of room.

Thus, focusing on the right IAQ levels to be achieved, rather than on airflows alone would give better guarantee to the occupants on the expected performance of the ventilation systems. This concept of a design method based on performance requirement, called "*performance-based*" approach, can be explained by the definition from the CIB W60 commission (Gibson, 1982) frequently cited in the literature as:

"THE PRACTICE OF THINKING AND WORKING IN TERMS OF ENDS RATHER THAN MEANS [...] WITH WHAT A BUILDING OR A BUILDING PRODUCT IS REQUIRED TO DO, AND NOT WITH PRESCRIBING HOW IT IS TO BE CONSTRUCTED."

The performance approach can go beyond energy and IAQ aspects and is applicable to all parts of a building project. It could ideally include acoustic comfort, visual comfort, accessibility, security, maintainability, sustainability, or many other aspects of the entire building life cycle.

Nevertheless, "*performance-based*" approach has struggled to be adopted in practice in the building market despite practical methods proposed by research (Sayın and Çelebi, 2020; Becker, 2008). There are a few exceptions, such as the use of "performance requirements" in the regulations for energy consumption for heating and cooling of buildings. However, for ventilation systems, regulations in buildings are still mainly based on "*prescriptive*" approaches such as airflows or air change rates requirements (Dimitroulopoulou, 2012) as highlighted previously.

An "*overall performance-based*" approach, including indoor air quality, comfort and energy performance would avoid conflicts between them, such as energy savings vs mould risk, the latter due to decreasing the indoor air temperature to 18°C instead of 20°C (Ginestet et al., 2020). Such "*performance-based*" regulations for ventilation of buildings are still to be developed. This is the heart of the present work, where we focus on IAQ and energy aspects for Overall Performance Assessment (OPA) of smart ventilation systems.

RESEARCH QUESTIONS & OBJECTIVES

Before proposing a Method for Overall Performance Assessment (MOPA) for smart ventilation, it is essential to understand the IAQ performance-based approach in the ventilation framework. The performance-based approach applied to constant-airflow ventilation strategies has been proposed by Guyot (Guyot, n.d.) and is the starting point of our study. This previous research on ventilation systems with constant airflow rates has made possible:

- To validate the appropriate level of detail needed for the study of indoor air pollutants,
- To confirm the importance of precise modelling of the air permeability of the interior walls,
- To identify the most relevant IAQ performance indicators.

For example, to track indoor air pollutants, it is necessary to work with a multi-zone model to obtain IAQ at the room scale and to be precise in defining wall air permeability (Geoffroy et al., 2018; Guyot et al., 2019). In addition, performance indicators such as cumulative CO₂ exposure, formaldehyde and PM_{2.5} doses, and humidity-based indicators are identified as a robust basis to start the performance-based approach for smart ventilation.

In the continuity of this work, it is nevertheless necessary to supplement these indicators with, for example, acute exposure indicators and energy performance indicators. Another challenge is to study the sensitivity of the method, to confirm its robustness and to ensure its applicability to smart ventilation systems.

OVERALL PERFORMANCE INDICATORS

The characterization of the overall performance of ventilation is an emerging topic, which, in order to be well addressed, must combine IAQ performance characterization and energy performance characterization.

First, in the available scientific literature, most of the studies deal with IAQ performance by focusing on the CO₂ concentration or humidity level as relevant parameters of IAQ. Furthermore, among the diversity of these case studies, no unified method for calculating and characterizing IAQ performance emerges. Thus, IAQ performance characterization is still under development, as IAQ is not limited to CO₂ and humidity levels alone.

The previous PhD research work allowed to identify and propose a first set of relevant IAQ indicators and to initiate the development of a method to characterize the IAQ performance of ventilation (Guyot, n.d.). However, these indicators have been applied only to constant airflow ventilation systems and their relevance need to be confirmed in the case of variable airflows with a smart ventilation application. With, among other things, questions on the method used to calculate the energy and IAQ performance indicators. *Does the airflows simulation provide good enough results to assess energy performance in the right order of magnitude? Do we need additional energy simulation or co-simulation to be realistic to assess energy performance?*

Secondly, the characterization of energy performance for ventilation systems, similarly to the IAQ indicators, is treated in the literature without much convergence in the method used. The first indicator that appears is the achieved energy savings, ranging from -60 % of saving to +26 % of over consumption when using smart ventilation systems (Guyot et al., 2017).

Finally, the characterisation of the overall performance for smart ventilation can be addressed by the following research questions:



WHAT ARE THE RELEVANT EXISTING IAQ INDICATORS? HOW TO COMPLETE THEM WITH ENERGY PERFORMANCE INDICATORS?



HOW TO DEFINE, MODEL AND CHARACTERISE THE ENERGY SAVINGS ACHIEVED BY VENTILATION SYSTEMS, IN ORDER TO BUILD AND VALIDATE A NEW SET OF PERFORMANCE INDICATORS COUPLING ENERGY AND IAQ?

POLLUTANTS EMISSIONS SOURCES AND SCENARIOS

In order to perform the calculations of the overall performance of a ventilation system, it is necessary to select boundary conditions, such as occupancy scenarios and related emissions, weather data, etc. Even if the development of occupancy scenarios or meteorological conditions is an active field of research, scenarios for indoor air pollutants emission rates at the dwelling level are still difficult to establish. Pollutant emissions used in current models are underestimated or overestimated compared to the results of measurement campaigns (Boulanger et al., 2012).

The difficulty here is to correctly characterise and estimate the emissions of a polluting source in order to integrate it into a realistic scenario. Indeed, the sources of indoor air pollutants in a building are multiple and very diversified according to the materials, products and activities of the building. For example, the emissions of carbon dioxide depend on the occupants; PM_{2.5} from cooking depend on the cooking practices, the type of cooking device, the type of meals etc., whereas formaldehydes and VOCs depend also on coatings and furniture. However, very little data is available in the scientific literature on the characterisation of these sources of pollution in the indoor air and under in-situ conditions. Indoor pollution measurements and modelling are complex, because of the physics of phenomena involved (e.g. diffusion, sorption, deposition, resuspension for PM, combined effects for formaldehyde) and available measurement techniques. Most of the data available in the literature were obtained in climatic chambers under standardised conditions (VOCs: ISO 16000-9) and are difficult to extrapolate to the scale of the building.

The proposal of pollutant emissions sources and scenarios to calculate the overall performance of ventilations in a MOPA can be developed through the following research questions:



HOW TO CORRECTLY ESTIMATE AND CHARACTERIZE THE EMISSION OF A POLLUTING SOURCE FROM DIVERSIFIED EXISTING MATERIALS, PRODUCTS AND ACTIVITIES IN A BUILDING, IN ORDER TO BUILD RELEVANT EMISSIONS SCENARIO AT THE HOUSING SCALE?



WHAT ARE THE IMPACTS OF HYPOTHESES AND PARAMETERS USED IN THE MODELLING OF THESE POLLUTANT SOURCES REGARDING THE LACK OF AVAILABLE DATA AND THE DIFFICULTIES TO EXTRAPOLATE THEM TO THE SCALE OF THE BUILDING?

METHOD UNCERTAINTY AND PERFORMANCE ASSESSMENT ROBUSTNESS

We know from the feedback on energy performance, that there is always a gap between theoretical performance at the design stage and real measured performances in occupied buildings. The reasons are: gap between standardized conditions used at design and real conditions (Weather data, real occupation, ...); error in modelling (physics and chemistry of pollutants for instance); error in measurements; lack of quality scheme for ensuring the quality of buildings (dysfunctions in ventilation systems...) etc. Nevertheless, to be relevant, a MOPA needs to provide a reference design performance result that should be as close as possible to the future real performance and with low uncertainty.


In this context, the uncertainty notion describes the error quantification between the performance results of a reference design and the calculated results from several scenarios. Indeed, during the modelling process at design stage, several input parameters and scenarios can be used. These input variations generate multiple performance results that can be spread over a large range or concentrated around a single value. This spread of performance results need to be quantified by an uncertainty measurement and it is crucial to understand which inputs are the most impacting on the OPA. The novelty of smart control strategies with potentially numerous design input parameters for control introduces additional uncertainty which should be quantified.


Secondly, the term “robustness” describes the ability of the MOPA to rank several tested designs according to their performance and ultimately to be used in a decision-making process. However, with the use of more than one performance indicator, the weight given to each indicator could influence the final order. In addition, this raises the question of the relative importance of IAQ versus energy to ensure an OPA. The risk is to develop a MOPA that artificially favours a specific ventilation strategy. For example, if an IAQ indicator advantages drastically low CO₂ exposure; a CO₂-controlled ventilation system will have a better performance than a humidity-controlled ventilation system that is not designed for this. *Does this mean that the CO₂-controlled ventilation system ensures better or good IAQ? However, does it also mean that the humidity-controlled ventilation systems have a poorer or poor IAQ performance?*

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RESEARCH QUESTIONS & OBJECTIVES

Therefore, to avoid overestimated (or underestimated) performance results and provide an unjustified advantage to one ventilation system over the others, the uncertainty quantification and a robustness need to be integrated in the MOPA through the following research questions:

 *WHAT IS THE UNCERTAINTY AND WHAT ARE THE MAIN INPUT PARAMETERS IMPACTING THE ASSESSED PERFORMANCE ?*

 *HOW TO BALANCE IAQ AND ENERGY PERFORMANCE ASSESSMENT TO PROVIDE A ROBUST RANKING OF THE VENTILATION SYSTEMS ?*

OBJECTIVES FOR THE MOPA DEVELOPMENT

One of the general aims of this work is to pursue the development of the MOPA for ventilation systems as a continuity of the method developed earlier in PhD work of Guyot. G (Guyot, n.d.), and in relation with the international collaboration within the IEA-EBC Annex 86. To address the research questions, the main objectives can be formulated as:

IMPROVE THE ASSESSMENT METHOD FOR THE THEORETICAL OVERALL PERFORMANCE OF VENTILATION SYSTEMS AT DESIGN STAGE

QUANTIFY THE UNCERTAINTY AND TEST THE ROBUSTNESS OF THIS METHOD REGARDING SMART VENTILATION SYSTEMS AND STRATEGIES

EXPLORE THE POTENTIAL OF PERFORMANCE-BASED APPROACH AS A DECISION-MAKING TOOL FOR VENTILATION SYSTEMS IN BUILDING DESIGN

As already mentioned, this PhD work has been involved in the IAE-EBC Annex 86 : “Energy Efficient Indoor Air Quality Management in Residential Buildings”. This collaborative project groups international expert working performance assessment methods for smart ventilation and IAQ management; with the aim to bring guidelines and tools into practice. This collaboration resulted in a in an international mobility of 3 months at DTU Denmark (with Dr. Jakub Kolarik co-leader of the annex subtask 4) providing some input into the discussion on the rating of existing smart ventilation strategies.

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The research questions, regarding the overall performance assessment for ventilation systems, could be addressed over the entire life cycle of a building. For example, at the design stage, the OPA can be used to select the most adapted ventilation system; at the commissioning stage to compare the design and real performance; in a building renovation project to evaluate IAQ improvement and energy savings due to installing a smart ventilation system. However, this work will focus only on the design stage for residential buildings and is oriented towards low energy buildings. In addition, a particular attention is paid to the applicability of the MOPA to the smart ventilation systems.

To pursue the development of the MOPA at the design stage, we oriented our research and build a methodology based on modelling, building simulations and numerical tools. Moreover, the research conducted for the method development was mainly focused on the European context and adapted as much as possible for France. However, international literature was also included and adapted when no specific information was found in the European / French context.

In the following sections, the simulation tools, case studies, and modelled ventilation systems that were used throughout this work are presented. Then the entire methodology is outlined step by step in the thesis layout and illustrated in Figure 4.

MODELLING TOOLS

In building simulations, large range of tools and models exist to describe several physical phenomena. For energy simulations TRNSYS and EnergyPlus are well known, but many other tools with specific use were developed (multizone, CFD, heat and moisture transfers) such as Bsim, Clim200, IDA-ICE, DOMUS, etc. (Janssens et al., 2008; Woloszyn and Rode, 2008). In this work we mainly focus on pollutant and airflow modeling with CONTAM and on energy simulations with EnergyPlus, DOMUS and IDA-ICE.

AIRFLOWS AND POLLUTANTS SIMULATION TOOL

The IAQ parameters were modelled based on the CONTAM simulation software developed by the NIST. CONTAM is a multi-zone pressure-driven model scientifically recognised and validated (Emmerich, 2001; Emmerich et al., 2004; Ng et al., 2018). This choice of CONTAM is justified by the need of a multi-zone model for this performance-based approach and recognised ability of the tool to efficiently model IAQ and ventilation systems (Emmerich et al., 2002; Rim et al., 2013; De Jonge et al., 2019; Guyot, n.d.). Moreover, CONTAM is relatively user-friendly and has a high flexibility to implement variable input scenarios for occupancy schedules, pollutants emissions and variable control for ventilations airflows.

CONTAM belongs to the category of pressure-based codes, i.e., it calculates the reference pressures in each of the zones from the mass balance (Equation 1) and thus can deduce, for each internal zone of a building, the inside reference pressure. Then the air flows are computed, as well as the pollutant concentrations.

$$\frac{\partial m_i}{\partial t} = \sum_j F_{j,i} = 0$$

EQUATION 1

With m_i the mass of the control volume in zone i , and $F_{j,i}$ [$\text{kg}\cdot\text{s}^{-1}$] the incoming (positive from j to i) and outgoing (negative from i to j) mass flow rates that are functions of the pressure difference between the two zones. A control volume is a volume containing a mixture of air and pollutants assumed to be homogeneous in concentrations, temperature and pressure.

The modelling choices and parameters inputs are detailed across all the chapters:

- The models of activities emission for H_2O and $\text{PM}_{2.5}$ are detailed in sensitivity analysis input description § 4.1.3.b); where the $\text{PM}_{2.5}$ deposition / resuspension models are detailed in §4.1.3.c)
- Input parameters: Wind modifier factors, pressure coefficients, film mass transfer and partition coefficients for hygroscopic buffering effect, penetration rate, deposition velocity, resuspension rate, pollutant emission rates are detailed in §1.1.6a); §3.1.2.c); §3.2.2.d) and §4.1.3

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Furthermore, CONTAM enables modelling of different ventilation systems with various control strategies. To this end, seven “*super-elements control*” have been designed for the modelling of the 6 ventilation systems described below. These *super-elements control* are described in the *Annex I*.

ENERGY PERFORMANCE SIMULATION TOOLS

The challenge of simultaneous simulations of IAQ and energy performance is often pointed out in the literature and several studies have been devoted to this topic. For example, according to CONTAM user guide, the coupling is already available with TRNSYS and ENERGYPLUS. The co-simulation with TRNSYS is quasi-dynamic which means that the two models converge independently while the co-simulation with ENERGYPLUS is dynamic with a convergence attained between the coupled tools (Dols and Polidoro, 2015).

However, in our case we decided to use a different energy performance simulation tool DOMUS, a Brazilian tool (Mendes, n.d.). DOMUS enables precise simulations of humidity in the indoor air, including interactions with the building envelope. Moreover, this choice was motivated by a common CAPES-COFECUB project (“*Mathematical models and numerical methods for the improvement of building simulation tools*” *Ma 899/18*). Through this project, the aim was to develop the co-simulation between CONTAM and DOMUS which led to a long international collaboration with the LST of PUCPR Curitiba (Brazil). We had the opportunity to work with code developers and have a privileged access to the source code. The development of such co-simulation between CONTAM and DOMUS is detailed in §2.2.1.a).

In addition, a co-simulation between CONTAM and ENERGY PLUS has also been performed as a comparison to validate the co-simulation process developed with DOMUS. Standalone DOMUS energy simulation was also used to challenge the need of energy simulation in the performance-based approach and to tackle the limits of the constant temperature in zone of the model in CONTAM as will be discussed in §2.1.1.b).

Moreover, IDA-ICE simulation tool has been used during the international stay at DTU. IDA-ICE is a building simulation tool with multi-zone energy and moisture model. It enables representing several phenomena and systems, such as sun, occupants, equipment, lighting, heating and cooling devices (Kalamees, 2004). It offers a great flexibility to model complex variable airflow controls for CO₂ and humidity-based ventilation. A comparison between IDA-ICE and CONTAM in terms of the CO₂ and humidity simulations is summarized in the *Annex I*.

CASE STUDIES

For the case studies, we restricted the framework to the scale of a dwelling and applied the OPA for ventilation of a single-family house and of an apartment in a multi-family building. Since the method focuses on the design phase, we selected recent energy-efficient buildings, such as the single-family house, which is a low-energy dwelling, and the apartment, which is a newly renovated building.

A FRENCH LOW ENERGY DETACHED SINGLE-FAMILY HOUSE

This case study is the principal building modelled and studied in the PhD work. It has been chosen because :

- This real single-family house is a low-energy house in accordance with the framework of this PhD work.
- Crucial buildings parameters as the air leakage distributions, the ventilation airflows at every component in each room, the occupancy schedules, as well as the weather data have been measured and are available.
- In-situ measurements data over two two-week periods were available and have been exploited in §2.1.1a)

The building configuration (Figure 2) and other details are described several times in the different papers and sections of this work:

- Presented in §1.1.6.a) and §3.1.3.a) as a CONTAM case study application of the performance-based approach.
- Described for the in-situ measurement data exploitation and modelled in DOMUS for comparison in §2.1.1. Then simplified for the co-simulation application in §2.2.3.a)
- Used as the final case study application for the sensitivity analysis in §4.2.1.b)

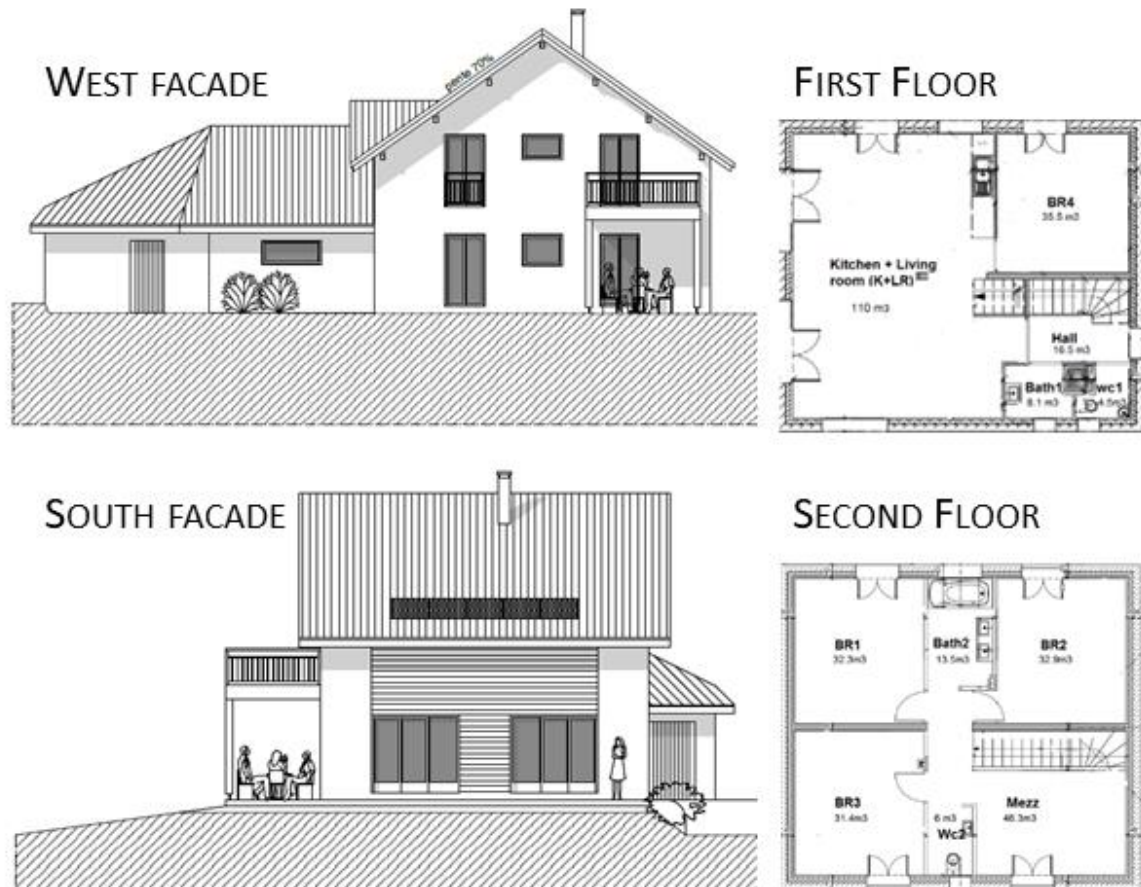


FIGURE 2 : FACADE VIEW AND FLOOR PLAN OF THE LOW ENERGY DETACHED SINGLE FAMILY-HOUSE

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A DANISH APARTMENT IN A MULTI-FAMILY BUILDING

This case study was developed during the international mobility at DTU, Denmark. It is a renovated Danish apartment in a multi-family building (Figure 3). It has been chosen because an innovative ventilation system with a smart control strategy was developed and integrated in this apartment after the renovation. It was also a good opportunity to implement this intelligent ventilation strategy (MVHR-rb) in CONTAM and add it to the developed models. Furthermore, it was an opportunity to test the integration and the performances of French ventilation systems (MEV-cav; MEV-rh; MVHR-cav) in the Danish context. More details are given in the conference paper in §3.2.2 c).



FIGURE 3 : PLAN AND FACADE PICTURE OF THE DANISH APARTMENT IN A MULTI-FAMILY BUILDING

VENTILATION SYSTEMS AND STRATEGIES

In this work, across the four chapters, 6 ventilation systems were modelled to extend the performance-based approach from constant-airflow ventilation systems to smart ventilation systems with variable airflows.

To describe ventilation, the terms ventilation “*strategy*” and ventilation “*system*” have been used. The term ventilation “*strategy*” has been used mainly to describe the airflow control strategies. With for example: *cav* for constant control; *rh* for humidity-based control. While the term ventilation “*system*” describes mostly the entire ventilation including:

- the ventilation type (*MEV* for exhaust only and *MVHR* for balanced systems with heat recovery),
- the ventilation strategy.

However, as the number of systems modeled has increased during this work, the names used for the same system may change slightly from one published article to another. Therefore, we have summarized below the different names used to describe the six ventilation systems modeled in this work.

REFERENCES SYSTEMS

These two ventilation types with constant airflows strategies were grouped here as “reference systems” to be compared with the smart systems.

MEV-cav, for mechanical exhaust-only ventilation with constant air volume, as named in §3.2.2 and §4.1.2. It is also referred as *exhaust-only constant ventilation system* (EV) in §1.1.6 and §3.1.3.c). This system was modelled in DOMUS for comparison with in situ measurements and simplified version for co-simulation.

MVHR-cav, for mechanical balanced ventilation with heat recovery and constant air volume, as named in §3.2.2 and §4.1.2. It is also referred as *balanced constant airflow ventilation system* (BV) §1.1.6; §3.1.3.c) and for in situ measurement data exploitation.

SMART SYSTEMS

These systems referred as *smart systems* are systems with variable airflows strategies, they could be punctually named as *demand controlled* DCV in §1.1.6; §3.1.3.c).

MEV-RH, for mechanical exhaust-only ventilation and humidity control, as named in §3.2.2 and §4.1.2. It is also referred as *humidity-based demand-controlled ventilation* (DCV) system in §1.1.6 and §3.1.3.c); because at that stage it was the only smart system modelled. The exhaust control of this system was modelled in DOMUS for comparison with the in-situ measurements.

It should be noted that two variants of air supplies in bedrooms and living room were modelled. The first one is called Hygro A and has self-regulated air inlets (same as MEV-cav). The second one, more recent, is called Hygro B and has hygroscopic trickle vents providing an airflow rate between $4 \text{ m}^3 \cdot \text{h}^{-1}$ and $31 \text{ m}^3 \cdot \text{h}^{-1}$ (at 10Pa reference pressure difference) depending on the relative humidity level. The Hygro B system is now the most common in dwellings built after 2013 in France and was the system modelled in §1.1.6.b), §3.1.3.c) and §3.2.2. The Hygro A was modelled in §4.1.2 to reduce modelling complexity and enlarge input variation possibilities for sensitivity analysis.

MVHR-RH, for mechanical balanced ventilation with heat recovery and humidity control at the apartment level. It was developed and detailed in §3.2.2.e) only for the Danish case study application. Indeed, it was not retained for the sensitivity analysis in order to limit the number of simulated systems and to facilitate the exploitation of the results.

MVHR-RB, for mechanical balanced ventilation with heat recovery and CO₂ & humidity control at the room level. It is the most advanced smart ventilation strategy we modelled and detailed in §3.2.2.e). It is an innovative ventilation system developed in Denmark. It was modelled in CONTAM during the international mobility at DTU Denmark. The implementation of the ventilation strategy in CONTAM was based on and validated by comparison with the existing model of this ventilation system developed at DTU in the Danish thermal model IDA ICE. (*Annex I*)

MEV-RB, for mechanical exhaust-only ventilation and CO₂ & humidity control at the room level, developed in §4.1.2, as a fictive adaption of the MVHR-rb, in order to test this smart ventilation strategy with the exhaust only.

The details of the implementation of the MEV-rh and MVHR-rb in CONTAM is available in the Annex I.

THESIS LAYOUT

As illustrated on Figure 4, this PhD manuscript is based on published or submitted articles, organized in 4 parts all linked together by intermediate “highlights and learnings” sections summarizing the contribution of each part regarding the research questions and thesis objectives.

Firstly, the general methodology for ventilation performance assessment regarding IAQ is developed through two articles. The **first article** describes the general methodology and proposes a review on relevant IAQ performance indicators. A **second article** focusses on the main indoor pollutants sources and proposes emission scenarios at the dwelling scale in order to complete the existing approaches. At this stage, the method developed focuses on IAQ aspects, which nevertheless provides some answers to the research questions about the overall performance indicators and the scenarios for pollutants emissions.

In the second part, the energy aspects of the method are explored. A first energy performance indicator is proposed to complement the IAQ indicators. Then, we evaluated the need for energy simulations in addition to the airflow computations, by comparing temperatures measured in-situ with simulated temperatures. Moreover, we conducted an exploratory work for co-simulation between airflow and energy models to evaluate the potentials of co-simulation to improve the ventilation performance assessment method. We presented the coupling process validation of the co-simulation on a simplified case study application. Thus, by challenging energy aspects for ventilation performance assessment, this part mainly tackles methodology and the overall performance indicators barriers.

The third part aims at demonstrating the applicability of the method at the design stage with several ventilation strategies from the standard to the smart ones. A **third article** proposes an application to a French low energy house with two mechanical ventilations with constant airflows and a humidity-based ventilation. The second case study is an application of smart ventilation in a Danish context, which was developed through the international mobility at DTU (Denmark) during the PhD. It is presented in the **fourth article**. In this part, five ventilation strategies are tested on two different types of buildings,

The last part regroups all the learnings from previous parts in order to demonstrate the applicability of the MOPA at design stage, with quantified uncertainty and a robust method for ranking the system performance in decision-making process. In a ***fifth article*** five ventilation strategies developed through the PhD work were tested on the French low energy house, as a final application case study. A sensitivity analysis proposes to quantify the uncertainty of the MOPA regarding inputs, such as pollutants emission scenarios, occupancy, permeability and using the performance indicators as output. Then, the robustness of the MOPA is explored with the application of existing robustness assessment method from the literature.

Finally, the improved MOPA - including overall performance indicators, standards scenarios, quantification of uncertainty and a robust method for assessing the performance of ventilation systems- is summarised to illustrate the improvements of the Method for Overall Performance Assessment.

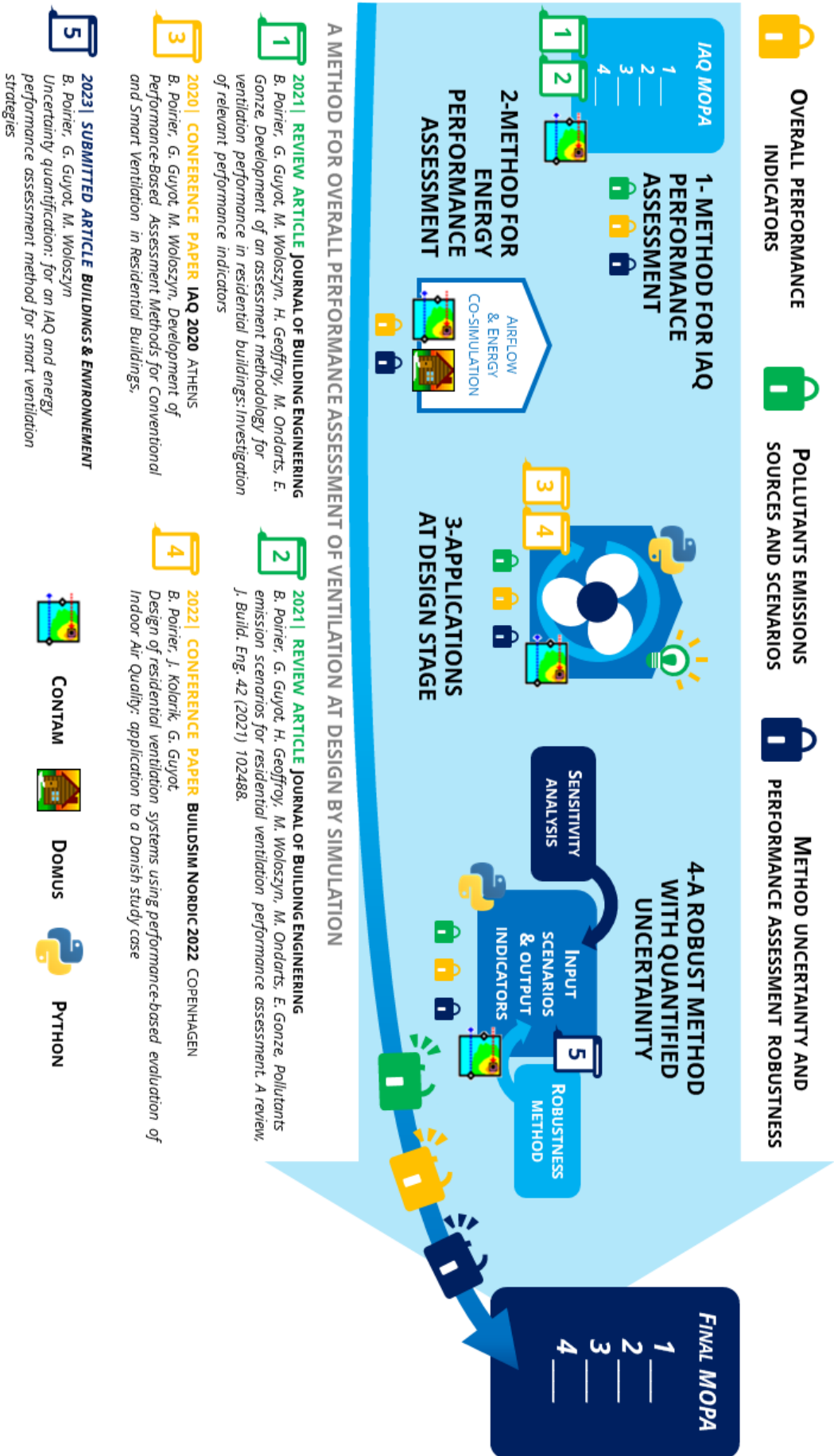


FIGURE 4 : MAIN STEPS OF THE PROPOSED METHODOLOGY FOR THE MOPA DEVELOPMENT AND RESEARCH QUESTIONS ANSWER

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PART 1



METHOD FOR IAQ PERFORMANCE ASSESSMENT



IAQ MOPA

1 Scenarios
2 Simulations
3 Indicators
4 _____



This first part is dedicated to the presentation and the development of the IAQ performance-based approach, in order to assess overall building ventilation performance. Part of this approach, this chapter describes the selection of the relevant IAQ performance indicators, as well as the selection of the input data in order to calculate these indicators, notably the pollutants emissions rate scenarios.

A first published article proposes five relevant IAQ performance indicators based on an extensive literature review and illustrates with a study case application the potential of using the performance-based approach for ventilation performance assessment.

A second published article details the main indoor pollutants sources in residences and proposes the pollutant emission scenarios and the occupancy schedules to be used in order to apply the developed IAQ performance-based approach at the dwelling scale. These ones will be used in the first article presented in Part 3. At this stage, the developed method focuses mainly on IAQ aspects and provides answers to the research questions about the overall performance indicators and the pollutants emission sources and scenarios.



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Development of an assessment methodology for IAQ ventilation performance in residential buildings: An investigation of relevant performance indicators

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Abstract

Ventilation of residential buildings is an important area of research, since it addresses crucial issues: providing healthy indoor air to occupants, avoiding condensation risk and damage of the building, as well as ensuring energy efficiency. With regard to regulatory or labelling requirements, performance-based approaches for ventilation should be developed. These must ensure that a ventilation system is designed not only to save energy but also to avoid risks to occupants' health. In order to formulate a performance-based approach, a crucial question has to be addressed: What are the relevant indoor air quality (IAQ) performance indicators to be calculated? In this paper, we present an extensive investigation of the literature on IAQ performance in order to identify a reduced set of relevant indicators. We identified five relevant IAQ performance indicators to be used as output data: maximum cumulative exceeding carbon dioxide (CO₂) exposure over 1,000 ppm, maximum cumulative occupant formaldehyde (HCHO) and fine particulate matter (PM_{2.5}) exposure, maximum percentage of time with relative humidity (RH) higher than 70% (condensation risk), and maximum percentage of time with RH outside a range of 30–70% (health risk). Importantly, we demonstrate that a performance-based method using these five IAQ indicators is relevant, applying it to a low-energy house.

Keywords Ventilation, indoor air quality, performance, residential buildings, indicator, review

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1.1 DEVELOPMENT OF AN ASSESSMENT METHODOLOGY FOR VENTILATION PERFORMANCE IN RESIDENTIAL BUILDINGS; AN INVESTIGATION OF RELEVANT PERFORMANCE INDICATORS

1.1.1 INTRODUCTION

Since people spend 60–90% of their life in indoor environments (e.g., homes, offices, schools), and because indoor air is generally more polluted than outdoor air, indoor air quality (IAQ) is a major factor affecting public health (Brasche and Bischof, 2005; Jantunen et al., 2011; Klepeis et al., 2001; Zeghnoun et al., 2010). For example, Logue et al. (Logue et al., 2011) estimated that the current harm to public health in disability-adjusted life years (DALYs) per person-year from all sources attributable to IAQ, excluding second-hand smoke (SHS) and radon, was somewhere in the range between the health effects of road traffic accidents (4,000 μ DALYs/person-year) and all-cause heart disease (11,000 μ DALYs/person-year). According to the World Health Organization (WHO) (WHO, 2014), 99,000 deaths in Europe and 81,000 in the Americas were attributable to household (indoor) air pollution in 2012. Health gains in the European Union (EU-26) due to effective implementation of IAQ requirements are very important: these have been estimated at more than 300,000 DALYs per year (WHO, 2014).

The main role of building ventilation is to ensure correct IAQ. The different regulations and standards throughout the world are mainly based on “prescriptive” approaches, using airflows or air change rate requirements as performance indicators (Brelvi and Seppänen, 2011; CEN, 2016; Dimitroulopoulou, 2012; Laverge et al., 2013; Zukowska et al., 2020). For example, the French building code for residential ventilation imposes air renewal rates adapted to the house size and the type of ventilation system (different airflow rates are required for constant airflow ventilation and for humidity-controlled ventilation) (JOFR - Journal officiel de la République française, 1982).

However, with the same ventilation rates, we could achieve a wide range of IAQ levels. As a result, standards and regulations generally set ventilation rates on the basis of comfort considerations and not on health criteria, as suggested in the Healthvent project (Guyot et al., 2018; Borsboom et al., 2016). These are all based on the assumption that airflows evacuating human bioeffluents, including odours, are sufficient means of controlling other contaminants (Cony Renaud Salis et al., 2017; Logue et al., 2011), which, however, cannot be guaranteed.

The European standard 15665 (CEN, 2009) proposed IAQ performance indicators for assessing ventilation performance, but the long list of criteria, as well as the lack of selection of parameters used to calculate these criteria, has made it inapplicable to date (Guyot, 2019; Laverge et al., 2013).

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A “performance-based” approach, where achieved IAQ is checked at the design stage of a building, is still lacking in regulations and standards and needs to be developed for building ventilation (Lv and Yang, 2019). The main purpose would be to evaluate IAQ performance level by considering the ventilation systems globally, rather than checking ventilation rates only.

From a review of performance-based approaches applied to residential ventilation (Gaëlle Guyot et al., 2018), we learned that such methods were rare and almost always use IAQ indicators based on carbon dioxide (CO₂) and humidity (condensation risk) only. Choosing relevant pollutants and relevant indicators to assess IAQ levels in residential buildings is a challenging task; indeed, the list of identified indoor pollutants is long and may still grow (Borsboom et al., 2016). Several reviews devoted to measurement studies of concentration levels in buildings have been conducted, discussing acceptable values and proposing metrics to assess IAQ performance and health impact (Cony Renaud Salis et al., 2017; Jennifer M. Logue et al., 2011; J. M. Logue et al., 2011). However, there is still no consensus in the literature on which pollutants are the most important to be considered, which precise indicators should be used, and how to compute them at the design stage of a building. The answers to these questions are a necessary step for performance-based assessment and represent the research gap addressed in our paper.

Moreover, the choice of IAQ performance indicators, being the main output of a performance-based method, also impacts the other steps of performance assessment: inputs and process, as shown in Figure 1.

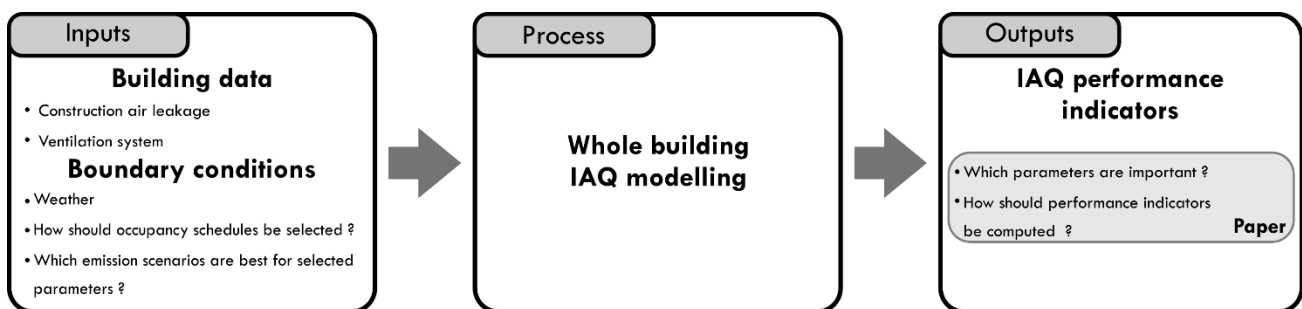


FIGURE 1. SCHEMATIC DIAGRAM ILLUSTRATING A PERFORMANCE-BASED APPROACH FOR VENTILATION AT THE DESIGN STAGE OF A RESIDENTIAL BUILDING.

In this paper, we propose an extensive review and analysis of the literature dealing with IAQ performance indicators in order to identify a reduced set of relevant indicators to be used in performance-based approaches, going beyond the only two historical indicators used today based on CO₂ and humidity. We then demonstrate that the proposed set of IAQ indicators can be applied in a performance-based approach to ventilation system assessment, illustrating this based on a case study.

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1.1.2 METHODOLOGY FOR THE LITERATURE INVESTIGATION

There is no consensus on a reduced set of IAQ performance indicators to be used in a performance-based method for ventilation, as illustrated by the long list of performance indicators proposed in the European EN 15665 standard "*Ventilation for buildings. Determining performance criteria for residential ventilation systems*" (CEN, 2009) and by the on-going research for its revision. The recent International Energy Agency's Energy in Buildings (IEA-EBC) Annex 68 "*Indoor air quality design and control in low energy residential buildings*" proposed metrics to evaluate the IAQ of low-energy residential buildings based on 14 pollutants of concern (Abadie and Wargocki, 2017).

In this paper, we used three important definitions given in the EN 15665 standard:

- **Parameter:** pollutant or marker that is used in the expression of a requirement
- **Criteria/performance indicator:** way (method) to express the required performance
- **Requirement/threshold:** level of required performance.

The first part of the paper addresses the first issue: the analysis and selection of the relevant parameters in residential dwellings. The second part of the paper goes on to analyse the corresponding IAQ performance indicators based on the selected parameters and the corresponding requirements (or thresholds). Then, the third part of the paper proposes a selection of five IAQ performance indicators and the corresponding requirements (or thresholds) to which they should be compared in a performance-based approach. Lastly, this paper presents the results of an application on a low energy house, using the selected IAQ indicators to compare the performances of three ventilation systems.

We reviewed standards (European Committee for Standardization [CEN] and American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE]), published literature, regulations from European countries, as well as resources from the Air Infiltration and Ventilation Center (AIVC, IEA-EBC Annex 5) related to residential building ventilation IAQ performance, using the keywords: ventilation performance, IAQ performance indicator, ventilation IAQ performance, ventilation IAQ criteria, IAQ criteria, performance-based ventilation. We selected only the literature relevant for the assessment of ventilation systems performance. As a result, 82 documents from 1983 to 2020 were analysed in this paper.

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1.1.3 REVIEW OF PARAMETERS OF CONCERN FOR VENTILATION PERFORMANCE ASSESSMENT

In order to select the most relevant parameters for the evaluation of ventilation performance, this study was motivated by a number of points: parameters already used for the evaluation of ventilation systems performance; pollutants presenting a major health issue because they are commonly observed and have a strong health impact; and pollutants relevant for ventilation performance assessment because they are impossible to reduce at source, such as those related to human metabolism or kitchen activities. We started from the two commonly used parameters, CO₂ and humidity, and extended our research framework to identify other pollutants that could complement them.

1.1.3.a) General studies on pollutants of concern

A starting point for our investigation was the AIVC technical note “TN 68: Residential Ventilation and Health” (Borsboom et al., 2016). Authors considered existing guidelines and standards, hazard assessment, cumulative risk assessment, as well as impact assessment exposure studies, and proposed a selection of high-priority pollutants for residential ventilation standards (Table 1). They confirmed the importance of considering fine particulate matter (PM_{2.5}), formaldehyde (HCHO) and acrolein, as pointed out elsewhere (Jennifer M. Logue et al., 2011). In that particular paper (Jennifer M. Logue et al., 2011), the authors estimated the population-averaged annual cost in DALYs lost due to chronic air pollutant inhalation in U.S. residential dwellings. The paper presents the results in DALYs lost per year per 100,000 persons for the 12 pollutants with the highest median DALY losses (PM_{2.5}, HCHO, acrolein, ozone, nitrogen dioxide [NO₂], ammonia, acetaldehyde, crotonaldehyde, 1,1-dichloroethene, styrene, carbon tetrachloride, 1,4-dichlorobenzene, chromium, + acute carbon monoxide [CO] deaths, radon and SHS for comparison).

HIGH-PRIORITY POLLUTANTS FOR CHRONIC EXPOSURE (RANKED BY POPULATION IMPACT)	HIGH-PRIORITY POLLUTANTS FOR ACUTE EXPOSURE
<ol style="list-style-type: none">1. Particulate matter2. Mold and moisture3. Formaldehyde4. Acrolein	Acrolein, chloroform, CO, HCHO, NO ₂ , PM _{2.5}

TABLE 1. SELECTION OF POLLUTANTS IN RESIDENTIAL VENTILATION STANDARDS (EN 15665, CEN 2009)

CO, radon and SHS were excluded in Table 1. Indeed, in the context of ventilation standards, it is important to consider ventilation as a way to dilute remaining pollutants once their sources have been reduced. From this perspective, Borsboom et al. (Borsboom et al., 2016) propose that tobacco smoke and radon should not be considered when establishing ventilation standards.

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Although these pollutants were clearly identified in a cumulative risk assessment study (Logue et al., 2011) and an impact assessment of chronic residential exposure (J. M. Logue et al., 2011), they are more impacted by home characteristics (such as the depressurization of subfloors for radon) and occupant behaviour than by ventilation strategies (Borsboom et al., 2016). We can assume that CO is, likewise, not a pollutant suitable for assessing ventilation performance, as shown by the results of a study (Emmerich et al., 2005) in which adjusting the stove had a greater impact than changes in airflows.

PM_{2.5} are defined as particles with an aerodynamic diameter equal or inferior to 2.5 µm, also known as fine particles. They are emitted inside and outside mainly during combustion (natural and anthropic). They can become the main contributor to the indoor pollutant concentration (He, 2004). Furthermore, due to their small dimension, these particles can penetrate the human airways to varying depths and may even infiltrate the blood (AFSSET, 2006). The inhalation of these particles has a wide range of effects, from eye, nose, or throat irritation to respiratory or cardiovascular dysfunction (such as myocardial infarction or stroke) depending on the time and intensity of exposure (AFSSET, 2010). As a result, several studies identified PM_{2.5} as one of the pollutants of concern in dwellings (Kirchner and al., 2007; WHO, 2010a; Jennifer M. Logue et al., 2011; Borsboom et al., 2016). Moreover, Logue et al. (Jennifer M. Logue et al., 2011) estimated that PM_{2.5} have a huge impact in terms of the total health damage due to indoor air pollutants in the DALY calculation. The French Agency for Food, Environmental and Occupational Health and Safety (ANSES) concluded that the socioeconomic cost of indoor air pollutants, calculated on the basis of early mortality alone, was €19.5 billion per year, of which €14.5 billion was directly attributable to suspended particulate matter (Kopp et al., 2014). Therefore, we decided to retain PM_{2.5}.

HCHO is a common volatile organic compound (VOC) that is interesting to survey in dwellings for many reasons, as proposed in (Borsboom et al., 2016; Jennifer M. Logue et al., 2011). Firstly, this substance is recognized as having wide-ranging health impacts, depending on the concentration as well as acute and chronic exposure. Effects are known to range from eye irritation to nasopharyngeal cancer (deemed to be unattributable to confounding factors), and are suspected to include other neurologic, reprotoxic, and carcinogenic effects (AFSSET, 2007; CIRC, 2006; INERIS, 2010). Secondly, this pollutant is nearly always present in homes, and it is also produced almost exclusively indoors (up to 10 times more than outside) due to the huge quantity of indoor emitting materials, furniture, and products (Kirchner and al., 2006a). It can also result from the oxidation or reaction of other VOCs into alkene and ozone (Uhde and Salthammer, 2007). As a result, several studies identified HCHO as one of the pollutants of concern in dwellings (Kirchner and al., 2007; Koistinen et al., 2008; WHO, 2010a; J. M. Logue et al., 2011; Jennifer M. Logue et al., 2011; Borsboom et al., 2016), and we consequently decided to retain it.

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In addition, humidity is one of the prioritized pollutants of concern identified in Table 1. Indeed, the WHO shows the relationships between adverse health effects such as respiratory and allergic symptoms and damp or mouldy indoor environments (Heseltine and Rosen, 2009). The risk of mold has been clearly linked to the lack of performance of ventilation systems and the energy efficiency programs that tend to decrease the indoor air temperature (Ginestet et al., 2020). Moreover, a review of performance-based approaches used in standards and regulations dedicated to smart ventilation showed that the performance indicators most widely used included criteria based on humidity to avoid condensation risk, as in France and Belgium (Gaëlle Guyot et al., 2018).

CRITERIA	POLLUTANT									
	PM _{2.5}	SHS	RADON	HCHO	ACROLEIN	CO (ACUTE)	NO ₂	CHLOROFORM	CO ₂	H ₂ O
<i>Parameters already used as indicators</i>									x	x
<i>Health issue based on (Logue et al., 2011) ranking</i>	1	2	3-6	4	5	7	8	9		x
<i>Adapted to ventilation performance evaluation</i>	x			X	x		x	x	x	x
<i>Total</i>	1x	2	3-6	4x	5x	7	8x	9x	xx	xxx
<i>Selected parameters</i>	X			X					X	X

TABLE 2. CRITERIA AND IDENTIFIED POLLUTANTS FOR THE SELECTION OF PARAMETERS FOR VENTILATION PERFORMANCE ASSESSMENT

Finally, in Table 2, we cross-tabulated the main pollutants previously discussed in the literature analysis with the three criteria we defined to characterize a relevant parameter for IAQ performance indicators. When deciding between the pollutants with health issues and also suited to ventilation performance evolution, such as HCHO, acrolein and NO₂, we gave priority to those with a greater impact on health. Therefore, using IAQ performance indicators based on at least the pollutants HCHO, humidity, and PM_{2.5} to assess ventilation performance appears important for risk avoidance. Moreover, CO₂ has already been used as an IAQ indicator, even if its role as a pollutant is not yet clearly established, as will be discussed in the following section.

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1.1.3.b) A focus on CO₂

There is debate in the literature regarding whether CO₂ should be considered a pollutant, despite the fact that it has no health consequences at concentrations observed in residential dwellings, or whether it could be considered as a relevant marker in ventilation standards.

Indeed, several studies have shown that health effects directly attributable to CO₂ are minimal at concentrations observed in indoor environments, which are commonly in the range of 350–2000 ppm, and sometimes up to 6000 ppm in bedrooms during night periods (Kirchner and al., 2006b). The American Conference of Governmental Industrial Hygienists considers 5000 ppm to be the threshold for 8-h exposure in indoor environments (ACGIH, 2011). In 2013, the ANSES published results of an analysis of available CO₂ epidemiological and toxicological studies, as well as of studies on the effects of CO₂ on health, performance, and comfort (ANSES, 2013). On the basis of the results, it was concluded that the only health threshold on which several studies converge is exposure of 10,000 ppm for 30 min, corresponding to respiratory acidosis for a healthy adult at a modest level of physical exertion. The analysis mentions an experimental study (Satish et al., 2012) of 22 human subjects, suggesting an effect on psychomotricity performance above 1000 ppm attributable to CO₂ but which, according to the authors, still requires further investigation. In addition, 1000 ppm is the old threshold proposed by Von Pettenkofer in 1858 to prevent odors from bioeffluents, assuming an outside concentration of 500 ppm (Von Pettenkofer, 1858). Other studies of specific applications such as bomb shelters, submarines (De Gids and Heijnen, 2011), and high-risk industrial facilities and homes (French ministry For Ecology, 2007) have used higher threshold values for CO₂. They confirm that CO₂ is not dangerous by itself at the levels measured in residential buildings.

The recent study by (Zhang et al., 2016) shows different results. A total of 25 individuals were exposed for 4 h 15 min, first to pure CO₂ (at either 1000 ppm or 3000 ppm) and then, by decreasing the ventilation rate, to all emissions from occupants (called “human bioeffluents”), including CO₂, and corresponding CO₂ levels (of either 1000 ppm or 3000 ppm). No statistically significant effects were observed in the first case; the second showed an increase in reported headaches, fatigue, sleepiness, and difficulty in thinking clearly. The authors conclude that moderate concentrations of bioeffluents, but not pure CO₂, will affect occupants at typical indoor exposure levels. This can also be seen as a study of dose–response relationships between human bioeffluents, including CO₂, and indicators of health, wellbeing, and performance.

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From the threshold values summarized in Table 3, we highlight that, despite the consensus that pure CO₂ has no effect on human health at concentrations observed in residential settings, moderate concentrations of human bioeffluents, including CO₂, will affect occupants at typical indoor exposure levels.

EFFECTS	CO ₂ THRESHOLD [PPM]	COMMENTS	REFERENCES
<i>Comfort</i>	1000	To prevent odors from bioeffluents	(Von Pettenkofer, 1858)
<i>No effect</i>	1000 or 3000 for 4 h 15 min	Pure CO ₂	(Zhang, et al., 2016)
<i>Increasing intensity of reported headache, fatigue, sleepiness, and difficulty thinking clearly</i>	1000 or 3000 for 4 h 15 min	Metabolic CO ₂ + human bio-effluents	(Zhang, et al., 2016)
<i>Hygienic threshold in indoor environments</i>	5000	For 8-h exposure	(ACGIH, 2011)
<i>Respiratory acidosis for a healthy adult at a modest level of physical exertion</i>	10,000	For 0.5 h	Several studies reviewed in (ANSES 2013)
<i>Bomb shelters</i>	20,000		(de Gids and Heijnen, 2011)
<i>Submarine</i>	30,000		(de Gids and Heijnen, 2011)
<i>Irreversible effects</i>	50,000		(French Ministry for Ecology, 2007)
<i>Mortality level - 1% lethal effects threshold</i>	100,000		(de Gids and Heijnen, 2011) [41] (French Ministry for Ecology, 2007)
<i>- 5% lethal effects threshold</i>	200,000		(French Ministry for Ecology, 2007)

TABLE 3. CO₂ CONCENTRATION LEVELS AND THEIR ASSOCIATED HEALTH EFFECT FOUND IN THE LITERATURE: NO EFFECT LINKED TO PURE CO₂ EXPOSITION; AN EFFECT BUT AN EFFECT FOR HUMAN BIOEFFLUENTS AT TYPICAL INDOOR EXPOSURE LEVELS

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Moreover, several authors agree that CO₂ is a good marker of occupant emissions, including bio-emissions and odours (Von Pettenkofer, 1858; Cain and Berglund, 1979; Cain et al., 1983; Fanger et al., 1988; Zhang et al., 2016), as well as some VOC and particle emissions from office equipment used by occupants (Emmerich and Persily, 2001; Fisk and De Almeida, 1998; Mansson et al., 1997). Emmerich and Persily, 2011 (Emmerich and Persily, 2001) justify the use of CO₂ as an indicator of ventilation rate per person based on regulations or standards, since the relationship between indoor CO₂ concentration and ventilation rates is well understood and described in (Persily, 2017, 1997; Persily and Dols, 1990). It has also been recommended that CO₂ be monitored to mitigate the risk of virus transmission during the COVID-19 pandemic and used, for example, as a traffic light indicator based on CO₂ level (yellow/orange light is set to 800 ppm and the red light up to 1000 ppm) (*REHVA_COVID-19*, 2021). Other slightly different values have been applied in specific countries such as France (HCSP, 2021) and Belgium (Wouters, 2021). All analysed performance-based approaches used in regulations and standards for smart ventilation have used performance indicators based on CO₂ (Gaëlle Guyot et al., 2018), as have most of the analysed literature on smart ventilation performance (G. Guyot et al., 2018a).

In summary, the analysed literature shows that using CO₂ is relevant as a parameter for performance-based approaches for ventilation. Indeed, it is at least correlated with bioeffluents, which affect occupant health at CO₂ concentrations widely measured in dwellings. Therefore, CO₂ is relevant, but needs to be used with other parameters.

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1.1.4 REVIEW OF IAQ VENTILATION PERFORMANCE INDICATORS AND THRESHOLDS BASED ON THE SELECTED PARAMETERS OF CONCERN

Once the parameters have been identified, relevant IAQ performance indicators also need to be determined. However, qualifying and quantifying IAQ is a complex issue. For each parameter, there are several ways of using measured or calculated data related to the individual parameter. Performance indicators could be related to background or peak exposures, or may be calculated over different time periods (whole year/heating period/one standardized week in the winter, etc.). Depending on the information we are looking for, it can be relevant to calculate the indicators per occupant (dose or exposure) or per zone (condensation risk), including either the whole building, specific zones, or all zones, etc.

1.1.4.a) Pollutants with dose–response law-based indicators

Most of the performance indicators based on pollutants in the literature come from measurement campaigns and are related to comparisons with a given threshold, set to different levels depending on guides and regulations in different countries and referred to as “IAQ metrics.” The IEA-EBC Annex 68 “*Indoor air quality design and control in low energy residential buildings*” (Cony Renaud Salis et al., 2017) proposed using three IAQ metrics:

- *For long-term exposure:* the maximum value, among the pollutants of concern, of the ratio between the mean concentration and the reference exposure limit value (ELV) set to the minimal value used worldwide, i.e., 9 $\mu\text{g}/\text{m}^3$ for HCHO (Office of Environmental Health Hazard Assessment (OEHHA), 2016) and 10 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ (WHO, 2010a)
- *For short-term exposure:* the maximum value among the pollutants of concern of the ratio between the mean concentration, over the reference period for the reference acute ELV, and the related acute ELV set to the minimum value used worldwide, i.e., for HCHO, 123 $\mu\text{g}/\text{m}^3$ for HCHO over 1 h (Canada) and 25 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ over 24 h (WHO)
- *The DALY metric* described elsewhere (Jennifer M. Logue et al., 2011).

Other studies use a different approach based on the dose–response law approach (Mølhave, n.d.; Samoli et al., 2003; Wong et al., 2006). The dose depends on the cumulative exposure, which is an indicator calculated per person as shown by Equation 1 (Watson et al., 1988). This indicator is rarely used in an in situ measurement context, as it would need to be calculated to know exactly where occupants are in the house at each time step and to measure the concentrations in each of the rooms, as well as at each time step.

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At the design stage of a building, it can be calculated starting from occupancy schedules used as input data.

$$CumExp_i = \sum_{t=0}^d C(t) \cdot \Delta t$$

EQUATION 1

Where the cumulative exposure $CumExp_i$ ($\text{kg}\cdot\text{m}^{-3}\cdot\text{h}$) for an occupant i , is the sum of $C(t)$ pollutant concentration level (in $\text{kg}\cdot\text{m}^{-3}$) to which the occupant is exposed at the instant t , multiplied by the time step Δt (depending on the measurement or the simulation time step) and d the total duration (of the measurement or the simulation).

The average occupant exposure, $AvgExp$, is another performance indicator proposed by the EN 15665 (CEN, 2009, p. 665). It is defined as the average concentration to which an occupant is exposed. It can be obtained by dividing the cumulative exposure by the total duration of the simulation (Equation 2).

$$AvgExp_i = \frac{\sum_{t=0}^d C(t) \cdot \Delta t}{d} = \frac{CumExp_i}{d}$$

EQUATION 2

Where $AvgExp_j$ (in $\text{kg}\cdot\text{m}^{-3}$) is the ratio between $CumExp_j$ (in $\text{kg}\cdot\text{m}^{-3}$) and the total duration d .

In a more general way, the EN 15665 standard (CEN, 2009) also proposes using the following IAQ performance indicators depending on whether they are related to specific activities or background pollution:

- For specific activities: maximum threshold, average and weighted concentration, average exceeding concentration over a threshold value, dose above a given value, decay criteria, time to obtain a percentage of the maximum value, and value after a certain time
- For background pollutants: maximum threshold, average and weighted concentration, average exceeding concentration over a threshold value, and dose above a given value

Table 4 provides an overview of the pollutants with dose-response law-based performance indicators.

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PERFORMANCE INDICATORS	THRESHOLDS	REFERENCES
Three IAQ metrics - $C_{\text{long-term}}/ELV_{\text{long-term}}$ - $C_{\text{short-term}}/ELV_{\text{acute}}$ - DALY	$ELV_{\text{long-term}} = 9 \mu\text{g}/\text{m}^3$ for HCHO and $10 \mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ $ELV_{\text{acute}} = 123 \mu\text{g}/\text{m}^3$ over 1 h for HCHO and $25 \mu\text{g}/\text{m}^3$ over 24 h for particulate matter $\text{PM}_{2.5}$ No threshold	(Cony Renaud Salis et al., 2017)
Cumulative exposure CumExp_i or average occupant exposure AvgExp_i	Depending on pollutant; $ELV \cdot d (\mu\text{g} \cdot \text{m}^{-3} \cdot \text{h})$	(WHO et al., 2006) (ANSI/ASHRAE, 2013; Laverge and Janssens, 2009)

TABLE 4. POLLUTANT-BASED PERFORMANCE INDICATORS IN THE REVIEWED LITERATURE

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1.1.4.b) Humidity-based indicators

We also reviewed IAQ performance indicators related to humidity. Variables associated with humidity are relative humidity (RH) and absolute humidity. RH is the ratio of water vapor pressure in the air at a given temperature to the saturation water vapor pressure at the same temperature. Absolute humidity is the mass of water vapor in the air per unit mass of air. It is rarely used as an IAQ performance indicator (EN 16798-1 (CEN, 2016)). RH is the parameter most commonly measured and used, as shown in Table 5. Performance indicators related to humidity can be divided into two categories:

1. To assess occupant comfort and health: indicators related to an acceptable range and number of hours out of this range, as proposed in the standard EN 15665 (CEN, 2009). For example, some authors (Koffi, 2009; Ribéron and Millet, 2004) note that the minimum thresholds for RH vary within the range of 20–30%, while the maximum thresholds vary in the range of 65–80%. Very rarely, only the number of hours when RH is lower than a threshold should be calculated. Mansson et al. (Mansson, 2001a) propose that the number of hours with RH lower than 30% should not exceed 800 h.
2. To assess the condensation risk in a building: the number of hours during a given period with humidity higher than a given threshold, set to 75% in the French regulation for demand-controlled ventilation (DCV) (CCFAT, 2015) or to 80% in the former Belgium regulation for DCV (ATG and BCCA, 2012). In Nordic countries, however, strongly varying thresholds could be set, with (Nielsen, 1992) proposing 45%.

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Some authors, such as Woloszyn et al. (Woloszyn et al., 2009), propose more detailed indicators as boxplots, which are also relevant for scientific analysis. However, they are less appropriate for use in a regulatory context.

This part of the literature is summarized in Table 5.

PERFORMANCE INDICATORS	THRESHOLDS	REFERENCES
Absolute humidity	< 12 g/kg	EN 16798-1 (CEN, 2016)
Number of hours with RH < 30% 4-Week period with water vapor content < 7g/kg during the heating season	< 800 h < 0	(Mansson, 2001)
RH	<i>Usual range</i> [min; max] Min [20–40%] Max [60–80%]	(Koffi, 2009)
RH	<i>Acceptable range</i> [30; 70%]	(Harriman et al., 2001) and TR 14788 (CEN, 2006)
Number of hours with RH under or over the range Time ratio when the value of RH is over the range during a selected period	Not given	EN 15665 [13]
RH boxplot	[40; 50%]	Inspired by EN 15251 (CEN, 2007; Woloszyn et al., 2009)
Number of hours with RH >75% Over the heating period	WC and main room < 100 h Kitchen < 600 h Bathroom < 1000 h	French regulation for DCV (CCFAT, 2015)
Time per month during which critical thermal bridges are exposed to RH > 80% from December 1 to March 1	No absolute threshold	Former Belgian regulation for DCV (ATG and BCCA, 2012)
Number of hours with RH > 45% (in Nordic countries)	Not given	(Nielsen, 1992)

TABLE 5. HUMIDITY-BASED PERFORMANCE INDICATORS IN THE REVIEWED LITERATURE

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1.1.4.c) CO₂-based indicators

We reviewed IAQ performance indicators related to CO₂. The EN 15655 (CEN, 2009) standard proposes using four different indicators for a background pollutant: the average concentration, the weighted concentration, the average exceeding concentration above a threshold value, and the dose above a threshold value. Concentrations can be compared with four classes in order to assess the IAQ level, as proposed by several standards such as EN 16798-1 (CEN, 2016), the Finnish Society of Indoor Air Quality and Climate (FISIAQ) (FISIAQ, 1995), and EN 13779 (CEN, 2007a), assuming an outdoor concentration of 400 ppm: CO₂ lower than 750 or 800 ppm, between 750/800 ppm and 900/1000 ppm, between 900/1000 ppm and 1200/1400 ppm, and higher.

Based on this approach, Ribéron et al. proposed using the air stuffiness index for homes (ICONE) (Ribéron et al., 2016). This index is given in Equation 3 as a log function of the percentage of time when the measured CO₂ concentration at night is higher than 1000 ppm (f_1), and 1700 ppm (f_2), in the main bedroom and the living room:

$$I_{ICONE} = 8.3 \log (1 + f_1 + 3f_2)$$

EQUATION 3

Recent studies on ventilation performance (Laverge, 2013; Laverge et al., 2013) used a large set of indicators (six): cumulative exposure over 1000 ppm (ppm.h), standardized by the duration of the heating period or by the exceeding period; average exceeding concentration above 1000 ppm; average concentration; percentage of time spent in four classes based on the three thresholds (400, 600, and 1000 ppm) above outdoor concentration; exposure cumulative frequency plot; and standard deviation of concentrations.

Most of the performance-based approaches for ventilation reviewed in (Gaëlle Guyot et al., 2018) (from France, Spain, The Netherlands, and Belgium), as well as some references such as the IEA (Mansson, (Mansson, 2001a), p. 27) and several papers (Faure and Ouvrier-Bonnaz, 2019; Laverge et al., 2013; Pecceu et al., 2018; Savin et al., 2014), propose adapting the “dose” concept initially used for pollutants and calculating a cumulative exceeding exposure over thresholds varying between 950 ppm and 2000 ppm. These are sometimes calculated per room or per person, and the calculation period can also vary (whole year, several definitions of heating period, etc.), as described in the last lines of Table 6.

Table 6 summarizes CO₂-based performance indicators and associated thresholds in the reviewed literature.

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CO ₂ -BASED PERFORMANCE INDICATORS	THRESHOLDS	REFERENCES
Average concentration, weighted concentration, average exceeding concentration above a threshold value, dose above a threshold value	Four classes based on 750; 900; 1200 (ppm) 800; 1000; 1400 (ppm) above C _{outdoor}	EN 15655 (background pollutant) (CEN, 2009) EN 16798-1 (CEN, 2016) + (FISIAQ, 1995) EN 13779 (CEN, 2007)
The air stuffiness index for homes, ICONE $I_{ICONE} = 8.3 \log(1 + f_1 + 3f_2)$	Not given (relative comparison)	(Ribéron et al., 2016)
<ul style="list-style-type: none"> - Cumulative exposure over 1000 ppm (ppm.h): standardized by the heating period duration or by the exceeding period - Average exceeding concentration above 1000 ppm - Average concentration - Percentage of time spent in four classes based on the three thresholds (400, 600, 1000 ppm) (outdoor=0) - Exposure cumulative frequency plot - Standard deviation of concentrations 	Not given (relative comparison)	(Laverge, 2013; Laverge et al., 2013)
Cumulative exposure over 1050 ppm (ppm.h)	Not given (relative comparison)	Annex 27 IEA (Mansson, 2001, p. 27)
Cumulative exposure indicator over 2000 ppm (ppm.h) in each room	400,000 ppm.h	French regulation for DCV (CCFAT, 2015)
Yearly averaged concentration in each room Yearly cumulative exposure over 1600 ppm in each room	900 ppm 500,000 ppm.h	Spanish regulation for ventilation (Spain, 2017)
Per-person cumulative exposure over 950 ppm	Not given (relative comparison)	Former Belgian regulation for DCV (ATG and BCCA, 2012)
Per-person exposure index over 1200 ppm (LKI ₁₂₀₀) $LKI_{1200} = \sum_{t=0}^T \left(\frac{C_{CO_2 > 1200}(t) - 1200}{1000} \right) * t$	30,000 ppm.h	Dutch regulation for DCV (Borsboom, 2015)

TABLE 6. CO₂-BASED PERFORMANCE INDICATORS AND THRESHOLDS IN THE REVIEWED LITERATURE

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1.1.5 PROPOSAL FOR A REDUCED SET OF PERFORMANCE INDICATORS AND ASSOCIATED THRESHOLDS

The challenge in our investigation consists in identifying and selecting, from the long lists of indicators described in Tables 4–6, a reduced set of performance indicators to assess the IAQ performance of ventilation at the design stage of a building. Indeed, if we compare our approach with the ones developed for energy performance, usually only two or three performance indicators are used (total primary energy consumption, summer comfort indicator, renewables integration indicator, etc.).

Since we identified four relevant parameters: HCHO, humidity, CO₂, and PM_{2.5}, to assess ventilation performance, we wanted at least one performance indicator per parameter. We proposed two indicators for humidity, since we wanted to assess two separate risks: the condensation risk (building damage risk and indirect health risk to occupants) and the direct health risk.

For pollutants with dose–response laws, HCHO and PM_{2.5}, our investigation considered the cumulative exposure indicator as important at the design stage of a building. Indeed, it is directly related to the response on health, and dose thresholds have been proposed in the literature from dose–response studies (WHO et al., 2006). In our work, we focused on long-term exposure. We also considered the maximum cumulative exposure among the occupants of a home as the most relevant performance indicator related to pollutants at the dwelling scale: *MaxExp* (Equation 4).

This could be compared with the cumulative exposure corresponding to the reference ELV set to the minimum value used worldwide, as proposed by Cony Renaud Salis et al. (Cony Renaud Salis et al., 2017).

$$MaxExp = \max_i \left(\sum_{t=0}^d C(t) \cdot \Delta t \right) = \max_i (CumExp_i)$$

EQUATION 4

Where *i* is related to the building occupants.

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Therefore, we proposed a reduced set of five IAQ performance indicators based on health and building preservation, including one indicator based on the bedrooms where occupants spent most of their time (Klepeis et al., 2001; Zeghnoun et al., 2010), one indicator based on all rooms, and three indicators based on occupants:

- I_{CO_2} = Cumulative CO₂ exposure exceeding the reference value (for instance: over 1000 ppm) – maximum of all bedrooms
- I_{HCHO} = Cumulative HCHO exposure of occupants – maximum of all occupants (health risk)
- $I_{PM_{2.5}}$ = Cumulative PM_{2.5} exposure of occupants – maximum of all occupants (health risk)
- I_{RH70} = Percentage of time with RH higher than a threshold (for instance: 70%) – maximum of all rooms (condensation risk)
- I_{RH30_70} = Percentage of time spent by an occupant with RH outside of a given range (for instance: 30%–70%) – maximum of all occupants (health risk)

The time intervals to be calculated over a total duration time d correspond to the heating period for mild climates where air conditioning is rare (as in France).

These performance indicators could then be compared with selected thresholds. In order to illustrate this proposal, we selected published thresholds presented in Table 7 and adapted them to a simulation duration d in hours. For CO₂, HCHO, and PM_{2.5}, we propose comparing the calculated cumulative exposure to the threshold exposure corresponding to a constant threshold concentration (1000 ppm, 9 µg.m⁻³, and 10 µg.m⁻³, respectively) during the entire simulation. For the maximum time spent with RH >70% in all the rooms, we propose comparing it to the ratio between the number of hours thresholds and the duration d used in technical agreements for French DCV (CCFAT, 2015). In this reference, the thresholds for number of hours with RH >75% are 1000 h in bathrooms, 600 h in the kitchen, and 100 h in all other rooms. With a simulation duration equal to 5568 h (during the heating period from 1 Oct to 20 May), we obtain the thresholds expressed in percentages equal to 18%, 10.8%, and 1.8%, respectively. We propose keeping the distinction made between rooms, calculating local indicators ($I_{RH70,r}$) for each of the three types of rooms.

For the maximum time spent indoors by an occupant with RH out of the range 30–70%, we propose comparing it to the ratio between a threshold and the duration d . Mansson (Mansson, 2001b) proposes the threshold of 800 h for time spent with RH <30%, but using three different heating period durations d depending on the location (Nice 13 Nov–27 Apr; London 27 Sept–20 May ; Ottawa 2 Oct–20 May). We calculated the ratio as a percentage threshold with the Ottawa duration equal to 5544 h, in order to have a duration d close to the one used for the I_{RH70} thresholds and to keep the same order of magnitude.

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IAQ PERFORMANCE INDICATORS		THRESHOLDS	REFERENCE USED TO CALCULATE THE INDICATOR
I_{CO_2}	Maximum cumulative exceeding CO ₂ exposure over 1000 ppm in the bedrooms (BR) (ppm.h)	1000 d (ppm.h)	(Zhang et al., 2016) 1000 ppm combined with occupants' bioeffluents
I_{HCHO}	Maximum cumulative occupant HCHO exposure (µg.m ⁻³ .h)	9 d (µg.m ⁻³ .h)	(Cony Renaud Salis et al., 2017) 9 µg.m ⁻³ proposed as the ELV for HCHO
$I_{PM_{2.5}}$	Maximum cumulative occupant PM _{2.5} exposure (µg.m ⁻³ .h)	10 d (µg.m ⁻³ .h)	(Cony Renaud Salis et al., 2017) 10 µg.m ⁻³ proposed as the ELV for PM _{2.5}
$I_{RH70,r}$	Maximum time spent with RH >70% By room r (%)	Bathrooms: 18% Kitchen: 10.8% Other rooms: 1.8%	(CCFAT, 2015) 1000 h/600 h/100 h are the thresholds for RH >75% in bathrooms/kitchen/other We keep these values in a conservative approach
I_{RH30_70}	Maximum time spent by the occupant with RH out of 30–70% (%)	14.4%	(Mansson, 2001) 800 h is the threshold for RH <30%. We select the value of 800 h in a conservative approach

TABLE 7. SELECTED IAQ PERFORMANCE INDICATORS AND CORRESPONDING THRESHOLDS CALCULATED FOR A SIMULATION DURATION D (HOURS).

Results could be given with the radar approach as proposed in Figure 2, plotting each normalized indicator Equation 5, which must be lower than 1 for a regulatory approach requiring compliance with thresholds values, as illustrated in black line on the radar.

$$I^n = \frac{I}{Threshold}$$

for I^{CO_2} , I^{HCHO} , $I^{PM_{2.5}}$, I^{RH30_70}
EQUATION 5

$$I^n = \max_r \left(\frac{I_r}{Threshold(r)} \right)$$

for I^{RH70}
EQUATION 6

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These could also be required to be lower than 80% to claim an IAQ label, as illustrated by the gray dotted line on the radar. In the given case for a completely hypothetical "House A," changes must be made to the ventilation design (and/or also to occupant behavior to reduce emissions levels) in order to allow the ratios $I^n_{CO_2}$ and $I^n_{PM_{2.5}}$, to be lower than 1.

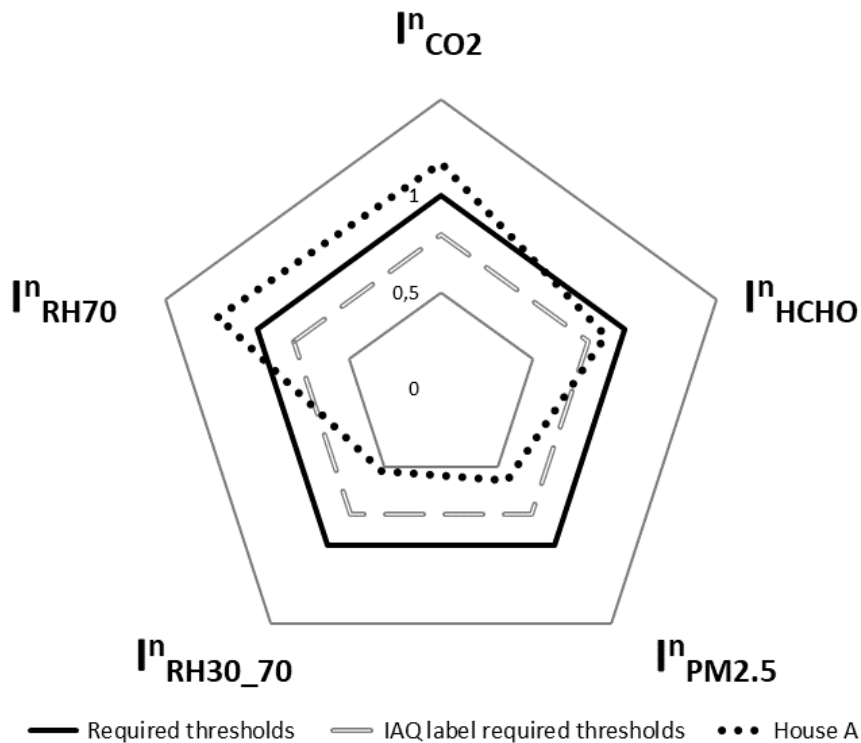


FIGURE 2. VISUALIZATION PROPOSAL: CALCULATED IAQ INDICATOR RATIOS WITH THEIR THRESHOLDS AT THE DESIGN STAGE OF "HOUSE A." THE BLACK PENTAGON ILLUSTRATES THE REQUIRED THRESHOLDS BY THE REGULATIONS (RATIO=1). THE DOTTED GRAY PENTAGON COULD ILLUSTRATE A BETTER PERFORMANCE RESULTS EXPECTED FOR AN IAQ LABEL (RATIO=0.8).

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1.1.6 APPLICATION TO A CASE STUDY: A LOW-ENERGY HOUSE

1.1.6.a) Case study

The case study is a low-energy, two-storey detached brick house, as shown in Figure 3 and described in (Guyot et al., 2019a). We assume being at the design stage of this house, which must comply with a hypothetical regulation, code, or label, requiring the proposed IAQ ventilation performance indicators to be calculated according to the proposed method.

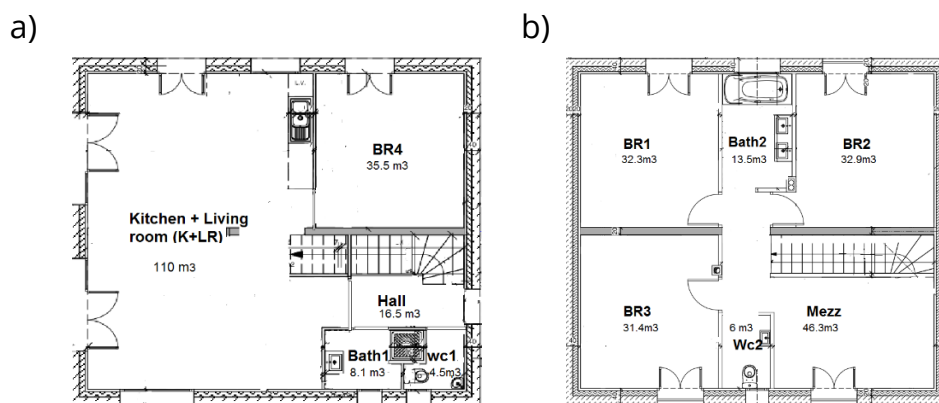


FIGURE 3. PLAN OF THE HOUSE STUDIED: (A) GROUND FLOOR (B) FIRST FLOOR.

Airflows, RH, PM_{2.5}, CO₂, and HCHO concentrations were computed using numerical modeling with CONTAM software (Walton and Emmerich, 1994). The house was modeled using 11 zones, each room represented by one zone. A 10-min time step was selected with weather data for a typical year in Lyon, France (ASHRAE IWEC Weather file, 2001). The calculation was performed over the heating period from October 15, 00:00 AM, to April 14, 12:00 PM, accounting for 4366 simulated hours. The inside temperature was set to 20°C during this period. The wind at the building was calculated from the weather data using a 0.3287 modifier factor, resulting from a power law used with factors from a suburban area and the house being 8.5 m in elevation. The pressure coefficients from the EN 15242 were used, assuming no barrier, i.e., +0.5 on the upwind facades and -0.7 on the downwind facades.

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The moisture buffering effect was represented using the boundary layer diffusion model in CONTAM. The simplified particles phenomena implemented in CONTAM were used with a default penetration rate of 1, a deposition velocity using 0.65 m.h^{-1} , and $9.90 \cdot 10^{-7} \text{ h}^{-1}$ as indoor particle resuspension rate based on measured median values in a four-resident dwelling given in (Thatcher and Layton, 1995). We used the pollutant emission data and occupancy schedules proposed in an extensive review (Poirier et al., 2021), as summarized in Figure 4. Only three indoor emission scenarios (low/medium/high) for HCHO and $\text{PM}_{2.5}$ were simulated.

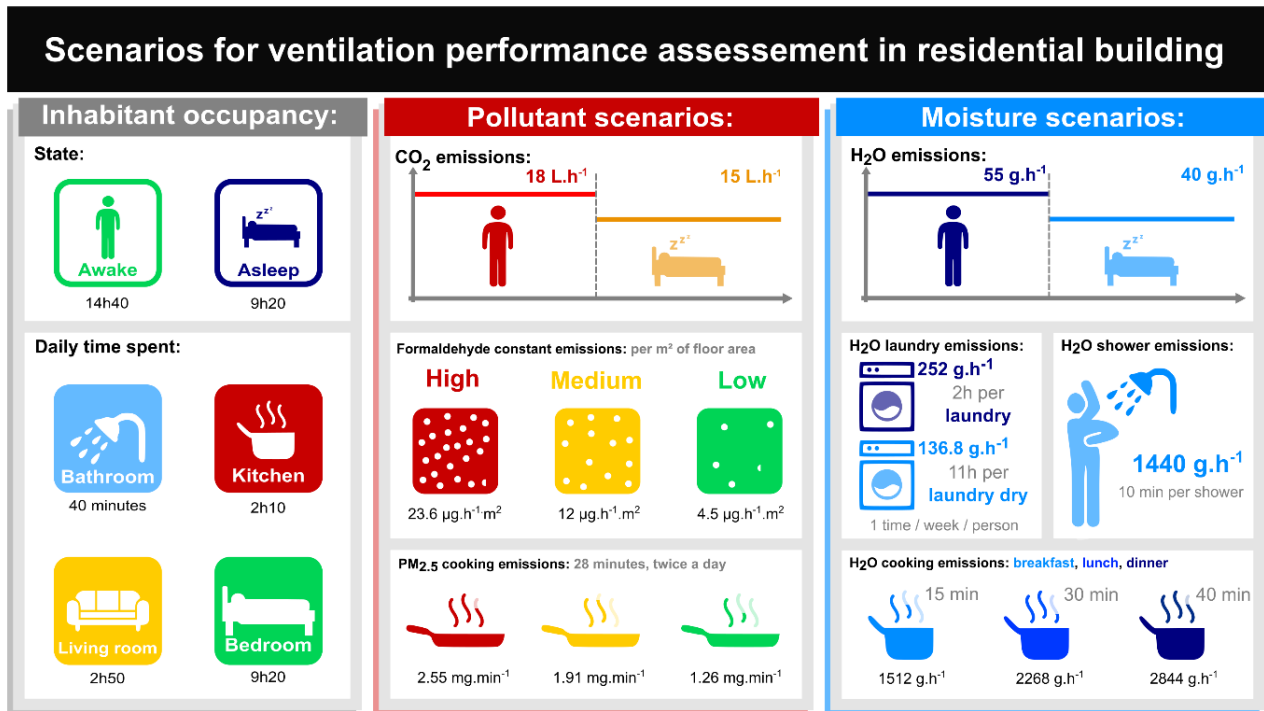


FIGURE 4. SCENARIOS OF POLLUTANT EMISSION AND OCCUPANCY SCHEDULES USED (FROM (POIRIER ET AL., 2021))

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1.1.6.b) Description of the three ventilation systems

Several options for the ventilation system were assessed, complying with French airing regulations (J.O., 1983):

1. **An exhaust-only** constant airflow ventilation system (EV)
2. **A balanced** constant airflow ventilation system (BV) (extracted airflows at each exhaust component are the same for 1 and 2)
3. **A humidity-based** demand-controlled ventilation (DCV) system, considered to be one of the references in France.

According to French regulations, for a seven-room house with two bathrooms and two toilets, a constant-airflow ventilation system must provide the following extracted flows: $30 \text{ m}^3 \cdot \text{h}^{-1}$ in each bathroom, $15 \text{ m}^3 \cdot \text{h}^{-1}$ in each toilet, and $45 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen. A high-speed ventilation system must also be able to provide $135 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen during peak periods. As a result, the total extracted airflow in the whole house is $135 \text{ m}^3 \cdot \text{h}^{-1}$ during basic mode and $225 \text{ m}^3 \cdot \text{h}^{-1}$ during peak mode. The basic mode accounts for an average dwelling air change rate of 0.4 h^{-1} .

The humidity DCV system adjusts the airflows according to the direct RH measurement through the extensions and retractions of a hygroscopic fabric modifying the cross-section of inlets and outlets (Jardinier et al., 2018). In our case study, this system includes:

- A kitchen exhaust Air Terminal Device (ATD) providing an airflow of between 15 and $55 \text{ m}^3 \cdot \text{h}^{-1}$, and a peak airflow of $135 \text{ m}^3 \cdot \text{h}^{-1}$ for 30 min if activated by the user
- Bathroom exhaust ATD providing an airflow of between 5 and $45 \text{ m}^3 \cdot \text{h}^{-1}$
- Toilet exhaust ATD providing a constant airflow of $5 \text{ m}^3 \cdot \text{h}^{-1}$, which could be switched to $30 \text{ m}^3 \cdot \text{h}^{-1}$ for 20 min thanks to an occupancy sensor
- One trickle ventilator in each bedroom and two in the living room, with an operating rate of between $4 \text{ m}^3 \cdot \text{h}^{-1}$ and $31 \text{ m}^3 \cdot \text{h}^{-1}$ (reference pressure of 10 Pa).

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1.1.6.c) Results and discussion

The main results of this case study are detailed in Table 8 for each of the three emission scenarios (low/medium/high for HCHO and PM_{2.5}). Figure 5 focuses on the medium emission scenarios as an example. It shows the IAQ performance of the three ventilation systems, assessed according to the five selected IAQ indicators for this case study.

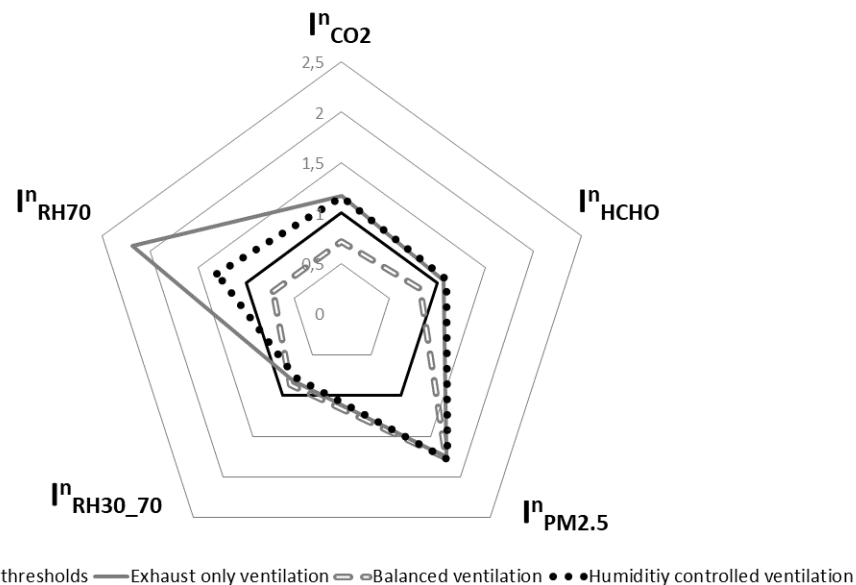


FIGURE 5. NORMALIZED PERFORMANCE INDICATORS FOR ALL THREE VENTILATION SYSTEMS (MEDIUM EMISSION SCENARIOS)

VENTILATION SYSTEM	NORMALIZED INDICATOR (WITH ASSOCIATED SCENARIO)								
	I ⁿ _{CO2}	I ⁿ _{RH30_70}	I ⁿ _{RH70}	I ⁿ _{HCHO}			I ⁿ _{PM2,5}		
				Low	Medium	High	Low	Medium	High
EV	1.17	0.82	2.18	0.52	1.06	1.88	1.21	1.76	2.31
DCV	1.16	0.78	1.3	0.53	1.09	1.94	1.3	1.78	2.33
BV	0.72	0.87	0.72	0.43	0.82	1.41	1.24	1.76	2.29

TABLE 8. VENTILATION SYSTEM PERFORMANCE RESULTS BASED ON THE FIVE NORMALIZED IAQ INDICATORS WITH INPUT SCENARIO VARIATIONS FOR HCHO AND PM_{2.5}

With this performance-based approach applied to this study case, we can first observe that none of these three ventilation systems either reaches all the IAQ targets or provides complying IAQ performance results. For example, the balanced ventilation system (BV) provides the best IAQ in terms of CO₂, HCHO, and condensation risk. However, the DCV system provides slightly better IAQ if one looks at the occupant-based humidity indicator, with a Iⁿ_{RH30_70} result 10% lower. The EV system shows almost the same performances as the DCV, except for the Iⁿ_{RH70} (condensation risk), for which this system is 67% less efficient than the DCV system. Indeed, this condensation risk score is reached in bedrooms: for the EV and DCV systems, the uncontrolled infiltration airflows are higher than for the BV systems.

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As a consequence, the air inlet flows in bedrooms vary more, and can be lower for EV and DCV than for BV systems. With the BV, the entering airflows in the bedrooms are therefore higher compared to EV, leading to higher air change rates and, as a result, a lower level of humidity in the bedrooms. In addition, DCV outperforms EV. This result confirms that the DCV strategy provides a clear benefit over EV, despite lower airflows during low humidity periods. Finally, the three system responses are close in terms of $I^n_{PM_{2.5}}$ indicators, and none reaches the acceptable threshold. Indeed, the airflow provided at high speed during cooking periods is the same in the three systems, and seems to not be efficient enough to remove $PM_{2.5}$ during peak emission.

The performances are far from acceptable for the $I^n_{PM_{2.5}}$ and I^n_{HCHO} indicators, except for the low and medium HCHO emission scenarios. These results highlight the interest of this performance-based method, taking into account IAQ parameters other than the traditional CO_2 and humidity, for a better consideration of IAQ in the choice and design of ventilation strategy.

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1.1.7 CONCLUSION AND PERSPECTIVES

In order to improve IAQ in buildings, we suggest that performance-based approaches should be used to choose and design the ventilation strategy at the design stage of a given residential building. The first challenge was to identify a reduced set of relevant IAQ performance indicators. As shown by the published literature, most of the IAQ performance indicators already considered for the assessment of ventilation performance are based on humidity and CO₂ only, and neglect other parameters.

In this paper, we first analysed and selected the relevant parameters for the assessment of IAQ ventilation performance in residential settings. We then analysed and selected the corresponding IAQ performance indicators based on the selected parameters and identified the corresponding requirements (or thresholds). We reviewed standards, the published literature, regulations in European countries, as well as resources from the AIVC.

As a result, based on four relevant parameters (HCHO, humidity, CO₂, and PM_{2.5}), we identified at least five relevant IAQ performance indicators (I_{CO_2} , I_{HCHO} , $I_{PM_{2.5}}$, $I_{RH_{30_70}}$, $I_{RH_{70}}$) to be used as output data of a ventilation performance assessment approach of this kind.

Applying such a performance-based method using these five indicators, we demonstrated in this paper how this could make it possible to compare the performance of three different ventilation strategies in a low-energy house. In this case, we observed a small advantage for the studied BV system on global IAQ performance and showed that humidity-based DCV, despite lower airflows during low-humidity periods, provides almost the same IAQ performance as EV-only ventilation, while clearly reducing condensation risk.

We also observed poor performances for indicators based on HCHO and PM_{2.5}, highlighting the importance of taking into account IAQ parameters other than the traditional CO₂ and humidity, for a better consideration of IAQ in performance-based approaches.

This list of performance indicators is intended to be improved as new knowledge in the field becomes available and can be expanded as soon as new pollutants of concern are identified. Moreover, within a broader overall performance framework, these IAQ indicators should be expanded to include energy performance indicators such as the energy losses or electricity consumption of systems, virus transmission prevention, and acoustic comfort, among others.

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At present, this paper proposes a clear contribution to the development of performance-based approaches for ventilation in residential buildings and the improvement of IAQ for future occupants. Furthermore, the proposed IAQ indicators can also be used to process data collected during IAQ measurement campaigns.

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Pollutants emission scenarios for residential ventilation performance assessment. A review

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Abstract

Given that performance-based approaches secure maximum energy consumption for new buildings in more and more building codes and standards, such approaches could ensure that ventilation is designed to avoid risks for occupants' health. We have developed a performance-based approach for assessing ventilation indoor air quality (IAQ) performance in low-energy houses at the design stage of a building, in line with regulatory energy performance calculations. In this context, the whole-building IAQ performance modelling process raises two key issues: What are the relevant performance indicators to be calculated? What are the corresponding emission scenarios and occupancy schedules to be used as entry data to calculate the performance indicators selected? This paper focuses on this second issue through a literature review: firstly oriented toward the occupancy considerations so as to define the emission rates for CO₂, moisture, formaldehyde and PM_{2.5} to be use as input for ventilation performance assessment.

Based on this review, we propose daily schedules for the occupants and their associated moisture and CO₂ emissions. We completed them with emission rate values for the main pollutant sources from indoor activities regarding moisture emissions from laundry, showering and cooking; PM_{2.5} emissions from cooking and formaldehyde from building materials and furniture. Finally, from these values we built three emission rates classified for PM_{2.5} and formaldehyde: high, medium and low.

Keywords: Ventilation, indoor air quality, performance, residential buildings, scenarios, review

1.2.1 INTRODUCTION

Net zero-energy residential buildings are in increasing demand in Europe because of the energy performance building directive (European Parliament, 2010). Ventilation strategies have a large impact on the heat balance and the associated air conditioning energy need. Improving ventilation strategies also has great potential to reduce the contribution of residential buildings to total energy consumption.

Ventilation systems and strategies play another important role in buildings' indoor air quality (IAQ), significantly affecting public health (Klepeis et al., 2001; European Commission, 2003; Brasche and Bischof, 2005; Zeghnoun et al., 2010; Jantunen et al., 2011). People spend 60–90% of their life in indoor environments (homes, offices, schools, etc.). The current damage to public health estimated by Logue et al. (Logue et al., 2011a, p. 20) in disability-adjusted life years (μ DALY) per person per year from all sources attributable to IAQ, excluding second-hand smoke (SHS) and radon, ranged between the health effects of road traffic accidents ($4,000 \mu$ DALY.pers⁻¹.year⁻¹) and heart disease from all causes ($11,000 \mu$ DALY.(pers⁻¹.year⁻¹). Health gains in Europe (EU-26) attributed to effective implementation of the energy performance building directive, which includes indoor air quality issues, have been estimated at more than 300,000 DALYs per year.

In this context, in new certifications and future building regulations, building performance should be extended to indoor environment quality, beyond simply energy performance. In the energy performance field, successive regulations encouraged a performance-based approach, based on an energy consumption requirement for heating and/or cooling at the design stage (Spekkink, 2005). In the building ventilation field, regulations throughout the world are mainly still based on prescriptive approaches, with airflow or air change rate requirements (Dimitroulopoulou, 2012). In contrast to such prescriptive approaches, it is possible to develop performance-based approaches for residential building ventilation. Since prescribed ventilation rates are only an imperfect way to achieve a given IAQ, using IAQ performance indicators instead of ventilation rates may be more appropriate.

Given the lack of data on the relevant ventilation method, we developed a performance-based approach for assessing ventilation performance at the building scale, at the end of the design stage, much like the regulatory energy performance calculation. This would ensure that ventilation is designed to avoid risks for occupants' health and building damage. We should also keep in mind that Indoor Air Quality relies on two principles: reduction of indoor pollution sources and efficient ventilation. Indeed, the ventilation system can not ensure the all pollutant dilution without a significant impact on the building energy performances.

PART 1 : METHOD FOR IAQ PERFORMANCE ASSESSMENT

1.2 POLLUTANTS EMISSION SCENARIOS FOR RESIDENTIAL VENTILATION PERFORMANCE ASSESSMENT. A REVIEW

The need to reduce sources of indoor pollution is also a key element in ensuring good IAQ, for example by avoiding smoking cigarettes indoors, burning candles etc... Sources reduction is out of the frame of the developed method, which is focussing exclusively on the ventilation performance assessment. The following scheme gives an overview of the whole building IAQ modelling process for this performance-based approach and the inputs and outputs needed (Figure 1).

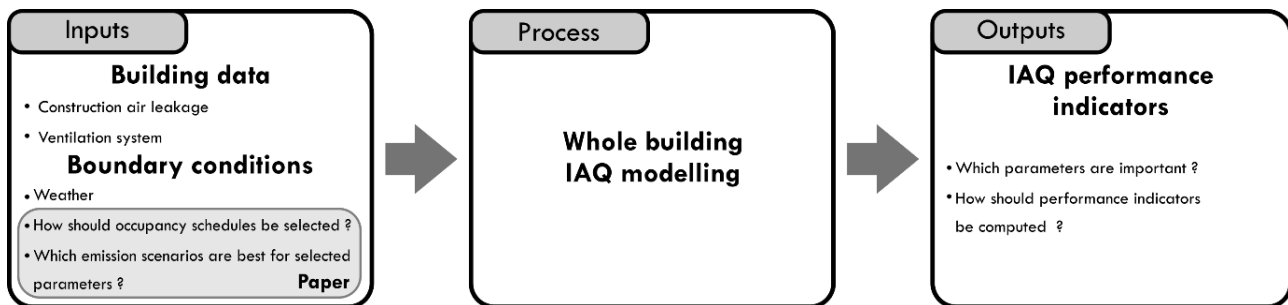


FIGURE 1. PERFORMANCE-BASED APPROACH FOR VENTILATION.

To develop this type of performance-based approach, the following two scientific barriers had to be considered:

- What are the relevant parameters, including pollutants, to use for calculating performance indicators and what indicators should be used?
- What are the corresponding relevant input data to use regarding occupancy and emission scenario parameters?

Relevant pollutants and performance indicators have been investigated and are often based on at least moisture, CO₂, formaldehyde and particle matter PM_{2.5} (G. Guyot et al., 2018b; Guyot et al., 2019b). Indeed, formaldehyde and PM_{2.5} are considered as two pollutants of concern in residential indoor air and were identified among the five pollutants with the highest median DALY loss estimates (He, 2004; Logue et al., 2011). In detail, the indoor sources contributing to elevated indoor particle matter levels are mainly related to human activities that generate peak emissions (Kirchner and al., 2007). On the contrary, the sources of formaldehyde emissions are more diffuse and related to building construction materials, furniture and decorative materials (Logue et al., 2011b, 2011a; He, 2004; Kirchner and et. al., 2007; Koistinen et al., 2008; WHO, 2010b; Borsboom et al., 2016). This makes PM_{2.5} and formaldehyde interesting for their complementarity. Moisture and CO₂ were selected as historical parameters widely used in the standards and in ventilation systems controls (G. Guyot et al., 2018b, 2018a). Several other pollutants could have been selected, but for the performance-based method to be applied, it is important to promote a low number of pollutants in order to build calculable, accurate and robust IAQ indicators.

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To calculate IAQ performance indicators as cumulative exposures, we also need the occupancy schedules and parameters emission rates at the design stage of a building. In this paper, we focus on this second barrier aspect through an extensive literature review on the occupancy schedule considerations in a building and CO₂, humidity, PM_{2.5} and formaldehyde emission rate scenarios.

1.2.2 METHODOLOGY

We reviewed the available literature (Standards, Research reports, Scopus, Elsevier, AIVC database) using the following terms:

- First: "ventilation performance", "smart ventilation performance", "ventilation assessment", "ventilation IAQ performance".
- Second: "occupancy patterns", "occupancy schedules", "occupancy IAQ" and "occupant IAQ".
- Last: "IAQ emission", "IAQ rate", "IAQ sources", "emission rate", "cooking emission rate", combined with "CO₂ "a", "moisture", "humidity", "formaldehyde", "fine particle matter", "PM_{2.5}", "pollutant", "occupant".

The first important point we have to consider in this review is the accuracy of the emission rates. These data are not directly measured but are calculated using mass balance equations, combining airflows or air change rate measurements and parameter concentration measurements. As a result, several sources of uncertainty exist: measurement uncertainties on airflows and air change rates, measurement uncertainties on parameter concentrations, and modelling uncertainties (mass balance includes assumptions on occupancy, room configuration, weather data, etc.). Measurement uncertainties include the precision and bias of the measurement device, the impact of the user, the impact of the weather data (for air change rates and airflows), and is well documented in the ISO guide (ISO/IEC, 2008). Air change rates (Haghighat et al., 1991; Kvisgaard and Collet, 1990; Modera and Wilson, 1990; Remion et al., 2019), ventilation airflows (Bailly and Berthault, 2016; Cóstola et al., 2010) and pollutant concentration measurement accuracy, notably sensor accuracy (Fahlen and Andersson, 1992; Fisk et al., 2006; Barsan et al., 2007; Chung et al., 2013; Guyot et al., 2017; AIVC, 2018), are a broad area of research for *in-situ* and laboratory measurements. We selected only research papers and literature with consistent data on emission rate calculation methodology and uncertainties.

In addition, at the design stage of a residential building, it is difficult to fully describe occupancy for the entire life span of a building: number and age of the occupants, activities, schedules, etc. It is also impossible to precisely describe all the parameter emission rates for the occupants, their activities, the building materials and furnishings. In a performance-based approach at the design stage of a building, the standards and regulations dealing with this issue must also be considered.

We therefore preferred using cyclic schedules (fixed schedules which are reiterated every week), differentiating metabolic emissions, building and occupants' activity emissions, as proposed for humidity and CO₂ in several standards and regulations (British standard, 1991a; CCFAT, 2015; CEN, 2006, 2009; G. Guyot et al., 2018b; Johansson et al., 2010a; Mansson, 2001b). Consequently, we selected only the reference building entry data in a standard approach, to avoid under-estimating or over-estimating the pollutant sources in a building, which could have a direct impact on the results of the ventilation performance evaluation. The standard approach provides a relative comparison of the performance of several ventilation systems, configurations and airflow rates, building design choices related to ventilation, IAQ labelling products, and even several occupant IAQ awareness levels.

Then we selected references allowing us to build a scenario to be used as entry data to calculate the performance indicators, in order to assess the ventilation performance of a building at its design stage.

This paper describes a detailed daily life required to calculate IAQ performance indicators. CO₂ and moisture performance indicators use occupants' metabolism and activity (only for humidity) emissions, combined with occupancy schedules, as input data. To calculate the cumulative exposure indicators (for instance, for formaldehyde and PM_{2.5}), we also need detailed occupancy schedules for each occupant. In this literature review, the duration of occupation by room throughout the day and the type of occupant (adult/child) were sought because they could influence the emission rates. In this section, we reviewed 10 papers.

Then the rates and scenarios for moisture, CO₂ and HCHO, PM_{2.5} emissions were studied. CO₂ and moisture emissions from human metabolism and activities are quite well documented. We reviewed 12 papers and then built and proposed a scenario based on this analysis.

In contrast, formaldehyde and PM_{2.5} emission rates remain exploratory, especially in a design approach for ventilation performance assessment. These pollutant emission and concentration measurements and modelling are complex, because of the physics of phenomena involved (e.g. diffusion, resuspension for PM, combined effects for formaldehyde) and available measurement techniques. In addition, formaldehyde emissions are highly dependent on building and furnishing materials. Consequently, we attempted to build low-, medium- and high-polluting emission rate scenarios and chiefly focus on measured pollutant emission rates stemming from the building, the furnishings and the occupants' activities.

However, multiple types of data are available and cannot be directly used together for scenario proposals, so they were categorised in the formaldehyde and PM_{2.5} subsections in three measurement types:

- *Chamber-tested loads*: Pollutant emissions due to specific activities, products and building materials obtained using test chambers under standardised conditions as described for VOC in ISO 16000-9 (International Organization for Standardization (ISO), 2006). We found more data on formaldehyde than PM_{2.5} emission rates.
- *Lab kitchen*: PM_{2.5} emissions due to specific activities measured in unoccupied homes or in experimental setups.
- *In-situ loads*: Emission rates measured at the dwelling scale in occupied or unoccupied buildings, resulting from the combination of pollutant concentration and air change rate measurements in dwellings. We found few data on formaldehyde and PM_{2.5} emission rates.

For PM_{2.5} emissions, of the first 29 references analysed on emission sources and particle exposure in indoor environments, we selected eight published articles to build and propose a scenario based on this analysis. For formaldehyde emissions, we reviewed 22 references to build a scenario.

At the end, based on 73 articles reviewed, we provide a summary of the occupancy and emission rate scenarios selected. For emission rates, we conducted a review of the international literature, then we selected the rates and built the scenarios for a European, or even French application. Nevertheless, the data analysed here are sufficiently described to be used for applications in other countries.

1.2.3 OCCUPANCY CONSIDERATIONS

1.2.3.a Residential occupancy schedules in the literature

Precisely described data fitting our purposes are rarely found in the literature. Energy performance calculation methods use global occupancy schedules at a whole building scale (indoor/outdoor), whereas a multizone approach requires assuming an occupancy scenario in each room of the house, at each time step, both for the emission rates and exposure aspects.

In energy performance calculations, (Aerts et al., 2013) proposed seven discrete occupancy profiles based on a time survey on more than 3000 Belgian dwellings. They differentiated outside, inside awake and inside asleep contexts.

A French IAQ national campaign based on a representative sample of the population included 567 homes and 1612 occupants (Zeghnoun et al., 2010). A total of 1375 occupants provided precise information on their schedules and occupation in the rooms (25% of the sample) so that a database of 1,386,000 ten-minute time steps with precise information on occupant location was available and analysed in this study. The results show that people spend on average 67.3% of their time in their homes. This is consistent with results of other surveys in Europe (EXPOLIS, 56–66%) and in the United States (NHAPS: 68.7%). Other interesting results are available in this study:

- The differences between weekend days and week days are minimal: the 3 days with the highest occupancy duration are Sunday (16.6 h), Wednesday (16.5 h) and Saturday (16.3 h), followed by Thursday (16.1 h). Friday is the least occupied day (15.7 h).
- There is no statistical difference between working periods and holidays.
- Occupants are more likely to be at home between 12.00 pm and 2 pm and between 7 pm and 7 am.
- Time spent at home is divided, on average, into 9 h 16 min spent in bedrooms, 2 h 49 min spent in the living room, 2 h 40 min spent in the kitchen and 38 min spent in the bathroom.

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To achieve the occupancy consideration in a building this schedule information needs to be completed by a description of the occupants. Human emissions stem from the metabolic functions such as respiration, transpiration and perspiration, depending on different factors such as age (Mansson, 2001a) (contradicted by (Bienfait et al., 1992)) and activity level. Because of the development and growth of the organs of a child, its basic metabolism can reach twice the adult rate. The basic metabolism is defined as the minimum energy expenditure of an organism to ensure daily functions at rest. It decreases between 6 years and 18 years: from 19% for boys to 27% for girls (Knoebel, 1963). As a result, as explained by (Déoux, 2010), even if their body surface area is lower, children's CO₂ and humidity emission rates are as high as those of adults and may even be higher. Measures taken in 20 occupied apartments showed that children's emissions were often under-estimated in the literature and were closer to adults' emissions (Bernard, 2009), with emissions measured at 13 L.h⁻¹ for a child and 16 L.h⁻¹ for an adult. The ECA guidelines for ventilation requirements in buildings (Bienfait et al., 1992) compiles data from three studies (Rasmussen et al., 1985; Pejtersen et al., 1991; Thorstensen et al., 1990), giving emission rates for adults and children (Table 1).

	CO ₂ EMISSIONS [L.h ⁻¹] BY OCCUPANT	WATER VAPOUR [g.h ⁻¹] BY OCCUPANT
<i>Sedentary adult</i>	19	50
<i>Low physical exercise</i>	50	200
<i>Medium physical exercise</i>	100	430
<i>High physical exercise</i>	170	750
<i>Children, 3-6 years</i>	18	90
<i>Children, 14-16 years</i>	19	50

TABLE 1: POLLUTANT LOAD CAUSED BY OCCUPANTS. SOURCE: (BIENFAIT ET AL., 1992)

1.2.3.b) Occupancy schedule proposal

For our purposes, we used the detailed data from the French IAQ national campaign (Zeghnoun et al., 2010). The following daily occupancy duration (rounded for a 10-min time step simulation) was retained:

- 9 h 20 min in bedrooms,
- 2 h 50 min in the living room,
- 2 h 40 min in the kitchen,
- 40 min in the bathrooms,
- For a total of 9 h 20 min asleep, 14 h 40 min awake, 9 h outside and 15 h inside.

These occupancy schedules should be carefully adapted depending on countries and their habits (meal times, school times, work times, etc.).

The number of occupants must be assumed, taking into account the size of the house, to avoid under-estimating the ventilation airflow rates. We would suggest setting the number of occupants based on the number of bedrooms, assuming two occupants in one bedroom and one in each of the others. At the design stage of a building, we could also assume that all occupants are adults, based on the data reported in Table 1.

In the next section, emissions due to occupants will occur where and when occupants are assumed to be present.

1.2.4 EMISSION RATE SCENARIOS FOR A VENTILATION PERFORMANCE ASSESSMENT AT THE DESIGN STAGE OF A RESIDENTIAL BUILDING

1.2.4.a) Moisture

Moisture emission rates in the literature

In a building the main moisture sources are linked to the occupants' activities such as showering, cooking, dish washing and laundry drying. In addition, the building envelope helps to regulate indoor humidity by exchanging moisture flows with the indoor air. This phenomenon must be represented in the model in order to provide realistic results. We consider this phenomenon of moisture exchange as a buffer (part of the model) and not as an emission source.

In most of the references analysed, mainly including standards, related production is given for a precise activity with a duration per day, sometimes depending on the number of occupants (British standard, 1991a; CCFAT, 2015; CEN, 2006, 2009; Mansson, 2001b) (Table 2).

Note that two normative documents (British standard, 1991b; CEN, 2006) proposing the schedule approach also alternatively suggest using an average constant moisture emission rate, depending on the overall moisture production and the number of occupants. Alternative approaches based on experimental measurements are also proposed (Johansson et al., 2010b; Pallin et al., 2011) (Table 2).

The occupants' metabolism is also a source of humidity. The most frequent distinction between activity levels is when occupants are asleep or awake. For a household of three people, a study used a value of $2.4 \text{ kg}\cdot\text{day}^{-1}$ of water production in each room (Woloszyn et al., 2009). Experimental studies also give useful information with confidence intervals comparable to (Johansson et al., 2010b; Pallin et al., 2011) (Table 3).

Finally, a review on the indoor moisture also showed sources ranging from very simplified to more realistic sources (Labat and Woloszyn, 2015). The simplest is an average constant emission based on (Walker and Sherman, 2007) which reviewed nine studies, suggesting the average emission of $270 \text{ g}\cdot\text{h}^{-1}$ to be used for a 1-year simulation. This review (Labat and Woloszyn, 2015) also showed that several experimental and numerical studies preferred using typical cyclic schedules. Lastly, stochastic scenarios could also be used, as demonstrated by (Page et al., 2008; Parys et al., 2011) in office buildings. For a one-zone experimental building, (Labat and Woloszyn, 2015) showed how constant emission rates could result in increasing the comfort range by 10–20%, compared to the use of stochastic scenarios.

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ACTIVITIES	EMISSION RATE	DURATION	REFERENCE
<i>Cooking /person</i>			CCFAT
- Breakfast	100 g.h ⁻¹	0.5 h	(CCFAT, 2015)
- Lunch (weekend)	75 g.h ⁻¹ (150 g.h ⁻¹)	1 h	EN 15665
- Dinner	300 g.h ⁻¹	1 h	(CEN, 2009)
Shower ^(a) CCFAT / EN 15665	300 g	0.5 h / 6 min	
Laundry ^(b)	100g.h ⁻¹	2 h	
Laundry drying ^(b)	50g.h ⁻¹	20 h	
Electric cooking device	2000 g.day ⁻¹ 3000		British standard, &
Gas cooking device	g.day ⁻¹		TR-14788
Hand dish washing	400 g.day ⁻¹		(CEN, 2006)
WC/shower/dish washing	200 g.day ⁻¹ .person ⁻¹		(called A)
Laundry	500 g.day ⁻¹		
Inside drying ^(c)	1500 g.day ⁻¹ .person ⁻¹		
<i>Cooking</i>			TR-14-88
- Breakfast	0.6 l.s ⁻¹	10 min	(CEN, 2006)
- Lunch	1 l.s ⁻¹	10 min	(called B)
- Dinner	1.5 l.s ⁻¹	10 min	
Shower/person	0.5 l.s ⁻¹	10 min	
Laundry drying	0.06 l.s ⁻¹	12 h	
<i>Moisture generation rate</i>	Low/medium/high		British standard,
- 1 person	3.5/6/9 kg.day ⁻¹		1991 [48] &
- 2 persons	4/8/11 kg.day ⁻¹		TR-14-788
- 3 persons	4/9/12 kg.day ⁻¹		(CEN, 2006)
- 4 persons	5/10/14 kg.day ⁻¹		(called C)
- 5 persons	6/11/15 kg.day ⁻¹		
<i>Cooking meals</i>			<i>Experimental data</i>
- Breakfast	109 ± 20 g	15 ± 5 min	
- Lunch	288 ± 68 g	30 ± 2 min	(Johansson et al.,
- Dinner	518 ± 152 g	40 ± 10 min	2010; Pallin et al.,
<i>Dish washing</i>			2011) cited in
- Breakfast	25 ± 3 g	29 ± 3 min	(Peuportier et al.,
- Lunch	20 ± 3 g	29 ± 3 min	2015)
- Dinner	240 ± 9 g	29 ± 3 min	
Showering	250 ± 50 g	10 min	
Laundry drying ^(d)	1850 ± 670 g	11 ± 2 h	
(a) With 1 shower.day ⁻¹ .person ⁻¹			
(b) With x laundry.week ⁻¹ (CCFAT, 2015) (x = 1–4 depending on the number of inhabitants) EN 15 665 (CEN, 2009) (x = 1)			
(c) Naturally or with dryer without vent			
(d) 20% of the total emissions during the first 2 h			

TABLE 2: MOISTURE EMISSION RATES OF ACTIVITIES

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METABOLISM EMISSION DATA	AWAKE	ASLEEP	AT REST	SOURCES
- 3–6 years - 14–16 years - Adult			90 g.h ⁻¹ 50 g.h ⁻¹ 50 g.h ⁻¹	ECA guidelines for ventilation requirements in buildings (Bienfait et al., 1992)
- <2 years - 10–13 years - >15 years	30 g.h ⁻¹ 45 g.h ⁻¹ 55 g.h ⁻¹	10 g.h ⁻¹ 15 g.h ⁻¹ 30 g.h ⁻¹		(Mansson, 2001)
- per person	55 g.h ⁻¹	38.5 g.h ⁻¹		(CCFAT, 2015) & (Riberon and Millet, 1991)
- per person	55 g.h ⁻¹	40 g.h ⁻¹		(CEN, 2009, p. 655)
<i>Recommended duration of emissions</i>	55 g.h ⁻¹ Living room 4 h	40 g.h ⁻¹ Bedroom 10 h		(CEN, 2006) & (British standard, 1991)
- Active people	70 ± 5 g.h ⁻¹	30 ± 2 g.h ⁻¹	50 ± 5 g.h ⁻¹	<i>Experimental data</i> (Johansson et al., 2010; Pallin et al., 2011) cited in (Peuportier et al., 2015)
- for 3 people	2.4 kg.day ⁻¹ (average 33 g.h ⁻¹ per person)			(Woloszyn et al., 2009)

TABLE 3: METABOLISM MOISTURE EMISSION RATES

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Analysis and scenario proposals

First of all, all the metabolism moisture emission rates in the literature reviewed are within the same range, so we suggest using the moisture generation rates for the metabolism emission of 55/40 g.h⁻¹ (awake/asleep). Next step is to quantify the dispersion of moisture emissions rates due to activities, given in Table 2. In order to compared them, we calculated for each reference ((CEN,2006)-A, (CEN,2006)-B,(CEN,2009), (CCFAT, 2015),(Pallin et al., 2011)) the related daily moisture emissions, assuming one or five occupants, taking into account metabolism, cooking, showering, laundry and clothes drying. We assumed one laundry, one clothes drying per person and per week, and we calculated an average weighted emission rate per day. Lastly, we compared the calculated results expressed as an average emission rate in kg per day to the thresholds given in TR 14 788-C (CEN, 2006) (). From these tables, we can observe that no standard gives high emission rates, and that these are in most cases low, and become medium if we consider five occupants.

	REFERENCE	CALCULATED DAILY EMISSIONS [KG.DAY ⁻¹]	LOW 6 KG.DAY ⁻¹	MEDIUM 11 KG.DAY ⁻¹	HIGH 15 KG.DAY ⁻¹
1 occupants	TR 14-788-A (CEN, 2006)	4.1	-	X	-
	TR 14-788-B (CEN, 2006)	2.6	X	-	-
	EN-15-665 (CEN, 2009)	1.4	X	-	-
	CCFAT(CCFAT, 2015)	1.6	X	-	-
	Experimental Data (Pallin et al., 2011)	2.0	X	-	-

TABLE 4. COMPARING CALCULATED DAILY MOISTURE EMISSIONS WITH THRESHOLDS GIVEN IN TR 14-788-C (CEN, 2006A), ONE OCCUPANT

	REFERENCE	CALCULATED DAILY EMISSIONS [KG.DAY ⁻¹]	LOW 6 KG.DAY ⁻¹	MEDIUM 11 KG.DAY ⁻¹	HIGH 15 KG.DAY ⁻¹
5 occupants	TR 14-788-A (CEN, 2006)	8.4	-	X	-
	TR 14-788-B (CEN, 2006)	7.2	-	X	-
	EN-15-665 (CEN, 2009)	4.9	X	-	-
	CCFAT, 2015 (CCFAT, 2015)	7.9	-	X	-
	Experimental Data (Pallin et al., 2011)	5.2	X	-	-

TABLE 5. COMPARING CALCULATED DAILY MOISTURE EMISSIONS WITH THRESHOLDS GIVEN IN TR 14-788-C (CEN, 2006), FIVE OCCUPANTS.

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Consequently, for our analysis, for the activity emissions, we suggest using the TR 14-788-A (CEN, 2006) data, because it is the most handicapping reference. We combined them with the emission duration given by (Johansson et al., 2010b; Pallin et al., 2011) because these data came from in-situ measurements, published in an IEA Annex and cited in (Peuportier et al., 2015). The following moisture generation scenarios could be used:

- One shower per person per day, with an emission of 1440 g.h^{-1} for 10 min per shower;
- Cooking periods per day: 1512 g.h^{-1} for breakfast for 15 min; 2268 g.h^{-1} for lunch for 30 min; 2844 g.h^{-1} for dinner for 40 min;
- One laundry per person per week: 252 g.h^{-1} for 2 h;
- One laundry drying per person per week (same days): 136.8 g.h^{-1} for 11 h.

This results in an average production of 6 kg.day^{-1} for five occupants, which is a rather low emission scenario.

1.2.4.b) Carbon dioxide

Emission rates in the literature: analysis and proposal

CO₂ emission rates are due to occupant metabolism and depend on the occupants’ size and activity. The literature gives the same order of magnitude and generally proposes making a difference between asleep and awake times, adults and children, as summarised in Table 6, which shows a quite good consensus around the value of 18 L.h⁻¹ for an awake adult with a low level of activity. For a sleeping adult, the emission rates vary between 10 and 16 L.h⁻¹.

EMISSION RATES	[L.(H.PERSON)⁻¹]	SOURCES
<i>Sedentary</i>		
- 3-6 years	18	<u>(Bienfait et al., 1992)</u>
- 14-16 years	19	
- Adult	19	
Awake	16	<u>(CEN, 2009, p. 665)+</u> <u>(CCFAT, 2015)</u>
Asleep	10	
<i>Awake/asleep</i>		<i>Annex 27 IEA</i> <u>(Mansson, 2001)</u>
- <2 year-old	8/4	
- 10- to 13-year-old	12/8	
- >15-year-old	18/12	
<i>Asleep, measured in occupied apartments</i>		<u>(Bernard, 2009)</u>
- Child	13	
- Adult	16	
Child (medium exercise)	10	<u>(Persily, 1997)</u>
Adult (office work)	18	
Adult (asleep)	15	

TABLE 6: CO₂ METABOLISM EMISSION RATES

Given this data, and as we are at the design stage of a building with generally no idea of occupant age, we considered that all occupants are adults, as explained in the above section. Finally, we used the emission rates proposed by Persily (Persily, 1997): 18 L.h⁻¹ and 15 L.h⁻¹ for an “awake” or “asleep” occupant of a residential building. The first value shows quite good consensus and the second allows one to avoid over-estimating ventilation performance.

1.2.4.c) Formaldehyde

Formaldehyde emission rates

General considerations

For formaldehyde, several authors have highlighted the correlation of concentrations and emissions with temperature, relative humidity and air exchange rates (Park and Ikeda, 2006). Using a multivariate model fit on observational data testing temperature, humidity, the air change rate and outdoor concentration, (Blondel and Plaisance, 2011) considered temperature to be the best correlated with the increase in the formaldehyde concentration. A chamber test study proposed a semi-empirical correlation law between the initial material's emittable concentration and the combined effect of humidity and temperature (Liang et al., 2016). Moreover, the formaldehyde emissions of new houses from construction materials, such as wood products, are known to be constant for approximately nine months and then start to decrease (Sherman and Hodgson, 2002), to reach a steady state emission rate after a few years (Park and Ikeda, 2006).

Rates obtained in chamber-tested loads

The study reported by Plaisance et al. (Plaisance et al., 2014) used a passive flux sampler for 6 h to define a linear equation between the formaldehyde mass collected and the emission rate of the tested material in a test chamber, according the ISO 16000-9 standard (International Organization for Standardization (ISO), 2006). Depending on the surface tested, they calculated emission rates within the range [11.2; 682] $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$. Several databases have been developed to verify such chamber-tested data. Pandora is a very large free-access database for indoor pollutant emission rates (Abadie and Blondeau, 2011), with more than 8000 emission rates from the literature classified by sources, including formaldehyde and $\text{PM}_{2.5}$. Other databases were found such as the one developed in the EPEHCT project (Missia et al., 2012) and the NIST Database (Howard-Reed and Polidoro, 2006), including formaldehyde. In these databases, formaldehyde emission rates for common materials can be found with a large spread, as for example for gypsum board (Pandora: in range [0.3; 42] $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$) or fibreboard medium (NIST: in range [14; 640] $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, Pandora: [237 – 320] $\mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$). As a conclusion, the range of emission values is quite different from one database to another and the relationship with the in situ rates obtained in houses is complex.

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In-situ rates obtained in houses

The EN-15251 standard (CEN, 2007b) provides two emission rates for formaldehyde: $50 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ for low-polluting buildings (glass, steel, rock) and $20 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ for very-low-polluting buildings (without tobacco), considering the material surface areas. EN-16798-1 (CEN, 2016) updates these emission rates to 100 and $50 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, respectively, based on the results calculated for the European Reference Room as specified in CEN/TS-16516.

A test conducted by (Hodgson et al., 2000; Sherman and Hodgson, 2002) was repeated three times on seven unoccupied prefabricated houses and on seven unoccupied site-built houses, located in eastern and southern USA, under two different climates, hot-humid and mixed-humid. The formaldehyde concentration was measured using two active samplers, inside and outside. The indoor sampler was located in the living/dining room 1.5 m above the floor. In addition, SF_6 was used as a tracer gas to measure the air change rates. The average constant emission rate was calculated from the average concentrations measured and the air change rate measured, using the mass conservation equation on the whole house considered as one zone. The result was an average emission rate of $44.17 (\pm 36\%) \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, considering the houses floor surface areas.

The study conducted by (Blondel and Plaisance, 2011) took measurements of 24 student residence rooms with five different surfaces (flooring, ceiling and walls, doors, bed and other furniture), for three construction ages. Formaldehyde concentrations were measured over 6 h with both conventional active samplers and passive samplers. Thirteen to 15 passive samplers were used per student room, with measurements taken in the room, in the common corridor adjacent to the room, and outside. Air change rates were measured using a CO_2 (tracer gas) injection method. Depending on the age of the building and the type of surface, the resulting average emission rates were within the range $[1.4; 87.3] \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, considering the material surface areas. Table 7 summarises all the emission rates reviewed.

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MATERIALS	EMISSION RATES [$\mu\text{g}\cdot\text{h}^{-1}\cdot\text{M}^{-2}$] PER M ² OF MATERIAL SURFACE AREA UNLESS SPECIFIED OTHERWISE	REFERENCE
Low-polluting building (glass, steel, rock)	50	EN-15-251 (CEN, 2007) <i>In-situ loads</i>
Very-low-polluting building (without tobacco)	20	
Low-polluting building (stone, glass, ceramics and non-treated metal)	100	EN-16798-1 (CEN, 2016) <i>In-situ loads</i>
Very-low-polluting building	30	
7 Unoccupied and 7 Occupied houses	[per m ² of floor surface area] average: 44.17 ± 36% median: 41.72	(Sherman and Hodgson, 2004, 2002) <i>In-situ loads</i>
H1 (built in 1998) - Flooring - Ceiling and wall - Door - Bed - Other furniture	[Average ± std dev (range)] 2.3 ± (1.2-5.5) 3.6 ± 1.7 (1.2-6.3) 4.0 ± 2.0 (1.2-6.4) 3.3 ± 1.8 (1.2-6.7) 2.8 ± 0.9 (1.2-3.6)	(Blondel and Plaisance, 2011) <i>In-situ loads</i>
H2 (built in 1975, renovated in 2003) - Flooring - Ceiling and wall - Door - Bed - Other furniture	1.4 ± 0.7 (1.2-2.4) 3.2 ± 2.0 (1.2-7.1) 2.6 ± 1.6 (1.2-5.5) 2.8 ± 1.7 (1.2-5.8) 3.4 ± 0.6 (2.8-4.4)	
H3 (built in 1991) - Flooring - Ceiling and wall - Door - Bed - Other furniture	5.3±3.5 (2.5-13.0) 8.8±2.8 (4.1-12.1) 7.0±4.2 (1.2-14.7) 87.3±37.5 (21.3-131.3) 2.9±1.9 (1.2-7.0)	
Fibreboard medium 1 Fibreboard medium 2 Fibreboard medium 3 Sealing plaster Finishing plaster OSB Chipboard	92.5 135.5 133.3 43.4 682 11.2 244.4	(Plaisance et al., 2014) <i>Chamber-tested loads</i>
More than 8000 emission rates from consumer products and building materials		Pandora Database (CNRS & LaSIE, 2014) EPEHCT project (Missia et al., 2012) NIST Database (Howard-Reed and Polidoro, 2006) <i>Chamber-tested loads</i>

TABLE 7: OVERVIEW OF FORMALDEHYDE EMISSION RATES FOUND IN THE LITERATURE

Analysis and scenario proposals

Few of these formaldehyde data are fully useful for a performance-based approach to ventilation. We found either few or no data on average in-situ loads directly measured at the dwelling scale, and especially in low-energy dwellings considered as representative. Consequently, the available data pose two problems:

- Firstly, it is difficult to extrapolate emission rate behaviours from test chamber conditions to *in-situ* conditions, notably because of the complex physical phenomena (combined effects, resuspension, etc.). As illustrated in Table 7, the order of magnitude of emission rates between chamber-tested loads in (Plaisance et al., 2014) and in-situ loads in (Blondel and Plaisance, 2011) varies by a factor of a 10 to 100.
- Secondly, it is difficult to build robust scenarios from the material, product and activity scale to the dwelling scale, as highlighted in (Boulanger et al., 2012). Indeed, due to the wide variety of materials available, the emission per m² of floor area varies from one building to another. In addition, the type of building materials and furniture and the quantities used (floor coverings, wall paintings, etc.) depend on the purpose of the buildings as well as on the design or construction methods used. Precise data are not yet described in scientific studies. In addition, emission rates for common materials are available with a high variability and even within the same type of material emission properties can vary considerably, as shown by the diversity of values presented in the databases (Abadie and Blondeau, 2011), (Howard-Reed and Polidoro, 2006) or as illustrated in (Plaisance et al., 2014) for the Fibreboard medium 1,2,3. Consequently, arbitrary choices must be made to establish input data (using databases such as Pandora) for a detailed IAQ modelling at the scale of a residential building, as shown by (Cony-Renaud-Salis et al., 2019).

We accordingly suggest using the simplified calculation method in (Poirier et al., 2020) and applying it to unpublished data gathered on French low-energy homes to calculate average *in-situ* loads at the dwelling scale.

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Based on these measurements, we define three classes of formaldehyde emissions to be used as input data for IAQ modelling, and for ventilation performance-based approaches at the design stage of low-energy houses:

- *The low-emission class:* $4.5 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, per m^2 of floor surface area, defined by the minimum calculated value;
- *The medium-emission class:* $12.0 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, per m^2 of floor surface area, defined by the median calculated value;
- *The high-emission class:* $23.6 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, per m^2 of floor surface area, defined by the maximum calculated value.

1.2.4.d) PM_{2.5} particles

PM_{2.5} emission rates in the literature

General considerations

The most widely studied PM_{2.5} indoor emission sources are principally candle combustion, smoking and cooking activities. The emission values of hairspray (Isaxon et al., 2015) are usually occasional and relatively low, in comparison with candle combustion (Bekö et al., 2013) or incense [78,79], cooking activities (Ji, 2010) and smoking emissions. As described in the introduction, this work focuses on the assessment of ventilation performance, which should be seen as complementary to the reduction of indoor pollution sources. Smoking is a significant indoor emission source but it is not included in this review because it is more relative to the performance of occupants than to ventilation system performance. The source of the emissions can easily be reduced by influencing the habits of the occupants. From this perspective, Borsboom et al. (Borsboom et al., 2016) propose that tobacco smoke should not be considered in setting ventilation standards. A similar choice is made for candles and incense: they are related to habits and are excluded from our study.

Several studies showed that cooking is one of the most PM_{2.5}-emitting activities (Abt et al., 2000; He, 2004; Long et al., 2000; Tuckett et al., 1998). Ji et al. (Ji, 2010) corroborated this, providing measurements in an experimental house to quantify occupant exposure to ultrafine particles. They directly calculated this indicator from concentration measurements using occupancy schedules, without calculating emission rates. Each source was tested at least three times, and the concentration was measured in three different spaces to quantify the impact of the pollutant on the entire dwelling. We could thus classify the source into four categories depending on its global impact intensity (high, medium, limited, low). This study highlighted that the largest sources were: cooking and extra-heating for the high-impact sources, the toaster for the medium-impact sources, and incense, cigarettes, and candles for the limited-impact sources.

PM_{2.5} concentrations and emissions were also strongly correlated with outdoor conditions, intensity and type of ventilation, air leakage level and deposition and resuspension conditions (Abt et al., 2000; Lai et al., 2004; Long et al., 2000; Morawska et al., 2001). Given their mass, particle matter is deposited on surfaces by gravity and various common actions can resuspend these particles. Moreover, particle matter can be formed by a chemical gaseous reaction such as between ozone and terpene (Rohr et al., 2003).

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Based on this first literature analysis, we retained only emissions from cooking activities to build the PM_{2.5} emission rate scenarios. Two review papers on the chemical components of particle matters (Abdullahi et al., 2013) and their impact on cooking emission rates (Amouei Torkmahalleh et al., 2017) have recently been published.

Rates obtained in test chambers

A study was carried out in a 32-m³ test chamber in a research laboratory to characterise emissions from various activities (frying, gas stove, smoking, vacuuming, heater, radiator, scented candle, pure wax candle) (Afshari et al., 2005). The PM_{2.5} concentration was measured by two different particle counters: a condensation particle counter and an optical particle counter. The concentration was continuously monitored before, during and after all the emission tests. A tracer gas decay method was used to determine the air change rate, based on concentration measurements made continuously over 2h with a photo-acoustic spectroscopy device. Emission rates were lastly calculated through air change rate concentration measurements and expressed as particles per minute. Unfortunately, these emission rates in particles per minute cannot be used in cooking emission rate research, because conversion into mg.min⁻¹ is impossible.

Finally, the recent study conducted by O'Leary et al. (O'Leary et al., 2019) used a test-chamber protocol with controlled ventilation to very precisely measure the PM_{2.5} emission rate throughout the cooking processes. The four meals selected for this experiment were based on typical European portions and food types from representative data, like the panel method (Olson and Burke, 2006) or the Western cooking type survey conducted by (Chen et al., 2018; Zhao et al., 2019).

Rates obtained in a lab kitchen

Firstly, the study of (Buonanno et al., 2009) characterised the particle emissions of several foods (cheese, chips, bacon) by testing the impact of the oil used (sunflower, peanut, olive), the cooking method (frying/grilling) and temperature. These cooking tests were conducted in laboratory conditions in an 82-m² kitchen using electric and gas stoves. The results show that the higher the cooking temperature, the higher the particle emission rate is, as shown with the 50-g bacon experiment; 0.52 mg.min⁻¹ emitted with minimum power (171°C ± 17°C) versus 13 mg.min⁻¹ with maximum power (242°C ± 5.2°C). Oil type may also influence the emission rate (chips, sunflower oil, 1.20 mg.min⁻¹; chips, olive oil, 2.80 mg.min⁻¹) and this confirms that grilling activities are the highest emission sources, especially with gas stove cooking.

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Other in-situ studies focused on cooking only one food, e.g. (Torkmahalleh et al., 2017) for the PM_{2.5} emitted during the cooking of ground beef in a dwelling. In this study, the test conditions were set up to limit other indoor and outdoor emission sources, for example, by closing all the doors during the test period and ventilating before the experiment. The resulting measurements were divided into four rate ranges [$3.3 \mu\text{m} > 2.1 \mu\text{m} > 1.1 \mu\text{m} > 0.65 \mu\text{m} > 0.43 \mu\text{m}$] and the value retained was the total average emission rate equal to $44.9 \text{ mg}\cdot\text{min}^{-1}$.

Recently, (Kang et al., 2019) also measured the PM_{2.5} and PM₁₀ generation rate *in situ* for cooking in an experimental building based on grilling and frying activities (fish, meat, egg). Measurements were taken for 30 min including the time for cooking the ingredients (fish broiling: 13 min; meat frying: 6 min; egg frying: 4 min; meat broiling, 3 min). The comparison of experimental building results (Kang et al., 2019) between frying (deep frying meat, $2.14 \text{ mg}\cdot\text{min}^{-1}$) and grilling (meat broiling, $16.08 \text{ mg}\cdot\text{min}^{-1}$) confirmed that higher particle emissions come from grilling/broiling activities.

In greater detail, (Chen et al., 2018; Zhao et al., 2019) tested 25 typical Chinese dishes in a domestic kitchen based on an online survey of 309 families to determine common cooking behaviours in China. A professional cook performed five cooking methods with gas stoves (stir-frying, pan-frying, deep-frying, steaming and boiling), varying the weight of the ingredients, the type of meat, the meat/vegetable ratio and the type of oil. Measuring the emission generation rate includes the use of cooking tools during the process, with doors and windows closed and ventilation systems turned off. They found that water cooking methods such as boiling [$0.08 \text{ mg}\cdot\text{min}^{-1}$] and steaming [$0.05 \text{ mg}\cdot\text{min}^{-1}$] produce fewer emissions compared to other frying cooking methods (stir-frying [$2.56 \text{ mg}\cdot\text{min}^{-1}$], pan-frying [$1.61 \text{ mg}\cdot\text{min}^{-1}$]).

In-situ rates obtained

The oldest *in-situ* study was conducted by (Ozkaynak et al., n.d.) in the 1990s on a panel of 178 residents in Riverside, CA (USA). The PM₁₀ measurements were taken with personal exposure devices; at the same time the PM_{2.5} rates were measured in each house using indoor and outdoor stationary monitors for two consecutive 12-h periods. The monitors used were based on a PM₁₀ filter behind an impactor plate. The PM₁₀ emission rate of cooking activities was estimated at $4.1 \pm 1.6 \text{ mg}\cdot\text{min}^{-1}$ with 40% of the particles smaller than $2.5 \mu\text{m}$, with $1.7 \pm 0.6 \text{ mg}\cdot\text{min}^{-1}$ as the PM_{2.5} cooking emission rate. Other sources excluding cooking and smoking were estimated to emit $0.093 \text{ mg}\cdot\text{min}^{-1}$ for the PM₁₀ fraction, with 20% smaller than $2.5 \mu\text{m}$ (approximately $0.018 \text{ mg}\cdot\text{min}^{-1}$) as PM_{2.5}. This study identified smoking and cooking as the two main indoor particle sources and provides an estimation of cooking emission rates but without distinguishing cooking methods.

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In Australia, PM_{2.5} measurements were conducted on 16 houses (He, 2004). The concentration was estimated simultaneously with a condensation particle counter and a photometer (sampling time 10 and 30 s) over more than 48 h in the kitchen. Air change rates were measured with a tracer gas method using CO₂ during the unoccupied period. The emission rate was then calculated using concentration, air change rate, volume, and penetration efficiency and deposition rate. The authors published data on cooking, frying, grilling, toasting, smoking, vacuuming and other emission rates within the range [0.07; 2.78] mg.min⁻¹. The results confirm that cooking activities are the main PM_{2.5} sources in dwellings, with high emission levels during frying and grilling activities. The concentration increased more than 30 times the normal background concentration level during frying and up to 90 times during grilling.

A study in the USA also took PM_{2.5} measurements on 37 residential homes over 7 consecutive days for each of four seasons (Olson and Burke, 2006). Concentrations were monitored for 24 h inside and outside using a filter-based monitor. The air change rate was measured with a tracer gas method, using perfluorocarbon. The air change rate was calculated with a mass balance. At the same time, each occupant carried a passive sample monitor, collecting the personal PM_{2.5} data every minute, and had to fill in a 15-min time-step schedule. This provided the occupants' location and activities so that emission rates of specific cooking actions (frying, grilling, toast, stovetop, burned) could be calculated with 36 mg.min⁻¹ as the average value within the range of [10; 470] mg.min⁻¹.

Recently, an *in-situ* campaign was conducted on 30 residential buildings and one experimental building to characterise PM₁₀ and PM_{2.5} generated by Korean cooking activities over 1 month (Kang et al., 2019). In the residential buildings the emissions of soup cooking, broiling and frying activities were measured for a total of 30 min including both cooking time limited to 15 min to prevent over-cooking and preparation time. The results were compared with Western cooking types (He, 2004) (Ozkaynak et al., n.d.): Asian cooking gave slightly higher emission rate values within the range [0.39 mg.min⁻¹; 20.54 mg.min⁻¹] (Table 8).

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COOKING ACTIVITIES	EMISSION RATE [MG.MIN ⁻¹]	DURATION [MIN]	REFERENCE
Cooking (any food preparation using stove, no frying or grilling)	0.11	10	(He, 2004) <i>In-situ loads</i>
Frying (any food preparation using frying)	2.68		
Grilling (any food preparation using grilling)	2.78		
Frying		8-10	(Buonanno et al., 2009) <i>Lab kitchen</i>
- Mozzarella 50 g (sunflower oil) electric pan, 190°C	0.03		
- Chips 50 g (sunflower oil) electric pan, 190°C	0.03		
- Chips 50 g (sunflower oil) gas stove, max power	1.20		
- Chips 50 g (peanut oil) electric frying pan, 190°C	0.06		
- Chips 50 g (peanut oil) gas stove, max power	1.80		
- Chips 50 g (olive oil) electric frying pan, 190°C	0.20		
- Chips 50 g (olive oil) gas stove, max power	2.80		
Grilling			
- Aubergine 30 g, gas stove, max power	0.52		
- Cheese 70 g, gas stove, max power	9.5		
- Wurstel 130 g, gas stove, max power	10		
- Bacon 50 g electric stove	1.5		
- Bacon 50 g gas stove, min power	0.52		
- Bacon 50 g gas stove, max power	13		
Cooking		13	(Kang et al., 2019) <i>Lab kitchen & In-situ loads</i>
- Residential building, minimum value	0.39		
- Residential building, maximum value	20.54		
Boiling			
- Residential building, soup	2.01		
Frying			
- Residential building	3.80		
- Experimental building, deep frying meat	2.14		
- Experiment building, frying 4 eggs	10.85		
Grilling			
- Residential building	12,02		
- Experimental building, fish broiling	22.84		
- Experimental building, meat broiling	16.08		
Grilling		20	(Torkmahalleh et al., 2017) <i>Lab kitchen</i>
- Ground beef	44.90		
Cooking		11	(Olson and Burke, 2006) <i>In-situ loads</i>
- All cooking events	36		
- Multiple events	29		
- Stove top	17		
- Oven	10		
- Burned	470		
Frying	60		
Grilling	173		
Boiling		28	(O'Leary et al., 2019) <i>Chamber-tested loads</i>
- Meal 2, chicken (oil), potatoes, green beans (water)	0.80		
- Meal 1, chicken, potatoes (oil), green beans (water)	0.62		
Frying			
- Meal 3, pasta (water) ,onion, bacon, beef, tomatoes (oil)	1.90		
- Meal 4, stir-fry, chicken, prechopped vegetable, noodles (oil)	3.20		
Boiling		3-33 mean: 13	(Chen et al., 2018; Zhao et al., 2019) <i>Lab kitchen</i>
- Steaming	0.05		
- Boiling	0.08		
Frying			
- Deep-frying	0.32		
- Pan-frying	1.61		
- Stir-frying	2.56		

TABLE 8: OVERVIEW OF PM_{2.5} EMISSION RATES

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Analysis and scenario proposals

We grouped cooking emission sources in four cooking types: boiling, frying, grilling and a total cooking category taking into account any food preparation (Table 9). As expected in the articles and confirmed by the minimum, mean, maximum and median values, grilling is the highest and boiling is the lowest PM_{2.5} emission cooking type.

COOKING TYPE	EMISSION RATE [MG.MIN ⁻¹]			
	<i>min</i>	<i>mean</i>	<i>max</i>	<i>median</i>
Boiling	0.05	0.74	2.01	0.44
Frying activities	0.03	5.32	60.00	1.85
Grilling activities	0.52	25.56	173.00	11.01
Total cooking	0.03	12.65	173.00	2.56

TABLE 9. EMISSION RATE VALUES

Finally, a few studies took into account the entire cooking process with several food types for a complete meal and the associated duration, especially for a representative French cooking scenario context.

Assessing ventilation systems and kitchen hood performance, the O'Leary study [89] is particularly relevant and fits our overall performance evaluation approach for ventilation systems. It took into account all the cooking steps in a European context. The authors proposed meal 1, with the lowest emissions, with chicken and potatoes fried in oil and green beans boiled in water [0.62 mg.min⁻¹]. Meal 3 with pasta bolognaise had an intermediary emission rate [1.9 mg.min⁻¹]. Meal 4 had the highest emissions with fried chicken and vegetable noodle wok cooking [3.2 mg.min⁻¹]. This gave three combinations of meal 1, 3 and 4 to propose three realistic cooking scenarios for 1 week:

- Low-emission cooking practices, with the hypothesis of 50% of the meals a week, emit fewer emissions, like meal 1, and the other 50% of the meals have medium emissions, like meal 3.
- Intermediate-emission cooking practices use diversified cooking methods, where the meal types are equally distributed over a week [1/3 meal 1; 1/3 meal 3; 1/3 meal 4].
- High-emission cooking practices, with the hypothesis that 50% of the meals a week emit a high level of emissions, such as meal 4, and the other 50% meals emit a medium range of emissions, such as meal 3.

These three scenarios are summarised in Table 10 as mean values repeated twice a day with a cooking duration of 28 min.

SCENARIO	EMISSION RATE [MG.MIN ⁻¹]	DURATION [MIN]
Low-emission cooking practice (mainly boiling)	1.26	28
Intermediate-emission cooking practice	1.91	28
High-emission cooking practice (mainly grilling)	2.55	28

TABLE 10. PM_{2.5} EMISSION RATE SCENARIOS

1.2.5 SYNTHESIS OF SELECTED OCCUPANCY AND EMISSION INPUT SCENARIOS

Figure 2 summarises the input data for assessing ventilation performance at the design stage of a building, classified into pollutant scenario data, moisture scenario data, and inhabitant occupancy data. For PM_{2.5} and formaldehyde emission rates, we propose three classes of emissions: high, medium and low, to be selected depending on the available data at the design stage.

For formaldehyde for instance:

- If only A-class IAQ-labelled materials (French Ministry for Ecology, 2011) are used and occupants are aware of this, the low-emission formaldehyde rate can be used in the IAQ calculation. To achieve a low emission rate, it is necessary to increase the occupants' awareness and help them become low-emitting occupants in all their activities and furnishings. Tools have been developed for occupants for this purpose (Déoux et al., 2016). An *in-situ* measurement campaign could also be required once the building is occupied to encourage the low emission rate.
- If no information is given, or only D-class IAQ-labelling materials are used, a high-emission formaldehyde rate must be used.
- In other cases, a medium-emission formaldehyde rate can be used.

For PM_{2.5}:

- If the occupants are aware of IAQ, and their habits confirm they rarely use grilling, and if they agree with an *in-situ* measurement campaign once the building is occupied, a low-emission PM_{2.5} rate can be used in the IAQ calculation.
- If no information is given, a high-emission PM_{2.5} rate must be used.
- If the occupants are aware of IAQ, and their habits confirm they rarely use grilling, a medium-emission PM_{2.5} rate can be used.

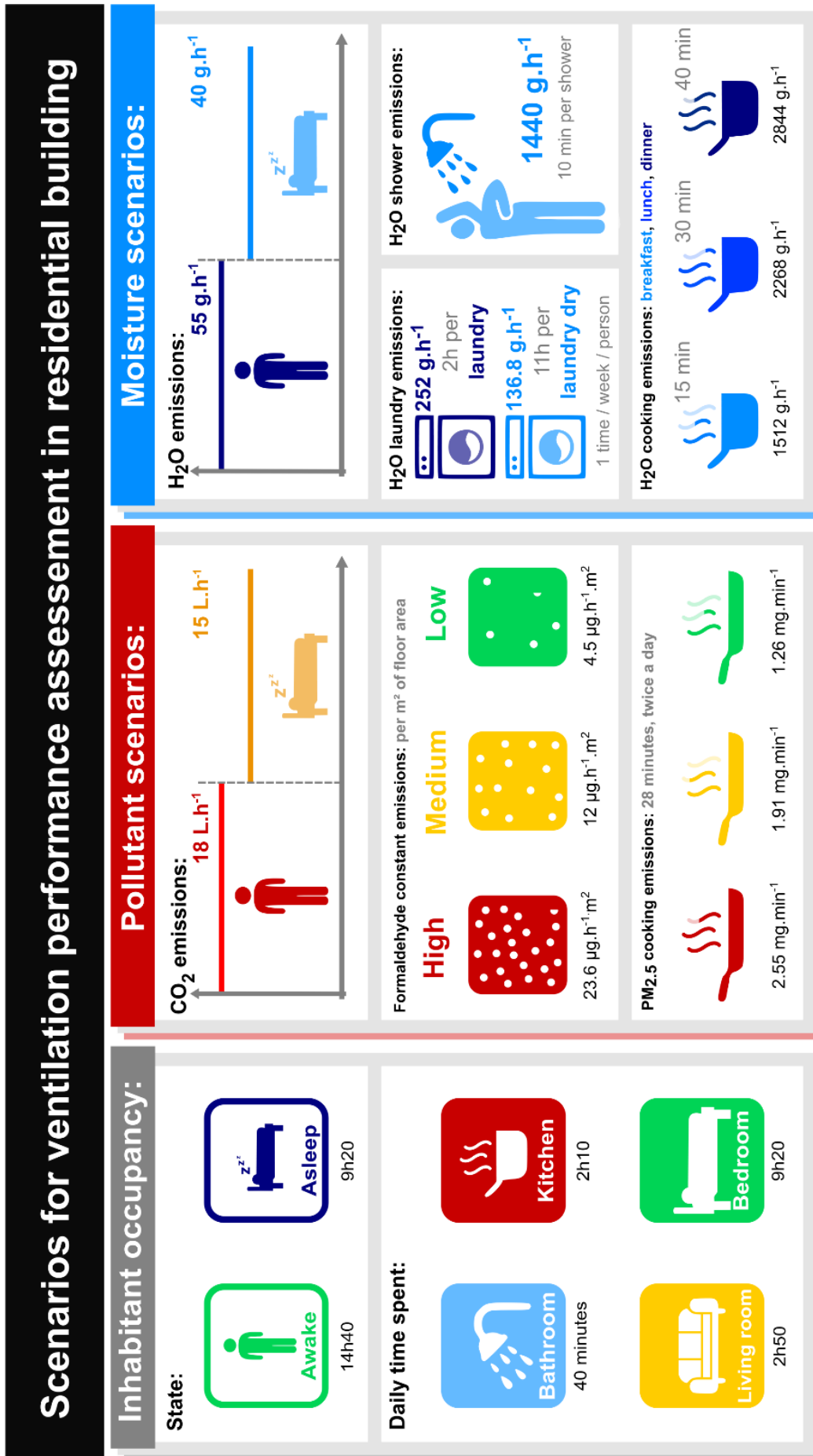


FIGURE 2. SELECTED INPUT DATA TO BE USED IN A PERFORMANCE-BASED APPROACH FOR VENTILATION.

1.2.6 CONCLUSION AND PERSPECTIVES

We need a performance-based approach for assessing ventilation performance at the building scale, at the design stage, like the regulatory energy performance calculation to ensure energy performance. We selected IAQ performance indicators for ventilation performance assessment based on CO₂, moisture, as they are commonly used, and on formaldehyde and PM_{2.5} as they are complementary. To calculate such indicators, few occupancy schedules and emission rate parameters are available today. This paper provides an extensive literature review of 73 articles covering detailed occupancy schedules throughout the day and the year in a house, with emission rates reflecting occupants and activities (e.g. showering, cooking), as well as building material and furniture emission rates.

We found relevant data on occupancy schedules, even if most of them were not precise enough to provide information on occupancy in all the rooms in a house. Substantial relevant data on CO₂ and humidity emissions due to inhabitants' metabolism and activities are available in the literature and we selected those that could be used in a performance-based approach at the design stage. We noted a lack of exploitable data that could be used to model PM_{2.5} and formaldehyde average and peak emissions at the dwelling scale. As a result, we proposed using three levels of constant emission rates for formaldehyde: the low-emission rate: 4.5 µg.h⁻¹.m⁻²; the medium-emission rate: 12.0 µg.h⁻¹.m⁻²; and the high-emission rate: 23.6 µg.h⁻¹.m⁻². For PM_{2.5}, we also proposed three classes of emissions for cooking activities associated with a 28-min period twice a day: the low-emission rate: 1.26 mg.min⁻¹; the medium-emission rate: 1.91 mg.min⁻¹; and the high-emission rate: 2.55 mg.min⁻¹.

Our objective was to build emission scenarios for a European, or even French, application. Nevertheless, the data analysed here are sufficiently described to be used for applications in other countries.

We focused on long-term exposure but this approach should also be adapted to consider acute exposure, another topic of interest and a health concern.

As for the study's limitations, there is a lack of consistent emission data on both formaldehyde and PM_{2.5} emissions at a building scale; consequently, the scenario proposals must be considered as a preliminary suggestion for overall ventilation performance assessment, which could be improved with further studies. The main objective of this work was to build a first baseline, directly usable in a method for assessing ventilation performance. Obviously, the proposed scenarios can evolve and be completed and improved in the future, as and when they are published, and according to the context of application in different regions or countries. One of the tracks would be to add relevant behaviours with other pollutant emissions, such as toasting toast for breakfast, for example, for PM_{2.5}.

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Another would be to link formaldehyde emissions to a series of scenarios for materials and furniture depending on the type of building and occupants, when consistent data are available. In addition, it is also possible to extend the IAQ indicators by adding other pollutants, although this then adds to the knowledge of emissions data and complicates the indication of IAQ levels and the operational aspect of the performance-based approach.

Nevertheless, it is now possible to assess the ventilation performance at the design stage of a residential building from an IAQ point of view, using the proposed occupancy schedules and emission scenarios as input data. In future work, these scenarios will be applied in a standardised approach, by modelling ventilation systems and strategies, air inlets and outlets configurations, airflow rates, etc. Such a standardised approach will allow for example a relative comparison of the performance of classic ventilation strategies and innovative ones, as smart ventilation strategies. In order to help at the design stage, the method can be used to select a ventilation system that targets a level of energy and IAQ performance, to comply with an overall performance requirement, but also to achieve IAQ labelled products and even improve IAQ awareness among occupants.

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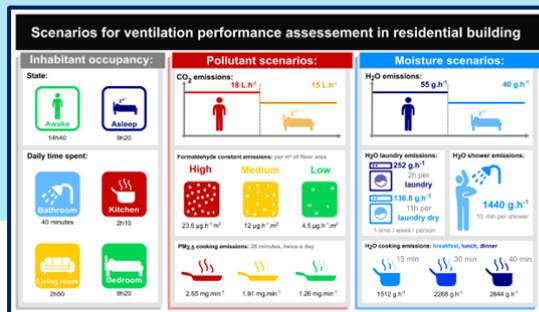
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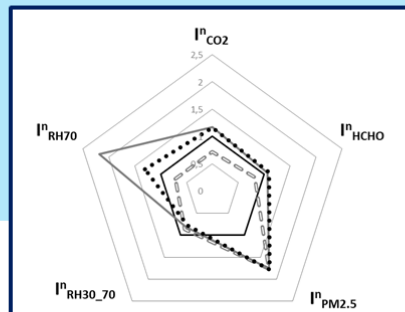
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PART 1

HIGHLIGHTS & LEARNINGS



INPUT : POLLUTANT EMISSION SCENARIOS & OCCUPANCY SCHEDULES



OUTPUT : FIVE IAQ PERFORMANCES INDICATORS



SIMULATIONS : A CASE STUDY DEMONSTRATION

In this chapter, we developed the first baseline of the MOPA regarding the IAQ performance assessment and demonstrated its direct usability through a case study application. The method approach is based on airflows simulations, here performed with CONTAM. We defined in two literature review works a relevant set of IAQ performance indicators as output, with their relevant associated pollutants emission scenarios and occupancy schedules as input.

The relative humidity, CO₂, formaldehyde and PM_{2.5} were selected as the restrained key indoor air parameters to be studied. Indeed, CO₂ and humidity are two parameters historically used and adapted for IAQ assessment, because their presence due to bioeffluent emission is a good marker of occupancy and poor air renewal in a room. Moreover, formaldehyde and PM_{2.5} have been identified as two priority indoor pollutants to be considered for their high health impact.

The pollutant sources can be described with the proposed three level (low, medium, high) of emission rates reflecting occupants and activities (e.g. showering, cooking), as well as building materials. These scenarios could possibly be adapted according to needs. It gives at least a low and high range of variation that is equivalent to the ideal and worst case configuration. In addition, at this stage, the medium scenario could be considered as a reference. In addition, the daily time spent by the occupants in the rooms should be used to build detailed occupancy schedules for the calculation of occupants exposure and pollutant emissions from occupant activities.

Then the five proposed IAQ performance indicators I_{CO_2} , I_{HCHO} , $I_{PM_{2.5}}$, $I_{RH_{70}}$, $I_{RH_{30-70}}$ can be calculated based on the pollutants concentrations in the rooms and on the occupants exposures. These five indicators were associated with a threshold that characterizes a limit performance beyond which the performance achieved is not acceptable. In order to compare the performance of several ventilation systems, these 5 indicators can be normalized, which makes the visualization and the comparison of the performance more direct. Thus, for a given ventilation system, when the value of a normalized indicator is greater than 1, the performance is not achieved.

However, these normalized indicators could lead to questionable performance results when the indicators are close to 1. Indeed, depending on the input scenarios used, one can easily oscillate between acceptable and unacceptable performance. The three scenarios tested may not be sufficient to valid the assessed performance. To address this impact of the input scenarios on the output performance indicators, we have carried out a quantification of the uncertainty quantification with the sensitivity analysis method in Chapter 4.

Lastly, these first performance results on the case study application highlighted the importance of taking into account IAQ parameters other than the traditional CO_2 and humidity, for a better consideration of IAQ in building. The next step consists in complementing the MOPA with energy based indicators in order to assess both the impact on IAQ and on the energy performance of ventilation systems.

PART 2



METHOD FOR ENERGY PERFORMANCE ASSESSMENT



In complement to the IAQ indicators developed in Part 1, we propose in this Part 2 to explore the possibility of CONTAM airflows simulation association with energy simulation for energy-based indicators calculation.

This Part presents the research work and results performed on energy simulation. They are grouped under two main sections. Indeed, the obtained results were not converted into publications compared to the other parts of the manuscript.

The first section focuses on the assumptions made on the room temperatures in CONTAM for the calculation of the energy indicator, based on in situ measurements and energy simulation.

The second section is an exploratory work on the co-simulation implementation between the energy simulation tool DOMUS and the airflows simulation tool CONTAM.

Before the two main sections, a short section introduces the challenges for energy indicators calculation with airflows simulation. We principally question the need of energy simulation to complete CONTAM simulations. In addition, it is detailed how energy in the building can be related to ventilation systems. This allows us to establish a provisional energy indicator to question the energy simulation.

ENERGY INDICATOR: THE CHALLENGES OF CALCULATION BASED ON AIRFLOW SIMULATION

The two main sources of energy consumption for ventilation systems are the direct ones, from the fan(s) electric consumption, and the indirect ones, due to heat losses from the air renewal. In French building regulation, RE2020, the energy performance assessment of the building is calculated by transient energy simulations at the design stage for the whole year. The heat losses due to air renewal are indirectly included within a coefficient called "Bbio". The reference values are obtained for a building with an ideal mechanical ventilation with heat recovery (MVHR-cav). In addition, the electrical consumption of fans is included in the Cep calculation. The Bbio is an indicator that measures the impact energy efficiency of the building on the needs of heating, cooling and artificial lighting. The Cep coefficient expressed in kWh/(m² of reference surface) of primary energy (or kWh_{ep}/(m².an) represents the energy consumption for heating, cooling, domestic hot water, auxiliaries and lighting of buildings.(RE-2020 ANNEXE III).

The limits of using such energy performance simulations at the buildings scale for assessing ventilation performance are that they do not directly focus on the ventilation systems. In this research work, we need a more detailed calculation focusing on the ventilation systems in order to better understand and quantify their impacts on building energy consumption. We propose as a first step to focus only on the heat losses from air renewal.

These heat losses, can be computed following Equation 1; inspired from the already mentioned method for Bbio calculation (RE-2020 ANNEXE III) and other studies (Abadie et al., 2017; Molina et al., 2021). Indeed, the amount of heat losses due to air renewal can be easily calculated with an airflow model as it is already using exhaust airflows and temperature difference between inside and outside:

$$H_{thl} = \frac{C_{pm}}{3600} \cdot (1 - \varepsilon_{heat_{ex}}) \int q_m(t) \cdot [T_{in}(t) - T_{ex}(t)] \cdot dt$$

EQUATION 1

With H_{thl} the thermal heat losses from air renewal [kWh], q_m the total exhaust mass airflows in [kg.s⁻¹], C_{pm} the heat mass capacity of air (we used 1 kJ.kg⁻¹. °C⁻¹), $\varepsilon_{heat_{ex}}$ the heat exchanger efficiency supposed ideal and constant. We can use for example a constant theoretical efficiency of 0.8 for ventilation with heat recovery and 0 with no heat recovery and this value can be adjusted depending on the systems design. T_{in} the zone temperature where the air is exhausted, and T_{ex} the external temperature [°C].

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

ENERGY INDICATOR: THE CHALLENGES OF CALCULATION BASED ON AIRFLOW SIMULATION

Before the implementation of this H_{thl} in the MOPA several questions must be addressed to make the heat losses fully usable as energy-based indicator. Indeed, at this stage, the use of the software CONTAM, based on a model without out energy simulation and a constant temperature assumption in zones, questions us about:

- What is the impact of a constant temperature assumption in each zone for the H_{thl} calculation?
- Is it necessary to take into account the variations of internal temperatures and to associate the airflow model of CONTAM with energy simulation?

From these two questions in this Part 2, we propose firstly an evaluation of the impact of variable temperatures on H_{thl} based on in-situ measurements. Finally, we have conducted an exploratory study for co-simulation between CONTAM and DOMUS to evaluate the potentials of co-simulation to improve the ventilation performance assessment method.

2.1 EVALUATION OF TEMPERATURE ASSUMPTIONS FOR ENERGY INDICATOR CALCULATION BASED ON IN SITU MEASUREMENTS AND ENERGY SIMULATION

2.1.1 METHODOLOGY

In order to assess the impact of the zone constant temperature assumption in CONTAM model, we propose to compare together:

- the real heat losses calculated with the measured in-situ variable temperatures.
- the theoretical heat losses calculated with a constant temperature as it could be calculated with CONTAM constant zone temperature.
- the simulated heat losses calculated with the variable temperatures from energy simulations.

2.1.1.a) IN SITU MEASUREMENT CAMPAIGN EXPLOITATION

Thanks to the in-situ campaign lead by N. Kanama with detailed IAQ measurement on a low energy house (Kanama et al., 2021), we had access to in-situ measurements on the house presented in the previous Part 1. Thus, the CONTAM models already available of this house were reused for results comparison.

As a reminder, this house was built in 2013 and is located near Chambéry in France. This is a low-energy house equipped with a constant airflows mechanical ventilation with heat recovery (MVHR-cav). According to the regulatory evaluation at the design stage, the heating needs of the house were $12 \text{ kWh}\cdot\text{year}^{-1}\cdot\text{m}^{-2}$ for a total energy consumption of $39 \text{ kWh}_{\text{ep}}\cdot\text{year}^{-1}\cdot\text{m}^{-2}$. With for total occupied surface of the building of 135 m^2 .

The measurement campaign was divided into two measurement periods of 1 week each. The first one in winter between the 8 February and the 15 February (C1) and the second one in spring from the 2 April to the 9 April (C2). During this campaign the following indoor air parameters were monitored: temperature (T), relative humidity (RH), CO_2 , TVOC, formaldehyde, the particle numbers and $\text{PM}_{2.5}$. In this section, we mainly focused on the analysis of temperature measurements for heat losses calculation H_{thl} .

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As presented below on Figure 1, the temperatures were measured outside in the living room (2 locations), in the bathroom of the second floor, and in the four bedrooms (measured with NEMO sensors $\pm 1^\circ\text{C}$ and WOHLER sensors 0.1°C accuracy $\pm 0.1^\circ\text{C}$). The measurement start time and stop time of the sensors were not synchronized. To correct for these time differences, during the post-measurement exploitation, the data were cut from the maximum available common period and resampled with a 10-minute time step (identical to the CONTAM simulation output time step). Including this correction, the first period C1 started on the 09-02-2019 at 3 p.m. and ended on the 15-02-2019 at 9 a.m. The second period C2 started on the 02-04-2019 and ended on the 11-04-2019. For the heat loss calculations, we used the theoretical ventilation airflow values according to the designed ventilation system.

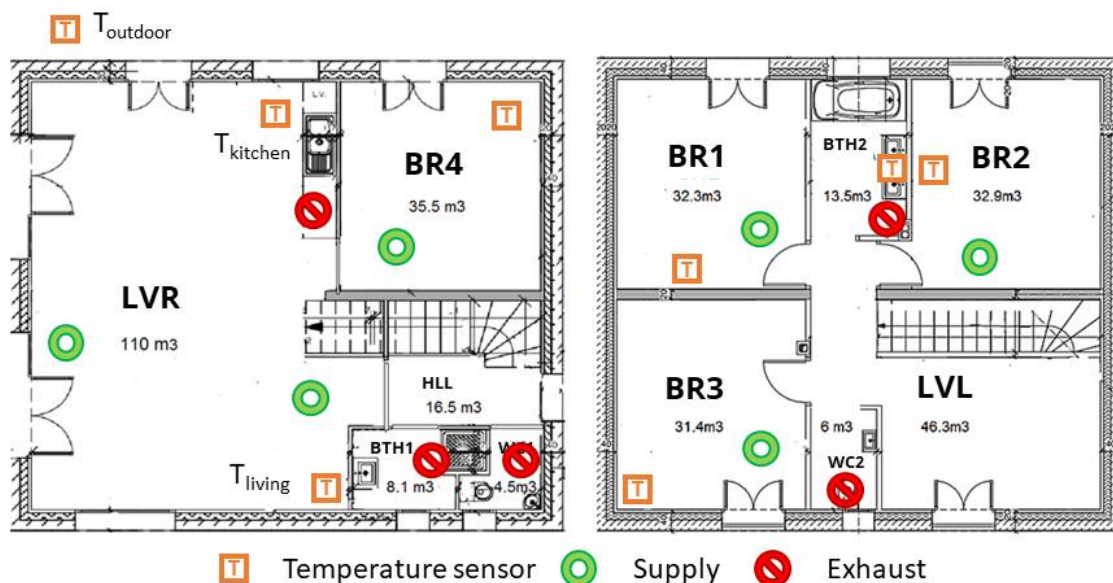


FIGURE 1 : TEMPERATURE SENSOR AND SUPPLY/EXHAUST LOCATION (F1)

The design airflows used were already described in Part 1. For balanced mechanical ventilation with heat recovery, the theoretical exhaust airflows are: $15 \text{ m}^3 \cdot \text{h}^{-1}$ in the toilets, $30 \text{ m}^3 \cdot \text{h}^{-1}$ in the bathrooms and $45 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen. This last one can be increased to $135 \text{ m}^3 \cdot \text{h}^{-1}$ during cooking periods (1 hour). In CONTAM modelling, these exhaust airflows in $\text{m}^3 \cdot \text{h}^{-1}$ were converted with ideal gas law (Equation 2-Equation 3) in $\text{kg} \cdot \text{s}^{-1}$ to control directly the design flow rate of CONTAM exhaust element.

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The reverse conversion, $\text{kg}\cdot\text{s}^{-1}$ to $\text{m}^3\cdot\text{h}^{-1}$ was done in the same way for the results analysis.

$$q(t, T) = \rho(t, T) \cdot \frac{Q(t)}{3600}$$

EQUATION 2

With

$$\rho(t, T) = \frac{P}{R \cdot T(t)}$$

EQUATION 3

Where, q the mass airflow in $[\text{kg}\cdot\text{s}^{-1}]$ function of the volume airflow Q in $[\text{m}^3\cdot\text{h}^{-1}]$ and ρ the density in $[\text{kg}\cdot\text{m}^{-3}]$; calculated with $R= 287.055 [\text{J}\cdot\text{kg}^{-1}\text{K}^{-1}]$ the gas constant for air, T the temperature of the zone $[\text{K}]$. The pressure $P = 101325 [\text{Pa}]$ is assumed to be constant and equal to the reference pressure for simplification purposes.

2.1.1.b) ENERGY SIMULATIONS WITH DOMUS

Then the heat losses were evaluated by energy simulation on the whole heating period with a constant indoor temperature control ($T_{\text{ctrl}} = 20^\circ\text{C}$). The selected heating period start from October 15, 00:00 AM, to April 14, 12:00 PM, according to the heating period used for ventilation performance assessment method (Poirier et al., 2021). And finally, two other variable temperatures control strategies were simulated in DOMUS to evaluate the relevance of modelling such variable strategies.

For the heat loss evaluation with DOMUS, the heating control temperature is set at 20°C according to the temperature control during the measurement campaign. In contrast with CONTAM model where the temperatures are set constant at 20°C in rooms; DOMUS calculates the temperature in rooms using energy balance equation based on heat losses and on internal gains from occupation and heating system as well as the external solar gains. In this case, the heating system was modelled in DOMUS with on/off electric heaters (control set point at 20°C). For extended variable temperatures control strategies $T_{\text{ctrl}_{20/16}}$ and $T_{\text{ctrl}_{19/16}}$ (described below) same on/off electric heaters were used but controlled with a schedule varying the control set point at 20°C or 19°C during occupancy (18h00 - 9h00) and at 16°C during unoccupancy (9h00 - 18h00).

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Two mechanical exhaust-only ventilation systems (MEV) were modelled with DOMUS. The first one provides constant airflows (MEV-cav) and the second one is a humidity-based system (MEV-rh). The theoretical exhaust airflows for the MEV-cav and the MEV-rh are described in the Table 1. Unfortunately, at this stage of the work it was not possible to model balanced ventilation systems with heat recovery using DOMUS for technical reasons.

Room	MEV-cav		MEV-rh				
	Airflows [$m^3.h^{-1}$]		Relative Humidity [%]		Airflows [$m^3.h^{-1}$]		
	Q	Qboost	RHmin	RHmax	Qmin	Qmax	Qboost
LVR	45	135	20	55	5	55	135
BTH1	30	/	23	63	15	50	/
BTH2	30	/	45	85	5	45	/
WC (x2)	15	/	Constant		5		/
Total exhaust	135	225			35	160	245

TABLE 1: MODELLED EXHAUST AIRFLOWS BY SYSTEM

In this case, the comparison with the measurement data could confirm that the simulations results are in the same order of magnitude. Indeed, such comparisons between measurement and other modelled systems are still relevant. As the airflows strategies were the same between MEV-cav and MVHR-cav; the main difference for heat losses calculation is the heat recovery efficiency of the MVHR-cav. Moreover, modelling the MEV-rh as an additional system allow theoretical assessment of what would be the performance with another ventilation strategies proposition modelled at design or in building renovation context.

2.1.1.c) TEMPERATURE ASSUMPTION VARIATIONS

Ideally, if the temperatures of all the rooms are available in a measurement campaign, the real temperatures of each zone with exhaust could be used for the heat loss calculation. In the present case, the temperatures of all the rooms were not available, consequently we needed to make some assumptions for the heat loss calculation. Indeed, the calculation of heat losses is possible at the whole building scale by application of Equation 1, but can also be detailed for the rooms with exhaust components (humid rooms) following the next decomposition by room in Equation 4:

$$H_{thl} = \frac{C_{p_m}}{3600} \cdot (1 - \varepsilon_{heat_{ex}}) \cdot \int_{t=0}^d \sum_r q_r(t) [T_r(t) - T_{ex}(t)]$$

EQUATION 4

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With H_{thl} the thermal heat losses from exhausted air [kWh]; q_r the exhausted mass airflow in the room r in [$kg.s^{-1}$], and T_r the indoor temperature [$^{\circ}C$] in the room r with an exhaust unit (in this case the living room + kitchen, the 2 bathrooms and the 2 toilets [LVR; BTH1; BTH2; WC1; WC2]), over d the total measurement or modelling duration.

As a result, in order to analyse the available measured temperatures, we proposed three variants (decompositions) of indoor temperatures at the whole building scale (using Equation 4):

- **Theoretical control (T_{ctrl}):** T_{int} is assumed constant and equal in all the rooms, according to the set-point temperature of the heating system at design. During the measurement campaign, the temperature control was set at $20^{\circ}C$ ($T_{ctrl_{20}}$).
- **Constant at building scale ($T_{c_{build}}$):** T_{int} is assumed constant and equal to the average of all measured temperatures of all the rooms during the whole measurement period.
- **Variable at building scale ($T_{v_{build}}$):** T_{int} is assumed variable in time and averaged in rooms. It is set equal to the average of all the rooms at each time step during the measurement period.

Similarly, two variants (decompositions) of indoor temperatures at the room scale are proposed, to be used with Equation 4 :

- **Constant at room scale ($T_{c_{room}}$):** T_{int} assumed constant in time and equal to the average measured temperature by room during the measurement period. With the following rooms decomposition:
 - o $T_{CLVR} = \text{average}(T_{C_{kitchen}} + T_{C_{living}})$
 - o $T_{CBTH} = \text{average}(T_{BTH2})$ supposed that $T_{BTH1} = T_{BTH2}$ as only T_{BTH2} was measured
 - o $T_{CWC} = \text{average}(T_{C_{other_rooms}})$ as T_{WC} was not measured, in this case the other rooms measured temperature available are in the bedrooms (BR1, BR2, BR3, BR4).
- **Variable at room scale ($T_{v_{room}}$):** T_{int} assumed variable in time and equal to the running average temperature by room during the measurement period; with the same room's decomposition described for $T_{c_{room}}$.

For measurements analysis, the heat losses of these five variants were calculated with the design airflows described above and with the external temperatures measured during the campaign.

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For the energy simulations results, the same temperature decompositions were kept as a conservative approach to compare measurement and modelling (referred as $T_{\text{build_md}}$, $T_{\text{vbuild_md}}$, $T_{\text{room_md}}$, $T_{\text{vroom_md}}$). The external temperatures used for the modelling are from standardised weather file of typical weather conditions in the region of the modelled Lyon, France (ASHRAE IWEC Weather file, 2001)

With the energy simulation, other temperature control strategies can be tested to evaluate their influence on the heat loss calculation. In addition to the constant 20°C temperature control set for the electric heaters in DOMUS simulation, two additional temperature control strategies were tested:

- $T_{\text{ctrl_19/16}}$, based on the French thermal regulation RE2020 that provides occupancy scenarios and the associated control temperature of 19 °C when the house is occupied and 16 °C when the house is not occupied. (RE-2020 ANNEXE III)
- $T_{\text{ctrl_20/16}}$, based on the same occupancy scenario provided by the RE2020 but using 20°C when the house is occupied and 16°C when the house is not occupied.

For result analysis, we calculated the relative difference ΔH_{thl} [%] between different estimations, using as the reference the theoretical heat loss computed using the control temperature as reference $T_{\text{ctrl_20}}$.

$$\Delta H_{\text{thl}} = \frac{H_{\text{thl}}[T_d] - H_{\text{thl}}[T_{\text{ctrl}_{20}}]}{H_{\text{thl}}[T_{\text{ctrl}_{20}}]}$$

EQUATION 5

With $H_{\text{thl}}[T_{\text{ctrl}_{20}}]$ the heat losses calculated with a constant temperature $T = 20^\circ\text{C}$ and $H_{\text{thl}}[T_d]$ the heat losses calculated with de desired temperature decomposition.

In addition, we completed the H_{thl} calculation with the average power for heating needed to compensate the heat losses from air renewal. This average power, described by the Equation 6 is adapted to identify the periods when the building has high energy needs. Indeed, the comparison of the H_{thl} calculated from two campaigns is often not relevant as their duration may be different.

$$P = \frac{H_{\text{thl}}}{d}$$

EQUATION 6

With P the instant power [W] need for heating to balance the Q_{thl} and d the total measurement or modelling duration in hour [h].

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2.1.2 RESULTS

2.1.2.a) HEAT LOSSES CALCULATED ON THE CAMPAIGN PERIODS

IN-SITU MEASUREMENTS

To give an overview of the two campaigns, the measured temperatures and the average temperature at the building scale are plotted in Figure 2 . In both campaigns, the living room had a warmer temperature (C1 22.6 °C; C2 21.3°C average) than the other rooms. The bedrooms had colder minimum temperatures in campaign 1 during wintertime (C1 17.7 °C average). The bathrooms temperatures (C1 19°C; C2 19.1 °C average) were close to the average temperatures of all rooms (C1 19.3 °C; C2 20°C average). In general, for both campaigns, the measured temperatures were rather close to the set-point temperature (T_{ctrl_20}).

The H_{thl} calculated for both campaigns with the constant temperature assumption and the four proposed measured temperatures variants are presented in Table 2. The total heat losses for the two campaigns were between 22 and 24 kWh, which is close from one campaign to the other. This is due to a compensation between lower exterior temperatures for C1 and longer duration for C2. As the duration is different, it more relevant to compare the average power: 159 W and 112 W for the campaign C1 and C2 respectively, calculated with T_{ctrl_20} . Proportionally the energy needs were higher during C1 in comparison with C2, which is coherent with the colder outside temperatures in winter times.

The ΔH_{thl} [%] comparison shows that the calculated heat losses with measured temperatures instead of the theoretical control temperature were in the same order of magnitude with less than 5% relative difference. The biggest differences were observed during the campaign C1 when the temperature decomposition at the building level were used ($T_{c_{build}}$; $T_{v_{build}}$), but even in this case the differences are very low. In C2 campaign, the relative differences between the theoretical heat losses and heat losses calculated with the measured temperatures are negligible.

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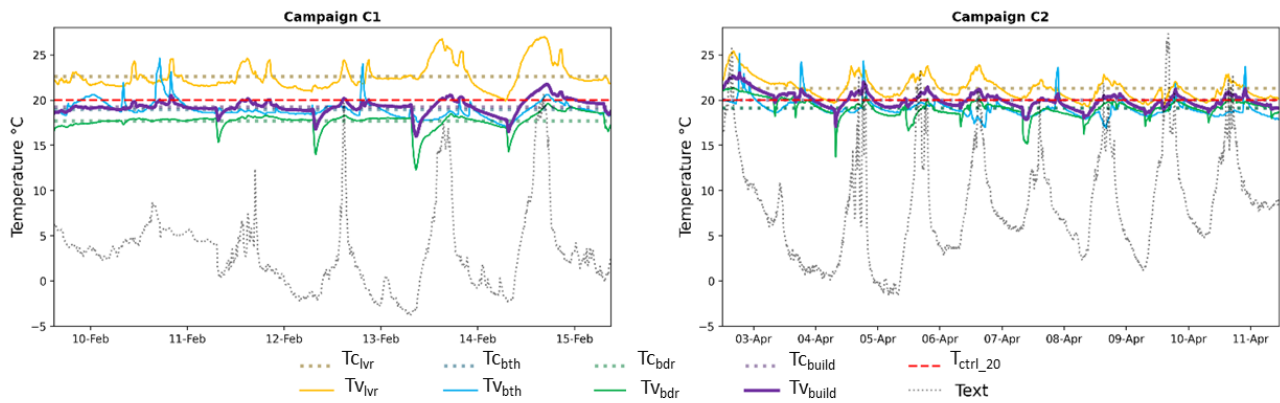


FIGURE 2 : TEMPERATURE DECOMPOSITION FROM MEASUREMENT CAMPAIGN C1 AND C2

	C1		C2	
	$H_{thl} [kWh]$	$\Delta H_{thl} [\%]$	$H_{thl} [kWh]$	$\Delta H_{thl} [\%]$
T_{ctrl_20} (assumption)	22.0	-	23.7	-
T_{build}	21.1	-4.2%	23.7	0%
T_{room}	22.1	0.2%	23.7	0%
T_{vbuild}	21.1	-4.3%	23.7	-0.2%
T_{vroom}	22.1	0.5%	23.8	0.3%

TABLE 2 : HEAT LOSSES CALCULATION RESULTS AND RELATIVE DEVIATION BETWEEN T_{CTRL_20} AND OTHER DECOMPOSITIONS

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SIMULATIONS

The simulated temperatures for both mechanical ventilation systems are plotted in Figure 3. In the simulated results, we can observe only small daily periodic oscillations around the control temperature with less irregularity in comparison to the variations observed on the measured temperatures in Figure 2. This evolution is typical for simulation results obtained with a perfect heating controller and cyclic schedules. There were no significant differences of temperatures between constant exhaust airflows and humidity-controlled airflows in the wintertime during the campaign C1. In the C2 campaign, the daily peak temperatures were about 1 to 2 °C higher for MEV-rh (max in LVR 38.9°C; in BDR1 35.0°C) in comparison with the MEV-cav (max in LVR 37.7°C; in BDR1 32,9°C). These higher temperatures in MEV-rh case can be explained by the lower exhaust airflows, that reduce the heat losses from ventilation and keep internal temperatures slightly higher.

The calculated heat losses with the simulated temperatures ranged from 61 to 108 kWh (0.45-0.8 kWh.m²) depending on the ventilation system and the campaign period. In comparison with the heat losses calculated using measurements, these values were significantly higher. This is explained by the MVHR-cav heat exchanger efficiency (around 0.8) installed in the house used for the measurement campaign.

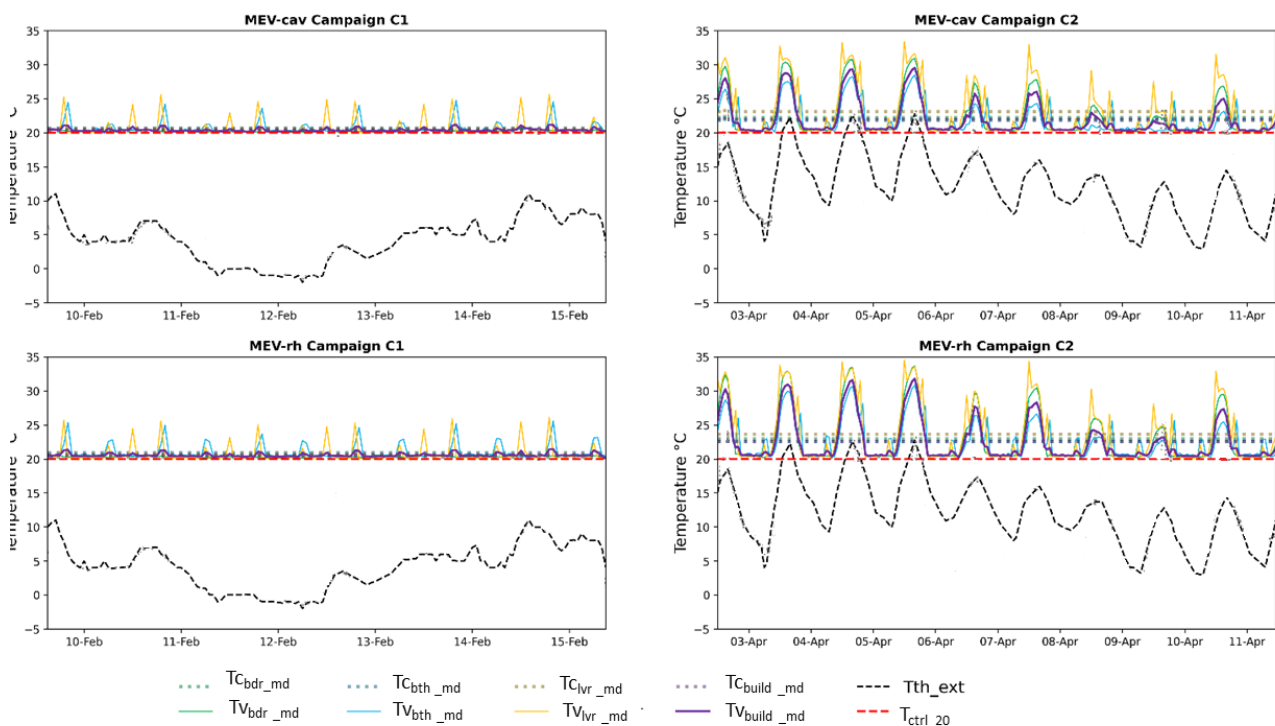


FIGURE 3 : SIMULATED TEMPERATURES DURING C1 AND C2 PERIODS

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Indeed, in the modelling, the two ventilation systems were assumed to be exhaust only mechanical ventilation systems without any heat recovery. If we apply “virtually” an efficiency coefficient of 0.8 on the MEV-cav and MEV-rh systems, the calculated heat losses range now from 12,3 to 21,8 kWh, which is closer to the 22 - 24 kWh calculated based on measured temperatures. In addition, the modelled MEV-rh system with airflows controlled by humidity had lower heat losses compared to the MEV-cav with constants airflows. This can be explained by lower average airflow values in the case of MEV-rh system.

	MEV-cav				MEV-rh			
	C1		C2		C1		C2	
	$H_{thl} [kWh]$	$\Delta H_{thl} [%]$	$H_{thl} [kWh]$	$\Delta H_{thl} [%]$	$H_{thl} [kWh]$	$\Delta H_{thl} [%]$	$H_{thl} [kWh]$	$\Delta H_{thl} [%]$
T_{ctrl_20}	103.8	-	79.1	-	76.1	-	61.5	-
TC_{build_md}	106.7	2.8	100.1	26.6	79.2	4.1	78.7	28.1
TC_{room_md}	107.6	3.7	102.8	30.0	80.0	5.0	85.3	38.8
TV_{build_md}	106.5	2.6	99.6	25.9	78.9	3.7	81.9	33.2
TV_{room_md}	108.9	4.9	105.7	33.7	81.9	7.5	85.4	38.9

TABLE 3: HEAT LOSSES CALCULATED USING SIMULATION RESULTS AND THEIR RELATIVE DIFFERENCE.

Over the period C1, the relative difference $\Delta H_{thl} [%]$ according to the simulated temperatures decomposition used for the heat loss calculation were acceptable with variations between 2.6% and 7.5%. On the opposite, over the C2 period, the relative differences were more significant up to 25.9% to 38.9% as compared to the theoretical heat losses using T_{ctrl_20} . This can be explained by the specific weather during C2 campaign with high solar gains and simulated indoor temperatures reaching high values, far from the reference of 20°C. Regardless the period, the calculation of heat losses with the two building scale temperatures decompositions (TC_{build_md} , TV_{build_md}) leads to results that were lower and closer to the theoretical evaluation (T_{ctrl_20}), than those calculated with the room scale decompositions (TC_{room_md} , TV_{room_md}).

These results from short periods (measurement campaigns), showed that when the modelled temperatures were more stable and closer to the theoretical value of 20°C , (as in C1 case) there were only low differences between the use of constant or variable temperatures for heat loss calculation. However, when the simulated temperatures were varying more due to seasonal higher temperatures (C2 case), the use of constant or variable temperature generated significant relative difference.

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2.1.2.b) HEAT LOSSES MODELLING ON THE HEATING PERIOD

To extend previous results and deepen the analysis, the simulations were performed over the whole heating period (from October 15, 00:00 AM, to April 14, 12:00 PM).

Figure 4 plots, for the two modelled ventilation systems, the calculated average temperatures at the building scale (previously defined as $T_{v_{build_md}}$). On the first plan, monthly boxplots are plotted, and, on the background, the daily average temperature with the daily extremums. We also represent with horizontal lines the 20°C constant control temperature (dotted red) and the average temperature on the entire heating period (dotted black/gray).

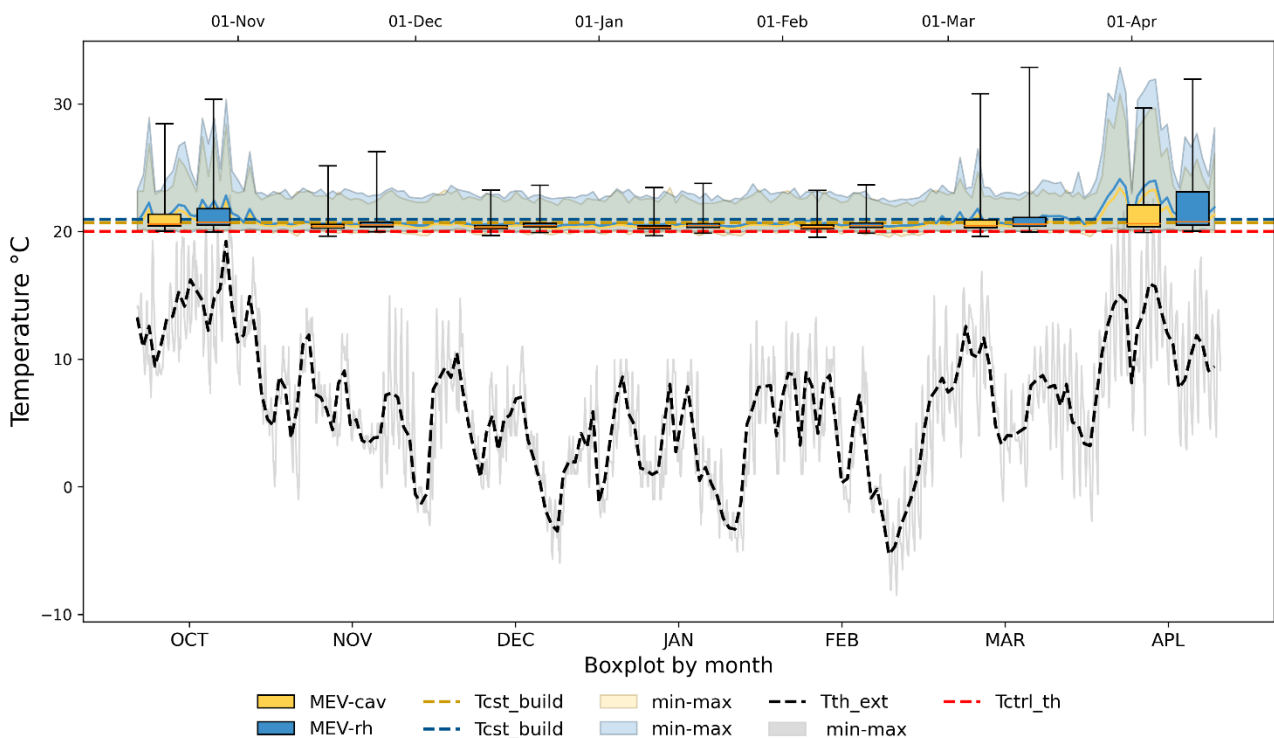


FIGURE 4: SIMULATED BUILDING AVERAGE TEMPERATURES OVER THE HEATING PERIOD FOR TWO VENTILATION SYSTEMS: DAILY AVERAGES AND EXTREMUMS AND MONTHLY BOXPLOTS.

This Figure 4 gives a global vision of the simulated temperatures and shows that over the coldest months, from beginning of November to the end of February, the average building temperature was close to the control temperature. However, and in line with what has been observed previously over the C2 period, the amplitude of variations of average temperatures in the building was higher during the inter-season (October, March, April). In addition, there is no significant differences in the temperature evolution between both ventilation systems, excepted slightly higher temperatures for MEV-rh.

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	MEV-cav		MEV-rh	
	$H_{thl} [kWh]$	$\Delta H_{thl} [%]$	$H_{thl} [kWh]$	$\Delta H_{thl} [%]$
T_{ctrl_20}	2818.21	-	2078.14	-
T_{build_md}	2972.70	5.48	2230.54	7.33
T_{room_md}	3007.64	6.72	2272.73	9.36
T_{vbuild_md}	2966.05	5.25	2229.82	7.30
T_{vroom_md}	3054.90	8.40	2328.41	12.04

TABLE 4 : HEAT LOSSES OVER THE WHOLE HEATING PERIOD FOR TWO VENTILATION SYSTEMS

The heat losses calculated on the entire heating period ranged from 2078 kWh to 3054 kWh (15.8-22.6 kWh.m⁻²) depending on the system and the temperature decomposition used for the calculation. Converted into average power, to better compare C1, C2 and heating period, the power ranged from 638 W to 692 W for the MEV-cav and from 470 W to 526 W for the MEV-rh for the heating period. These values are between the average power calculated over the C1 and C2 periods, as shown on the Figure 5. For both systems, the average power values were however closer to the values calculated using the C1 period. This is anticipated, as the exterior temperatures during C1 period are more representative of winter period (heating season) than the inter-season period C2.

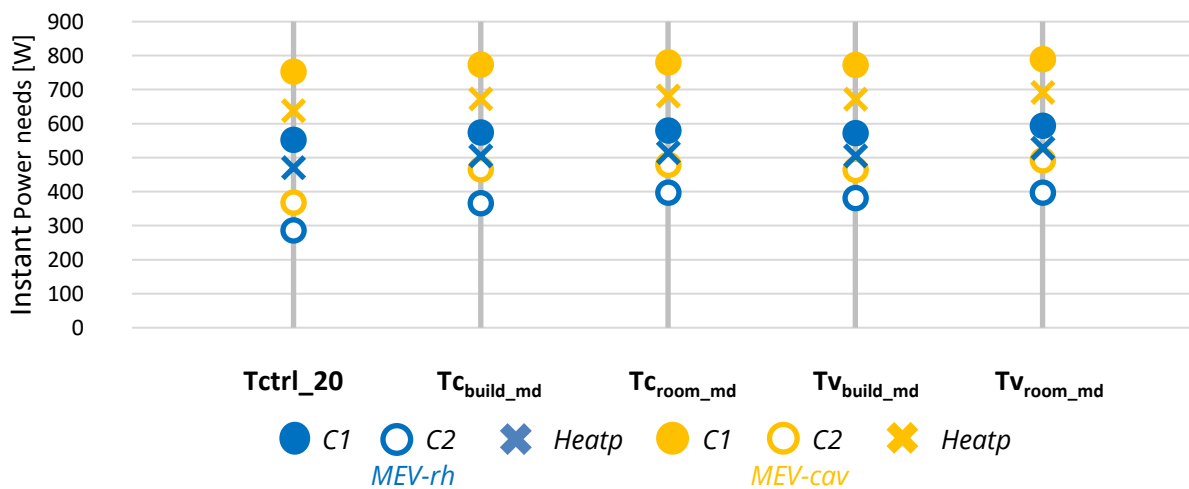


FIGURE 5 : AVERAGE POWER SIMULATED FOR TWO VENTILATION SYSTEMS ; FOR 3 PERIODS (C1, C2 AND WHOLE HEATING SEASON)

The relative differences $\Delta H_{thl} [%]$ ranged from 5.2 % to 12.0 % which is a little higher than the relative differences during the C1 period. The deviations for MEV-rh were from 1.9 % to 3.6% higher than for the MEV-cav. That means, that the heat losses calculation for the MEV-rh is more influenced by temperatures variations than for the MEV-cav. Moreover, similarly to what was observed for C1 and C2 periods; the calculations using building average (T_{build_md} and T_{vbuild_md}) were closer to the theoretical heat loss (calculated using T_{ctrl_20}) than the calculations using room averages (T_{room_md} and T_{vroom_md}).

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These results shows that there are few differences in using a constant averaged temperature on the period or the variables temperature from simulations; in this case with a T_{ctrl_20} constant control strategies modelled. That reinforce the choice to test the other variables control strategies $T_{ctrl_20/16}$ and $T_{ctrl_19/16}$, to evaluate the impact of variable control strategies in comparison with a constant control strategy assumption.

2.1.2.c) IMPACT OF STEP-WISE TEMPERATURE CONTROL STRATEGIES

Figure 6 shows the monthly boxplots of the building average temperatures for the three modelled temperature control strategies (T_{ctrl_20} ; $T_{ctrl_20/16}$; $T_{ctrl_19/16}$) and the two ventilation systems (MEV-cav, MEV-rh). We observe that the amplitudes of monthly temperature variations are similar from November to February. In these colder months, for the simulated stepwise control strategies the temperature ($T_{ctrl_20/16}$; $T_{ctrl_19/16}$) mainly stays in the range 20-16 °C or 19-16 °C respectively. The main difference between $T_{ctrl_20/16}$ and $T_{ctrl_19/16}$ is that the temperature stays under 20°C for $T_{ctrl_20/16}$ or 19 °C for $T_{ctrl_19/16}$. During the warmer inter-seasonal months (October, March, April), the simulated temperatures were often above 20°C (or 19°C) respectively. We observed the same results as previously on the heating period: for T_{ctrl_20} the average temperatures with the MEV-rh were slightly higher than the temperatures with the MEV-cav.

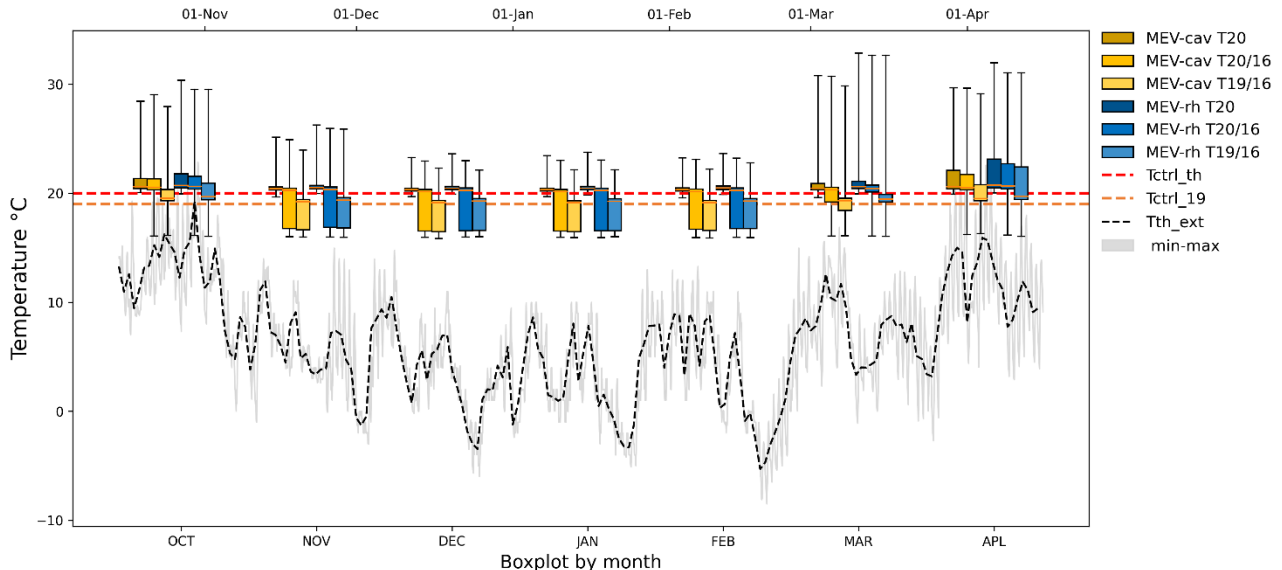


FIGURE 6 : BUILDING-AVERAGE TEMPERATURES: MONTHLY BOXPLOTS FOR 3 TEMPERATURE CONTROL STRATEGIES AND 2 VENTILATION SYSTEMS

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According to the heat losses calculated in Table 5, for the MEV-cav the $T_{ctrl_19/16}$ strategy reduce the heat losses between 150-210 kWh (1.1-1.5 kWh.m⁻²) in comparison with the $T_{ctrl_20/16}$ and between 217-247 kWh (1.6-1.8 kWh.m⁻²) compared to the T_{ctrl_20} . For the MEV-rh the heat loss reduction is lower, with 49-56 kWh (0.6-0.4 kWh.m⁻²) in comparison with the $T_{ctrl_20/16}$ and between 40-146 Kwh (0.3-1.1 kWh.m⁻²) compared to the T_{ctrl_20} .

In addition, according to the ΔH_{thl} [%], the heat loss calculation with the $T_{ctrl_19/16}$ modelling for the MEV-cav system, look less sensitive to the rooms temperature decomposition used. In comparison to the previous ΔH_{thl} [%] analysis for MEV-rh the absolute lower ΔH_{thl} were observed with temperature decomposition at the room scale (T_{Croom_md} , TV_{room_md}). Is this case the lower ΔH_{thl} is observed at the building scale (T_{Cbuild_md} , TV_{build_md}). Moreover, this modelling of a variable temperature control strategy between 16 °C and 20 °C, gives on the entire heating period similar relative deviation than the observed one with heat losses calculated during the in-situ measurement campaign.

	$T_{ctrl_19/16}$				$T_{ctrl_20/16}$			
	MEV-cav		Mev-rh		MEV-cav		Mev-rh	
	H_{thl} [kWh]	ΔH_{thl} [%]	H_{thl} [kWh]	ΔH_{thl} [%]	H_{thl} [kWh]	ΔH_{thl} [%]	H_{thl} [kWh]	ΔH_{thl} [%]
T_{ctrl_20}	2839.49	-	2229.06	-	2829.70	-	2179.09	-
T_{Cbuild}	2591.62	-8.73	2083.11	-6.55	2741.10	-3.13	2135.92	-1.98
T_{Croom}	2603.21	-8.32	2141.42	-3.93	2789.35	-1.43	2195.34	0.75
TV_{build}	2591.97	-8.72	2091.22	-6.18	2740.95	-3.14	2147.60	-1.45
TV_{room}	2621.98	-7.66	2188.64	-1.81	2831.28	0.06	2237.88	2.70

TABLE 5 : HEAT LOSSES ON THE TOTAL HEATING PERIOD FOR TWO TEMPERATURE CONTROL STRATEGY

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.1 EVALUATION OF TEMPERATURE ASSUMPTIONS FOR ENERGY INDICATOR CALCULATION BASED ON IN SITU MEASUREMENTS AND ENERGY SIMULATION

2.1.3 CONCLUSION

To conclude, the use of a constant indoor temperature for the heat loss calculation from exhaust airflows gives acceptable results and does not lead to huge deviations on the heating period. Based on measured data, the use of variable or constant temperature distributions resulted in similar orders of magnitude of the heat losses. With the data from C1 campaign, the use of decomposition at the building scale resulted in approximately 4% lower heat losses evaluation. In absolute, it changes of only 1 kWh: 21 kWh instead of 22 kWh, that is not significant and could be neglected. In this case study on both campaigns, the use of $T_{ctrl_20} = 20^{\circ}\text{C}$ for heat loss calculation gives an acceptable evaluation.

However, the extended modelling over the entire heating period, highlighted the limitations of using this constant temperature assumption during the inter-seasonal months. Indeed, we observed a higher impact on heat losses during October, March, and April, when the outside and inside temperatures are higher. During the C2 period, the heat losses calculated with variable temperature were indeed up to 38.38 % higher than the ones evaluated with a constant temperature ($T_{ctrl_th} = 20^{\circ}\text{C}$). Here on these inter-seasonal periods, the drawback of the proposed H_{thl} indicator is that it does not consider the difference between the “costly” thermal gains from heating system and the “free” thermal gains from solar gains. Indeed, during warmer seasons, the internal temperature could easily be higher than the set point value, and, in this case, it is unfortunately still accounted for as a thermal loss from ventilation. In future, an advanced H_{thl} indicator could account for heat losses only when the heating system is turned on. Such advanced indicators could also deal with cooling needs issues or summer thermal comfort.

In addition, the modelling with variable temperature control only shows that, as anticipated, a lower temperature set point $T_{ctrl_19/16}$ leads to energy savings. However, the differences between T_{ctrl_20} and $T_{ctrl_20/16}$ are very low and give very similar values for heat losses. As a result, the modelling of variable temperatures could be done in case of specific requirements provided by standards. However, it could also be simplified with a constant temperature strategy, that could save some modelling development costs and resources.

Finally, the use of a constant temperature assumption at the building scale is acceptable for ventilation systems heat losses evaluation over the heating period and even more relevant for the cold months. For this purpose, thermal model with variable internal temperatures is not necessarily required. However, thermal model with variable temperatures could have an impact on relative humidity that need to be explored and may influence IAQ performance evaluation for ventilation systems relatively to the moisture-based indicators.

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

2.2.1 INTRODUCTION TO THE CO-SIMULATION

The following section brings together several results from an exploratory work performed for the development of the co-simulation between the CONTAM airflow model and the DOMUS energy model. First, the context and the process of coupling CONTAM with an energy simulation are presented. Then, a validation work based on the IAE BestCase (MZ320) has been performed and finally the coupling process is tested on a simplified 3- zones case study.

2.2.1.a) MOTIVATIONS FOR CO-SIMULATION DEVELOPMENT

The building simulation model proposed in CONTAM focusses on airflows and pollutants and does not allow the description of the thermal aspects of the building. It describes the transfers of air and pollutants from one zone to another through the walls, calculating mass balances with pressure network. Currently in CONTAM, the internal temperatures are constant in each zone, and no zone energy balance is computed.

In order to develop energy performance indicators and get beyond the limit of constant temperature during the inter-seasonal months, we explored coupling CONTAM with an energy performance simulation tool. Indeed, with the use of CONTAM alone, the energy performance indicators are limited. Possible energy indicators calculated with CONTAM results are for example: electric consumption of the fans using their operating time and thermal losses related to the extracted airflow, as presented above. Thus, the use of a fully coupled energy-airflow model opens the possibility for developing comprehensive energy indicators based on the temperatures calculated in the zones. Moreover, these variable temperatures in zones have an influence on airflows between zones, humidity models and pollutant concentrations.

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

According to CONTAM user guide, the coupling is already available with TRNSYS and EnergyPlus. The co-simulation with TRNSYS is quasi-dynamic which means that the two models converge independently while the co-simulation with EnergyPlus is dynamic with convergences obtained between the two models. In TRNSYS, this process is implemented through the Type56 multizone building heat transfer module which allows inputs and outputs shared with CONTAM. For EnergyPlus the co-simulation is based on the Functional Mock-up Interface (FMI) and the link is made with a ContamFMU (Functional Mock-up Unit) developed and provided by NIST(Dols et al., 2016).

Nevertheless, in the framework of the Franco-Brazilian project *CAPES-COFECUB named " Mathematical models and numerical methods for the improvement of building simulation tools " Ma 899/18* (an international collaboration in with the LST in PUCPR Curitiba), DOMUS, has been chosen to be coupled with CONTAM. DOMUS is an energy simulation tool calculating heat and mass transfers through the building envelope coupled with the air balance in zone. It's also a free tool developed by the PUCPR (Mendes, n.d.). Among others, it requires air change rates as input values. It does not model the air and contaminants flows through the building. The co-simulation CONTAM – DOMUS can use the same ContamFMU component as EnergyPlus. Several advantages have been foreseen for this dynamic co-simulation:

- better consideration of the incoming solar irradiance and solar mask
- the use of user-friendly DOMUS graphical interface The possibility of changing directly the source-code as it has been developed by researchers being involved in this work (Pr Nathan Mendes, Dr Walter Mazuroski)
- Future perspectives integration of other coupling for external environment (CFD, CFX or Openfoam), and heat and mass transfers in the walls (Berger et al., 2019).

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

2.2.1.b) Co-simulation Process

During the coupling process CONTAM simulations provide the airflows infiltrations, the airflows between zones and the pollutants concentration (excepted the humidity). The DOMUS model is coupled with Python through a PyFMU to communicate and send control ventilation strategies and moisture emissions scenarios to DOMUS during simulations. This coupling was necessary in order to replicate the input schedules for vapour generation rates and the exhaust airflow from CONTAM to DOMUS. This ensures the use of same values for ventilation systems cooking boost and humidity sources in both tools.

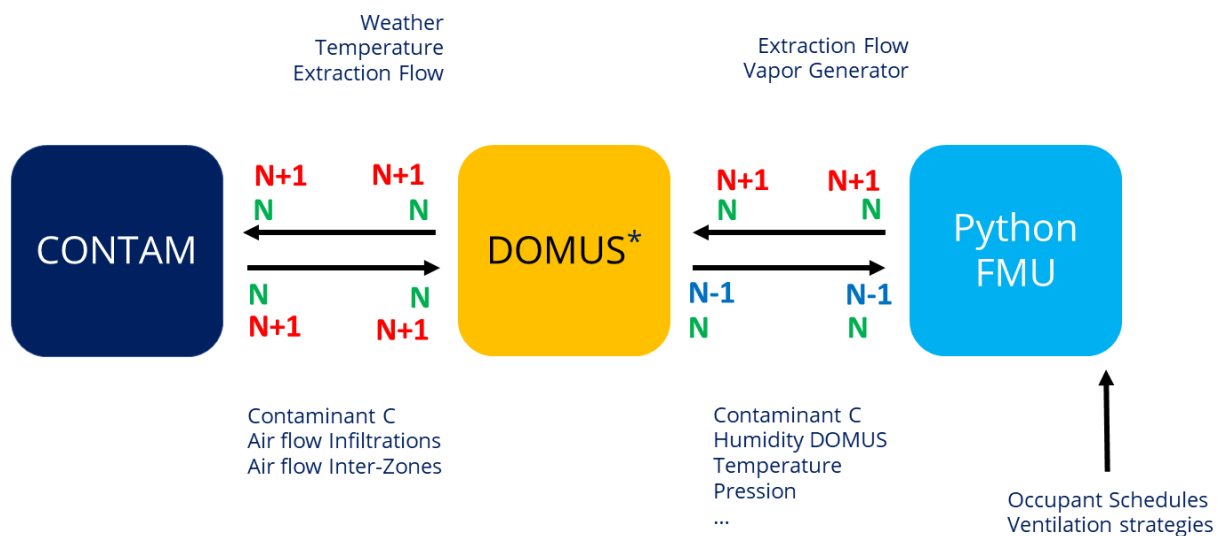


FIGURE 7 : COUPLING PROCESS AND EXCHANGED VARIABLES

On the side of DOMUS simulation during coupling process information are sent to CONTAM with ContamFMU, a second FMU built based on existing FMU used for coupling CONTAM and EnergyPlus. In this step the ContamFMU sends to CONTAM the zones temperatures, the extraction airflows and weather data. Based on these temperatures and extraction airflows, CONTAM calculates the new infiltration airflows, inter-zone airflows and pollutants concentrations. During this co-simulation process, the humidity model of CONTAM is not used, only pollutants concentrations other than water vapour are available in the CONTAM results (here CO₂, PM_{2.5}, formaldehyde for example). After that, with ContamFMU, CONTAM sends back the calculated infiltrations and inter-zone airflows to DOMUS.

In short, pollutants concentrations, infiltrations, inter-zone airflows are calculated by CONTAM, extracted ventilation airflows and humidity generation schedules are sent by PyFMU and, finally, air temperatures and humidities are calculated by DOMUS, according to Figure 7.

2.2.2 VALIDATION OF THE COUPLING ON THE IAE BESTEST(MZ320)

The implementation and the coupling between DOMUS and CONTAM were validated during a 2-week collaboration with Dr Walter Mazuroski from PUCPR Curitiba hosted at LaSIE (Univ. La Rochelle, in 2019). The following development for DOMUS and CONTAM co-simulation is adapted from the existing method presented in (Dols et al., 2016) to couple EnergyPlus and CONTAM. To validate the co-simulation, an analytical case based on the IAE BESTEST(MZ320) was modelled and simulated (Figure 8).

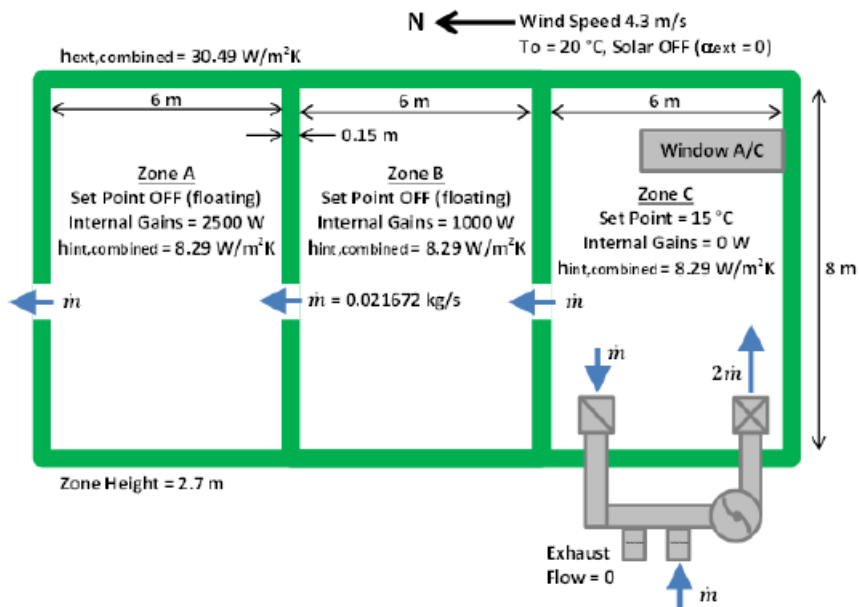


FIGURE 8 : ANALYTICAL CASE BASED ON IAE BESTEST (DOLS, 2016)

The next section detailed the results of this BESTEST co-simulation reproduced between DOMUS and CONTAM. The analysis of this coupling focussed on the comparison of CONTAM/DOMUS results with the analytical values given by the IAE BESTEST and the co-simulation EnergyPlus/CONTAM realised by (Dols et al., 2016).

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

2.2.2.a) RESULTS

The following Table 6 presents the air temperatures after reaching the steady state with standalone thermal simulations (EnergyPlus, DOMUS) and co-simulation (EnergyPlus /CONTAM, DOMUS/CONTAM). The analytical case values are the theoretical air temperatures analytically calculated by (Dols et al., 2016).

TEMPERATURE [°C]	ZONE A	ZONE B	ZONE C
Analytical case	30.309	23.952	15
DOMUS	31.023	24.776	15
DOMUS / CONTAM	30.259	23.912	15
EnergyPlus	31.058	24.798	15
EnergyPlus / CONTAM	30.310	23.953	15

TABLE 6 : TEMPERATURES RESULTS BY MODELS

Figure 2 shows a comparison between standalone simulations and co-simulations with DOMUS and EnergyPlus. The warm-up in DOMUS takes about 1 week to reach the steady state. With the co-simulation, temperatures are almost equal to the analytical case (black dotted line on the Figure 2).

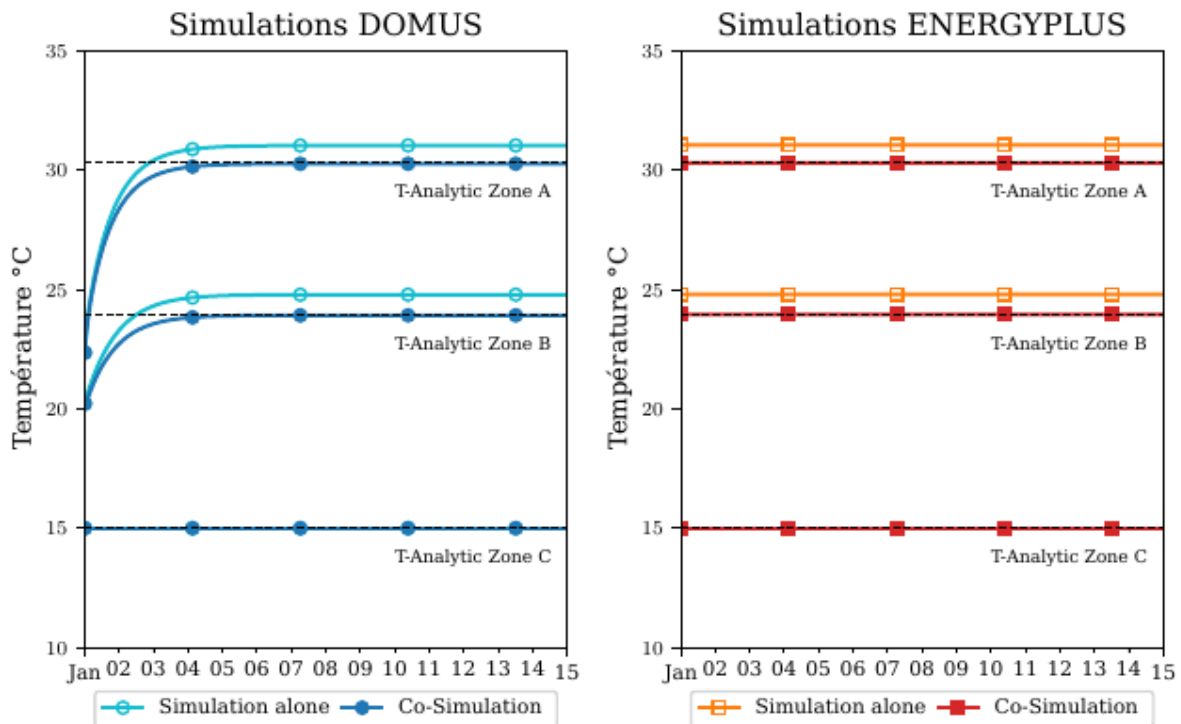


FIGURE 9 : TEMPERATURES EVOLUTIONS BY MODELS

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

We can observe that with the co-simulation, the temperatures converge to the analytical results. With the standalone simulations, temperatures are above the analytical values. In Table 7, the temperatures errors ΔT [%] (Equation 7) between the analytical case and simulations (DOMUS or ENEnergyPlus) have been calculated.

$$\Delta T [\%] = \frac{T_{model} - T_{analytic}}{T_{analytic}}$$

EQUATION 7

The standalone simulations errors are almost the same for EnergyPlus and for DOMUS, with temperatures about 2.4% higher than the analytical values. With the co-simulation, DOMUS results are close to the analytical ones with an acceptable temperature ΔT [%] difference of -0.16%;-0.17%

ΔT [%]	ZONE A	ZONE B	ZONE C
DOMUS	2.36	3.44	0
DOMUS / CONTAM	-0.16	-0.17	0
ENERGY PLUS	2.47	3.53	0
ENERGY PLUS / CONTAM	0	0	0

TABLE 7: ERRORS BETWEEN ANALYTIC CASE AND MODELS

ΔT [%]	ZONE A	ZONE B	ZONE C
DOMUS - DOMUS/CONTAM	-2.46	-3.49	0.0
ENERGYPLUS - ENERGYPLUS/CONTAM	-2.41	-3.41	0.0

TABLE 8 : ERRORS BETWEEN STANDALONE SIMULATION AND CO-SIMULATION

In Table 8, we calculated the errors between standalone simulations and co-simulations. These errors show that the temperatures resulting from co-simulation are around (2.4-3.4%) colder than the temperatures resulting from standalone simulations. Moreover, the temperatures are almost the same by zone between DOMUS and EnergyPlus. These results validate the DOMUS/CONTAM coupling process with the ContamFMU that we adapted for DOMUS.

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

2.2.3 APPLICATION ON A MORE COMPLEX CASE

Then, a second collaboration session with Dr Walter Mazuroski from PUCPR Curitiba hosted at the LASIE (Univ. La Rochelle, also in 2019) allowed to extend the coupling functionalities, to debug and to test the coupling process on a more complex case. Indeed, an intermediate case between the IAE BESTEST and the modelling of a complete real house is necessary to ensure that the whole process works properly.

2.2.3.a) PRESENTATION OF THE CASE STUDY

The intermediate case study is a simplified 3-zone case study based on the existing 2-story low-energy house studied earlier. We decided to focus only on the first floor and regroup some rooms in order to reduce the number of zones from five to three. It was done by keeping the living room, the bedroom and extending the bathroom zone to include the hall, the WC and the bathroom.

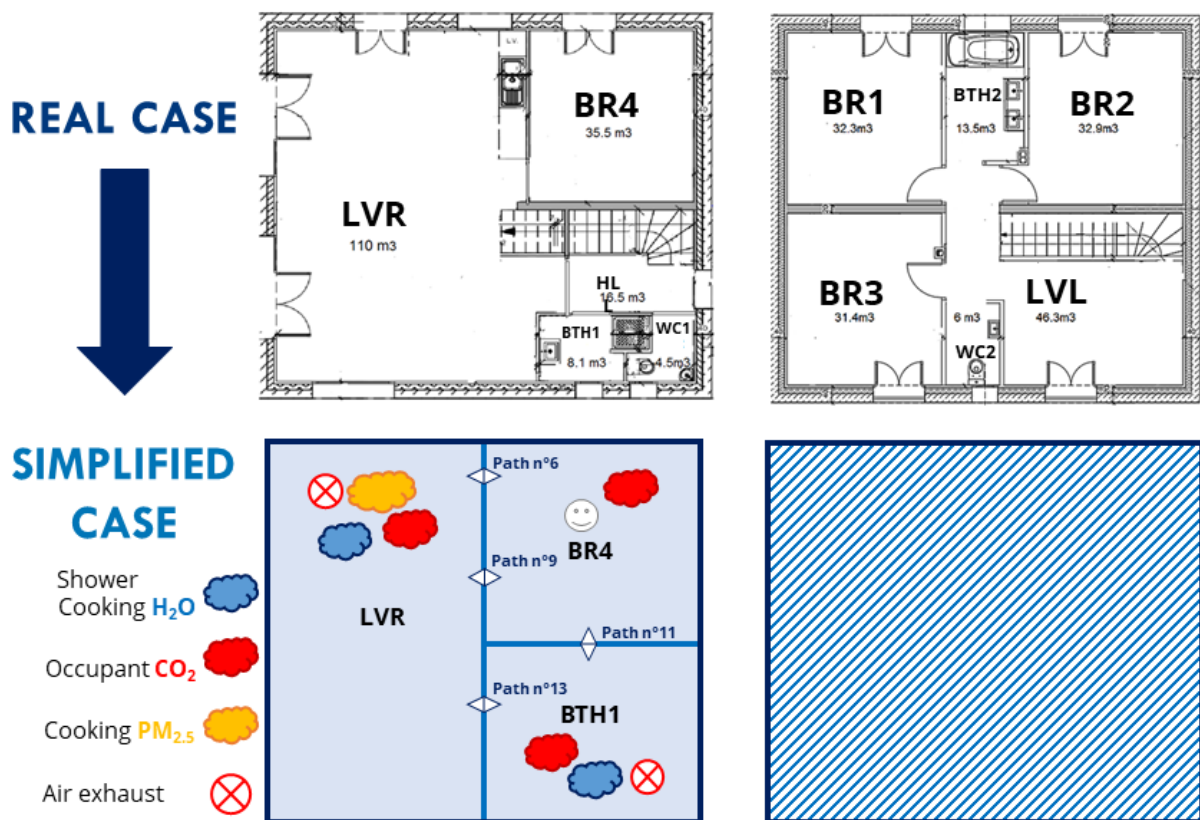


FIGURE 10 : FROM A REAL CASE STUDY TO A SIMPLIFIED 3-ZONES CASE STUDY FOR CO-SIMULATION PROCESS APPLICATION

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

To begin with, we used simplified emission scenarios to better track the evolution of pollutants between zones and easily compare the standalone simulation and co-simulation. A single occupant is considered in the house, emitting CO₂ in the room where he is and taking two showers a day. Then, PM_{2.5} is emitted twice a day (lunch - dinner) in the living room from average cooking activities. The emission rate values used are derived from scenarios proposed in the chapter 1. These assumptions allow the pollutant to be associated with a room: the PM_{2.5} becomes a marker for the living room, H₂O from the rooms with an air exhaust, and CO₂ for the bedroom, especially during night.

In addition, the ventilation system modelled for this case is the mechanical exhaust ventilation with constant airflows (MEV-cav). It includes air exhausts in the bathroom (30 m³.h⁻¹) and in the living room (45 m³.h⁻¹, with 135 m³.h⁻¹ cooking boost). Indeed, this system is simple to implement and has a steady state that facilitates model comparisons. In DOMUS standalone modelling process, the ventilation airflows are implemented with air change rate at the zone scale. The air change rate of 0.94 h⁻¹ ; 0.39 h⁻¹ ; 1.19 h⁻¹ corresponding to 30 m³.h⁻¹ in bathroom; 45 m³.h⁻¹; 135 m³.h⁻¹ in living room is dynamically controlled by the PyFMU. However, for the airflows in the bedroom two modelling options were possible:

- A conservative one, named "DOMUS", with no air change rate (ACH) in the bedroom. It corresponds to a strict application of the extracted airflows only on the concerned zones and without any interzonal airflow.
- An alternative one, named "DOMUS*", with a constant ACH applied in the bedroom. This corresponds to an equivalent virtual inter-zonal airflow that normally is not modelled in DOMUS. The constant ACH value used is 0.35 h⁻¹ (13 m³.h⁻¹), the average ACH in the bedroom calculated by the CONTAM standalone simulation.

These two options allow us to evaluate the impact of interzonal airflows on the simulations results and compare the difference between the virtual interzonal airflows proposed with the DOMUS* option with the dynamic interzonal airflows calculated from the DOMUS/CONTAM co-simulation.

The co-simulation was conducted over two weeks, from February 1, 00:00 AM to 14, 12:00 PM, a period of relatively stable outdoor weather conditions that may be equivalent to the C1 measurement period presented in the previous section.

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

2.2.3.b) RESULTS

TEMPERATURE / HUMIDITY ANALYSIS

Figure 11 represents the evolution of the temperature and the relative humidity in the 3 zones for simulations from DOMUS, from CONTAM and from the DOMUS-CONTAM co-simulation. For a better visualisation of the results, we decided to plot the average and median values, with in the background, the 1st and 3rd quantile of the 15 simulated days, at each time step. This gives a better view of the average daily patterns during the simulations.

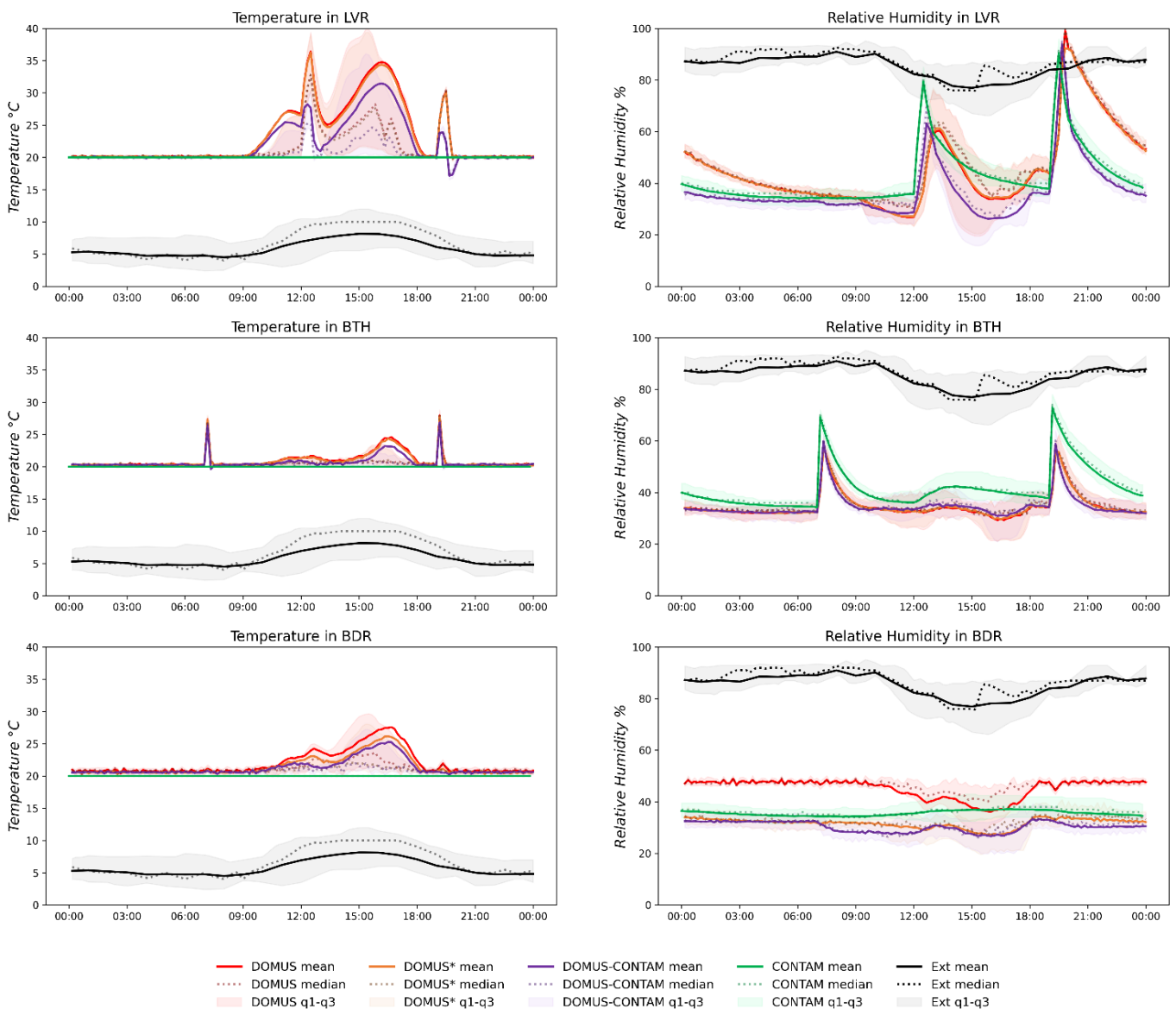


FIGURE 11 : AVERAGE/MEDIAN/Q1-Q3 TEMPERATURE AND HUMIDITY OF C1 PERIOD REGROUPED ON A DAY

Regarding temperature and relative humidity in the living room and the bathroom, the DOMUS and DOMUS* simulations do not show a significant difference and seem to follow almost the same curve. In contrast, the temperature in bedroom for the DOMUS* is between the DOMUS and the DOMUS/CONTAM simulations. DOMUS* results are

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

much closer to the co-simulation results for the humidity. That confirms the influence of interzonal airflows (or the virtual interzonal ones modelled by the ideal ACH in DOMUS* bedroom) on the humidity and the temperature. The two temperature peaks observed in the living room (as well as in the bathroom) can be explained by the vapor generation model used in DOMUS, that generates vapor at the default temperature of 50°C. It creates an internal heat gain that increases punctually the temperature. The other temperature increase in rooms is explained by the solar gains from windows, with large windows in the living rooms, standard windows in the bedroom and two small windows in the bathroom (see annexe *Annex II.3* for windows descriptions).

However, the maximum temperature in the living room reaches 75 °C (the max temperature simulated in living room referenced on boxplot *Annex II.3*), which is not realistic and an improvement in the description of the thermal model must be made. This increase in temperature during the day leads to a decrease in relative humidity, which can be clearly observed in the bedroom without a moisture source, compared to the night when temperature and humidity are constant. Lastly, the second humidity peak in the living room decreases drastically faster in the DOMUS/CONTAM co-simulation than in the DOMUS simulation, which is close to the behaviour observed in the CONTAM simulation.

In addition, we have proposed in Figure 12, a boxplot of the gap between; DOMUS and CONTAM ; DOMUS and DOMUS* ; DOMUS and DOMUS-CONTAM. The Table 9-10 complete these boxplots with the average delta temperature and humidity calculated on the daily mean. The average temperature is lower with co-simulation DOMUS/CONTAM than with DOMUS standalone simulation (-1.34 ; -4.39 %), in accordance with observations on the IAE BESTCASE validation. The temperature of CONTAM simulations was not compared because CONTAM does not have a thermal model and the temperature are assumed to be constant. However, the boxplots on Figure 11 show that CONTAM and DOMUS humidity models are different. Humidity could be in average 20 % higher in CONTAM model in the bathroom, while it is 20% lower in the bedroom. Nevertheless, with DOMUS* simulation and co-simulation the humidity results are mainly lower than in CONTAM simulation.

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

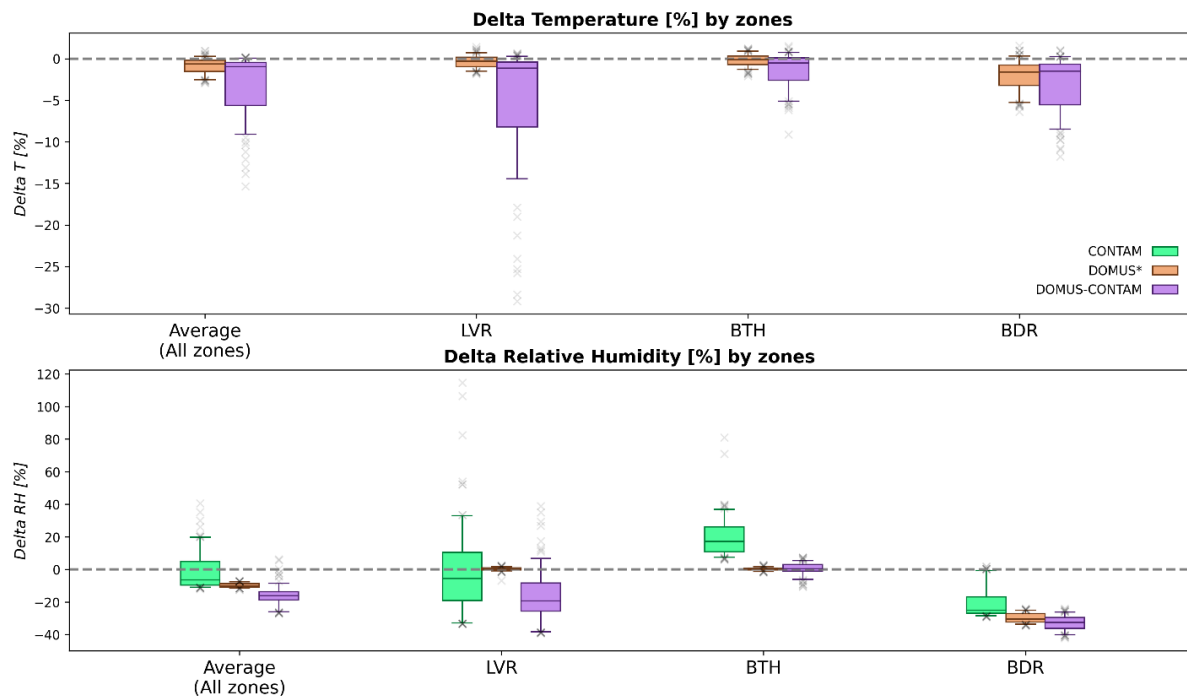


FIGURE 12 : DELTA [%] BETWEEN DOMUS AND OTHER MODELS ; BOXPLOTS BY ZONES OVER THE 1ST -15TH FEB

	LVR	BTH	BDR	Average (All Zones)
DOMUS*	-0.37	-0.20	-2.06	-0.88
DOMUS-CONTAM	-4.39	-1.34	-2.92	-2.88

TABLE 9 : AVERAGE DELTA TEMPERATURE [%] BY ZONE CALCULATED ON DAILY MEAN

	LVR	BTH	BDR	Average (All Zones)
DOMUS*	0.32	0.21	-29.84	-9.77
CONTAM	-2.40	19.76	-20.69	-1.11
DOMUS-CONTAM	-16.56	0.29	-32.83	-16.37

TABLE 10 : AVERAGE DELTA RELATIVE HUMIDITY [%] BY ZONE CALCULATED ON DAILY MEAN

PART 2 : METHOD FOR ENERGY PERFORMANCE ASSESSMENT

2.2 CO-SIMULATION BETWEEN DOMUS AND CONTAM - EXPLORATORY WORK

POLLUTANTS CO₂ AND PM_{2.5} ANALYSIS

Finally, after the co-simulation process, it is possible to export the other results for pollutants concentrations calculated by CONTAM (but not sent to DOMUS). As shown in Figure 13. given by the CONTAM standalone simulations and the ones given by co-simulation.

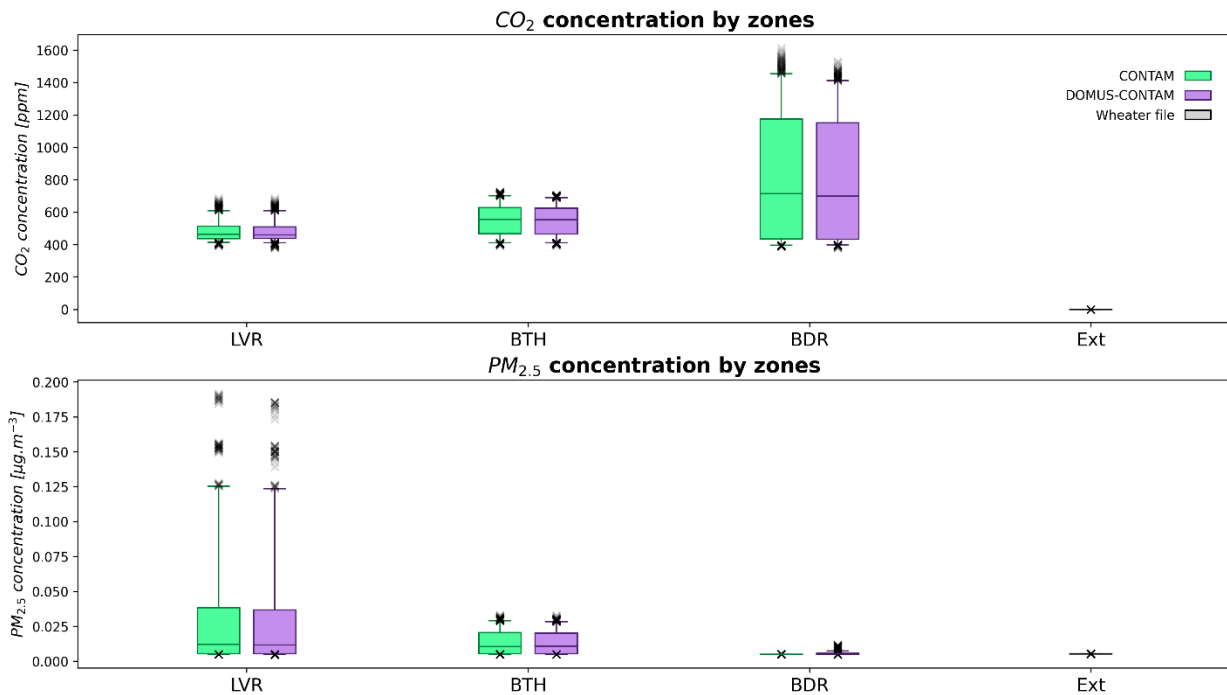


FIGURE 13 : POLLUTANTS CONCENTRATIONS IN DIFFERENT ZONES (1ST -15TH FEB)

These small differences on the pollutant concentrations can be explained by the fact that the principal changed parameter in the CONTAM model during co-simulations is the temperature. The variable temperatures during co-simulation introduce small differences temperatures between zones compared to CONTAM standalone temperatures. That could have a small impact on the mass balance, resulting to small changes on the airflows between zones (see annexe A-II.3). For example, a small transfer of PM_{2.5} from the living room to the bedroom is observed during the co-simulation, which, was not observed in the standalone CONTAM simulation. This could be considered as negligible for the impact of PM_{2.5} concentration in this exploratory configuration (simplified three-zone case study with limited pollutant scenarios tested). However, it could have an impact on more complex scenarios and case studies.

2.2.4 CONCLUSION

Despite the limited exploitable results compared to the initial expectations on the possible benefits of such a co-simulation process, this exploratory work allowed to initiate the co-simulation between CONTAM and a new energy tool: DOMUS. The coupling was validated on the IAE BESTEST case. It shows that CONTAM could work together with DOMUS with an impact on the calculated temperatures. Moreover, on the simplified 3-zone case study, we highlighted that relative humidity models implemented in DOMUS and in CONTAM present differences, resulting in a lower relative humidity in DOMUS during co-simulation.

Unfortunately, it has not been possible to achieve the next steps of application on a whole building case. This is because the complexity of implementing the coupling process is proportional to the number of modeled zones. This led to problems with the inputs and outputs shared between CONTAM and DOMUS, which resulted in inconsistent results concerning the air flows between zones and relative humidity. Despite several unsuccessful attempts at correction, calibration and debugging, it was decided, due to time constraints, to stop the development of the full housing case study. That justify why only the simplified 3-zones case study results were presented instead of on full case application on the low energy house.

This full co-simulation would have been ideal for the detailed calculation of the heat losses related to the exhaust airflows. However, at this stage, the implementation of the co-simulation process is still too complex compared to the value added on a simple calculation of the air heat losses with airflows simulation only.

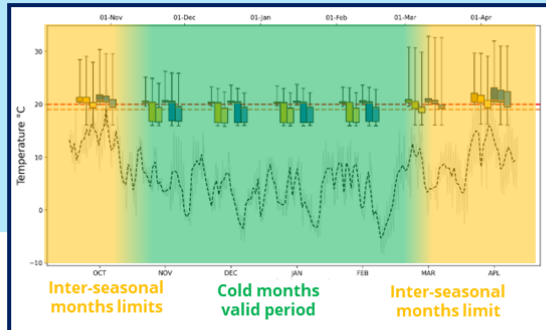
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PART 2



HIGHLIGHTS & LEARNINGS



SIMULATIONS : VALIDATION OF CONSTANT TEMPERATURE IN ZONES FOR HEATING PERIOD

THERMAL HEAT LOSSES CALCULATION FROM EXHAUSTED AIRFLOWS

$$H_{thl} = \frac{C_{p_m}}{3600} \cdot (1 - \varepsilon_{heat_{ex}}) \int q_m(t) \cdot [T_{in}(t) - T_{ex}(t)] \cdot dt$$

OUTPUT : PREPARATION OF THE ENERGY INDICATOR CALCULATION



CO-SIMULATIONS : EXPLORATORY WORK

In this second part, we first performed several energy simulations based on DOMUS to question the use of constant temperatures in CONTAM and energy simulations for the energy indicator calculation. For this purpose, a simple energy indicator based on thermal heat losses calculation from the total exhausted airflows (H_{th}) has been proposed.

As a result, the use of constant temperatures instead of variables temperatures from energy simulation does not significantly change the H_{th} calculation. In addition, the use of a constant average temperature assumption at the building scale without detailing at the rooms scale is acceptable for ventilation heat losses evaluation and even more relevant for the cold months. As a result, for the MOPA, the constant temperature assumption can be used to simplify the modelling process without losing too much accuracy. However, the extended energy simulation over the whole heating period highlighted that using this constant temperature assumption presents some limitation on the inter-season months during October, March, and April (Spring and Autumn months in Europe).

Then, a co-simulation exploratory work in collaboration with the LST laboratory in the PUCPR University (Curitiba, Brasil) has allowed to initiate the coupling between DOMUS and CONTAM. The use of DOMUS has a great potential such as the control with PyFMU. But at this stage, the complexity of the coupling with CONTAM reduced the added value on a simple calculation of the air heat losses with airflows simulation only.

Lastly, at this stage the H_{th} is a provisional energy indicator as it hasn't been tested on a complete OPA case study. Nevertheless, this test will be next performed in the Part 3 on the Danish case study, with the integration of the fan consumption in the calculation. Moreover, the normalisation declination of the energy indicator will be developed in the Part 4 to be integrated in the MOPA to build a complete set of overall performance indicator.

PART 3



APPLICATION AT THE DESIGN STAGE CASE STUDIES

FROM CONSTANT TO SMART VENTILATION SYSTEMS



After the description of the general IAQ performance-based method in the Part 1, and the performance-based method extended to energy-based indicators explored in the Part 2, different applications of the developed methods will be presented in this Part 3.

Indeed, modelling developments and examples of applications have been needed in order to obtain a first overview of the method applicability, including the behaviour of the indicators results. In CONTAM, it is relatively easy to implement ventilation systems with constant airflows strategies, but variable airflows strategies (like in smart ventilation strategies) need further developments. In this chapter, the results of a progressive development both of the performance-based approach and of the implementation in CONTAM from classic to smart ventilation systems are presented through two conference papers.

The first paper introduces a mechanical ventilation with humidity-based control (MEV-rh) and two constant airflows ventilation systems (MEV-cav and MVRH-cav) in a French context. In this study, the performance-based approach consists in testing three pollutants input scenarios regarding IAQ performance on these three ventilations systems.

In the second conference paper, two other ventilation systems with variable airflows based on humidity and CO₂ have been developed (MVHR-rh and MVHR-rb). Here, the performance-based approach consists in evaluating the potential of reducing the minimum airflows to achieve energy savings without reducing the IAQ level. In addition, an extended energy indicator including the fan consumption in addition to the heat losses indicator was tested.

All these modelled ventilation systems and study results constitute the basis for the studied ventilation systems in the Part 4 for methods robustness and sensitivity quantification.

Development of Performance-Based Assessment Methods for Conventional and Smart Ventilation in Residential Buildings

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IAQ 2020: Indoor Environmental Quality Performance Approaches

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Abstract heading

In future building regulations, building performance is going to be extended to global performance, including indoor air quality (IAQ). In the energy performance (EP) field, successive regulations pushed for a "performance-based" approach, based on an energy consumption requirement at the design stage. Nevertheless, ventilation regulations throughout the world are still mostly based on prescriptive approaches, setting airflows requirements. A performance-based approach for ventilation would insure that ventilation airflows are designed to avoid risks for occupant's health. An extensive review work combined with complementary analysis allows us to come up with the development of a performance-based approach for house ventilation to be used at the design stage in a calculation. We select the use of five relevant IAQ performance indicators, based on CO₂, formaldehyde and PM_{2.5} exposures, and RH-based indicators assessing both condensation and health risks. We propose also pollutant emission data and occupancy schedules to be used. Importantly, we demonstrate that our proposed performance-based method was applicable, applying it to a low-energy house case study. We assume being at the design stage of a house which should comply with a hypothetical regulation, requiring IAQ performance indicators and associated thresholds.

PART 3 : APPLICATION AT DESIGN STAGE CASES STUDY

3.1 DEVELOPMENT OF PERFORMANCE-BASED ASSESSMENT METHODS FOR CONVENTIONAL AND SMART VENTILATION IN RESIDENTIAL BUILDINGS (A FRENCH CASE STUDY)

3.1.1 INTRODUCTION

In new European labels and future building regulations, building performances, should be extended to indoor environment quality, beyond energy performance. In the energy performance field, successive regulations pushed to a "performance-based" approach, based at least on an energy consumption requirement for heating and/or cooling at the design stage (Spekkink 2005, Directive EPBD 2003:2010).

Nevertheless, in the building ventilation field, regulations throughout the world are mainly still based on "prescriptive" approaches, such as airflows or air change rates requirements (Dimitroulopoulou 2012). As the list of identified indoor pollutants is long and may still increase, it has been impossible to create definitive IAQ indicators for standards and regulations governing residential buildings (Borsboom et al. 2016). As a result, standards and regulations generally set ventilation rates based on comfort considerations and not on health criteria as suggested in the Healthvent project (Wargocki 2012).

Against such prescriptive approaches, it is possible to develop performance-based approaches for residential building ventilation. Regarding the fact that prescribed ventilation rates are only an (unperfected) way to achieve a given IAQ, it could be imagined to require IAQ performance indicators instead of ventilation rates. In order to develop such a performance-based approach, we need to address the following topics, these three steps being scientific barriers that we propose to come down in this work.:

1. What are the relevant pollutants and/or parameters to use for calculating performance indicators and what indicators should be used?
2. What are the relevant input data to use regarding the occupancy and pollutant emission scenario?
3. Lastly, what level of detail should we use for modelling airflows and pollutants throughout the house, concerning general modelling assumptions (multizone, weather data ...), the air leakage distributions, the moisture buffering effect?

3.1.2 DEVELOPMENT OF A PERFORMANCE-BASED APPROACH IN THREE STEPS

Because this specific field has been shown as worthwhile for identifying both existing performance-based approaches for ventilation and performance indicators, the “smart ventilation” concept (Durier, Carrié, et Sherman 2018) has been investigated. The analysis of performance-based approaches that both enable and reward smart ventilation used in five countries (France, Belgium, The Netherlands, USA, Spain) reveals emission scenarii, often multizone modelling levels and indicators taken into account (Guyot, Walker, et Sherman 2018). Through a meta-analysis on the performance reported in 38 studies of various residential smart ventilation systems since 1983, (Gaelle Guyot, Walker, et Sherman 2017b) identified a very clearly lack of ventilation performance indicators, because most of them being only CO₂ and humidity based indicators.

From these both reviews, we showed the need of robust performance-based approaches for ventilation, using notably better IAQ performance assessment calculation and better IAQ indicators. Moreover, their applicability to all types of ventilation and not only to smart ventilation is an issue of concern. Consequently, the proposed method should allow to obtain a more robust IAQ assessment, based on several IAQ performance indicators using several indoor pollutants, to avoid such pitfalls.

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3.1.2.a) FIRST: INDOOR AIR QUALITY PERFORMANCE INDICATORS PROPOSITION

In the first step, we propose to use the five IAQ performance indicators identified by (Guyot 2018b) as output data. They are calculated using x , the simulation duration (in hours), and are normalized by their acceptable thresholds, proposed as comparison values for a better analyse of the ventilation performance output results (Poirier et al. 2020a). A ratio higher than one signifies that the ventilation system in the building does not comply with the threshold.

1. $I^n_{CO_2}$: The ratio between the maximum cumulative exceeding CO_2 exposure over 1000 ppm in the bedrooms, and the acceptable threshold = $1000.x$ ppm.h,
2. I^n_{HCHO} : The ratio between the maximum formaldehyde dose received by the occupants and the acceptable threshold = $9.x$ $\mu\text{g.m}^{-3}.\text{h}$,
3. $I^n_{PM_{2.5}}$: The ratio between the maximum $PM_{2.5}$ dose received by the occupants and the acceptable threshold = $10.x$ $\mu\text{g.m}^{-3}.\text{h}$,
4. I^n_{HR70} : The ratio of the maximum of the percentage of time with Relative Humidity (RH) higher than 70% in all rooms for the condensation risk, and the acceptable threshold = $1000/x$ %
5. $I^n_{HR30_70}$: The ratio of the maximum of the percentage of time with RH outside of the range [30%–70%] in the bedrooms for health risk, and the acceptable threshold = $800/x$ %

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3.1.2.b) SECOND: OCCUPANCY SCHEDULES AND ASSOCIATED POLLUTANT EMISSION DATA PROPOSITION

In the second step, we proposed pollutant emission data and occupancy schedules to be used, from an extensive review (Poirier et al. 2020b). In this paper, we give the summary results from this article.

Humidity and CO₂. For the occupancy schedules, we propose to use data from the French national campaign on the IAQ of dwellings from 2005 (Zeghnoun, Dor, et Grégoire 2010), based on a representative sample of the population and included 567 dwellings and 1612 occupants. The results show that people spend on average 67.3% of their time in homes, including 2 h 40 min spent in the kitchen, 2 h 49 min in the living room, 9 h 16 min in bedrooms, and 38 min in bathrooms, which is consistent with the results of other surveys in Europe and the United States.

Based on (Persily 1997) (CEN 2006) and (Pallin, Johansson, et Hagentoft 2011) we propose to use humidity and CO₂ emission rates associated with occupancy schedules, as it is sum up later in Table 3.

PM_{2.5}. Several studies showed that cooking is indoor one of the most PM_{2.5} emitting activity (Abt et al. 2000; He 2004; Ji 2010; Long, Suh, et Koutrakis 2000; Tuckett, Holmes, et Harrison 1998). We propose to use the recent study performed by (O’Leary et al. 2019) in a test chamber protocol with controlled ventilation to measure very precisely the PM_{2.5} emission rate during the whole cooking process (28 min duration). The meals selected in this experiment are based on typical European cooking types. We build three realistic cooking scenarios (for a whole week), based on a combination of three meals from O’Leary’s study (Table 1): the less emissive (meal 1, 0.62 mg.min⁻¹), the medium emissive (meal 3, 1.9mg.min⁻¹) and the higher emissive (meal 4, 3.2 mg.min⁻¹).

SCENARIO PROPOSED	MEAL 1	MEAL 3	MEAL 4	ACCEPTABLE THRESHOLD
<i>Low-emitting cooking practice</i>	1/2	1/2	-	1.26 mg.min ⁻¹
<i>Medium-emitting cooking practice</i>	1/3	1/3	1/3	1.91 mg.min ⁻¹
<i>High-emitting cooking practice</i>	-	1/2	1/2	2.55 mg.min ⁻¹

TABLE 1 : PM_{2.5} EMISSION RATE SCENARIOS (O’LEARY ET AL. 2019), MEALS COMBINAISONS

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Formaldehyde. Formaldehyde emissions can directly be expressed as a quantity per hour for specific activities, products and building materials (Howard-Reed, Polidoro, et Dols 2003; Abadie et Blondeau 2011; Missia et al. 2012). This type of data brings up two types of limit: firstly, it is difficult to extrapolate emission rate behaviours from standard chamber conditions to real-use conditions, notably because of the combined effects of relative humidity and temperature on formaldehyde emissions. Secondly, it is difficult to build a robust scenario extrapolating from the material and activities scale to the dwelling scale, as highlighted in (Boulanger et al. 2012). Emission rates measured directly at the dwelling scale are rarely found in the literature (Chan et al. 2019; Hodgson et al. 2000; Ng et al. 2016; Sherman et Hodgson 2002), most particularly in low-energy dwellings. Consequently, we propose to use a simplified method detailed in (Guyot 2018b), based on the mass balance equation in steady-state conditions to calculate average formaldehyde emission rates, from the measurement campaign described in (Gaëlle Guyot et al. 2017).

This simplified method uses the mass balance equation applied on a house considered as one zone to obtain an average pollutant emission rate.

$$V \cdot \frac{dC}{dt} = C_{out} \cdot Q + g - C(t) \cdot Q$$

EQUATION 1

With $C(t)$ the inside concentration [$\mu\text{g} \cdot \text{m}^{-3}$], C_{out} the outside concentration [$\mu\text{g} \cdot \text{m}^{-3}$], V the volume of the house, Q the total ventilation volume airflow [$\text{m}^3 \cdot \text{h}^{-1}$] and g the emission rate [$\mu\text{g} \cdot \text{h}^{-1}$].

Assuming steady state over the measurement period, since often only the average measured concentration is available because of the use of passive methods, the emission rate can be approached by:

$$g = Q \cdot (C_{average} - C_{out})$$

EQUATION 2

During the campaign of (Guyot et al. 2017) carried out on 10 recent French low-energy houses a measurement of airflow or pressure at each of the air-vents and an IAQ winter campaign. During 7 days, 16 VOC, 8 aldehydes, NO_2 , $\text{PM}_{2.5}$, CO_2 , temperature and relative humidity were measured in the living room and in the main bedroom. The outside concentration of formaldehyde was not measured during this campaign.

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For the house total ventilation airflow calculation, we used, when they are both available, the two used airflows for basic conditions and peak conditions (Q_{basic} and Q_{peak}) weighted by their duration of use (peak airflow used 1 hour a day). In eight houses equipped with a balanced ventilation system (numbered n°1-5;7;9-10 in Table 1), airflows measurements were taken at each supply Air Terminal Device (ATD) and at each exhaust ATD of each house. For the airflow values (Q_{basic} and Q_{peak}), we decided to select the highest value between the total supplied and extracted airflows, as infiltrations would balance both airflows. As a result, we used (Equation 3).

$$\begin{cases} Q = \frac{23}{24} \cdot Q_{basic} + \frac{1}{24} \cdot Q_{peak} \\ Q_{basic} = \max\{Q_{basic,supplied}; Q_{basic,extracted}\} \\ Q_{peak} = \max\{Q_{peak,supplied}; Q_{peak,extracted}\} \end{cases}$$

EQUATION 3

For the two houses equipped with humidity-controlled ventilation (numbered n° 6 and 8 Table 1), pressure measurements were taken at each exhaust ATD of each house. The total airflow was estimated using the average airflow proposed in the corresponding technical agreement, called "Avis technique" (CCFAT 2015). These airflows depend on the used ventilation system and the size of the house, especially the number of dry and humid rooms. This average airflow was then corrected in order to take into account the gap between the in-situ measured pressure difference (P_i) at each of the exhaust ATD and the theoretical minimum pressure of the range (P_{min}). This correction factor (δQ) was calculated according to (Equation 4), using the measured pressures (P_i) at the N exhaust ATD.

$$\delta Q = \left(\frac{\sum_{i=1}^N P_i}{N * P_{min}} \right)^{0.5} - 1$$

EQUATION 4

All tested houses comply with the envelope airtightness requirement in the French EP regulation: the indicator q_{a4} (leakage rate per unit of envelope area at 4Pa [$m^3 \cdot h^{-1} \cdot m^{-2}$]) must be under $0.6 m^3 \cdot h^{-1} \cdot m^{-2}$. We decided to neglect in the total airflow the part due to infiltrations through the building envelope, except the part already used to balance the flow as explained in (Equation 3).

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Formaldehyde concentrations were measured over a week during the winter period, using passive (diffusive) samplers by reaction with 2-4 DNPH, liquid chromatography and UV detection, according to the standard ISO 16000-4 (ISO 2011). Since measures were taken in the living room and the main bedroom, we used also the average of both values. The outside concentration of formaldehyde was not measured during this campaign. In France, the outdoor formaldehyde concentration is commonly very low compared to the indoor one (ANSES 2017). We assumed an outdoor constant value of $2.9 \mu\text{g}\cdot\text{m}^{-3}$, measured in a study on nursery schools in the same region as the IAQ campaign (DRASS Rhône-Alpes 2007).

The retained input data from the campaign for calculation and the calculated formaldehyde emission rates per floor area square meter are given later for each house in Table 2. Based on these measurements, we propose to define three classes of formaldehyde emissions to be used as input data for IAQ modelling, and for ventilation performance-based approaches at the design stage of low-energy houses:

1. The low-emission class: $4.5 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, defined by the minimal calculated value;
2. The medium-emission class: $12.0 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, defined by the median calculated value;
3. The high-emission class: $23.6 \mu\text{g}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, defined by the maximal calculated value.

The sample used here is rather small and the results need further validation. Therefore, we hope this method could be tested and consolidated in future publication and works.

HOUSE	FLOOR AREA [M ²]	VOLUME [M ³]	Q [m ³ .h ⁻¹]	C [μg.m ⁻³]	CONSTANT EMISSION RATE G [μg.h ⁻¹ .m ⁻²]
1	174	452	110.3	22.9	12.7
2	121	302	73.7	31.1	17.2
3	168	437	308.4	9.0	11.3
4	161	419	209.8	10.3	9.7
5	176	456	286.0	17.4	23.6
6	67	174	40.6	17.9	9.1
7	150	375	60.7	24.1	8.6
8	151	378	79.8	35.9	17.4
9	112	314	40.1	15.4	4.5
10	80	209	150.0	11.9	16.8

TABLE 2 : FORMALDEHYDE EMISSION RATES FROM THE (GUYOT ET AL. 2017) CAMPAIGN.

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In summary, Table 3 gives an overview of our propositions of emission rates and scenarios, which could be used in a performance-based approach at the design stage for ventilation (Table 3).

POLLUTANT OR PARAMETER	EMISSION RATES AND ASSOCIATED DURATIONS
CO₂	Awake: 18 L.h ⁻¹ /person Asleep: 15 L.h ⁻¹ /person
Humidity <i>Moisture due to activities :</i> <i>1 shower per person per day</i> <i>3 cooking periods per day</i> <i>1 laundry per person per week</i> <i>5 laundry drying per week (same days):</i>	Awake: 55 g.h ⁻¹ /person Asleep: 40 g.h ⁻¹ /person A total of 6 kg/day : 1440 g.h ⁻¹ , 10 min per shower. 1512 g.h ⁻¹ breakfast, 15 min 2268 g.h ⁻¹ lunch, 30 min 2844 g.h ⁻¹ dinner, 40 min 252 g.h ⁻¹ for 2 h 136.8 g.h ⁻¹ during 11 h.
Formaldehyde	Low-emission class: 4.5 µg.h ⁻¹ .m ⁻² Middle-emission class: 12.0 µg.h ⁻¹ .m ⁻² High-emission class: 23.6 µg.h ⁻¹ .m ⁻²
PM_{2.5}	Low-emission cooking: 1.3 mg.min ⁻¹ . For 28 min for lunch and dinner. Middle-emission cooking: 1.9 mg.min ⁻¹ . For 28 min for lunch and dinner. High-emission cooking: 2.6 mg.min ⁻¹ . For 28 min for lunch and dinner.

TABLE 3 OVERVIEW OF PROPOSED EMISSION RATES FOR A PERFORMANCE-BASED APPROACH

3.1.2.c) THIRD: MULTIZONE-MODELLING ASSUMPTIONS

In the third step, (Guyot et al. 2019) has shown notably that it is essential to use multizone modelling, with detailed airleakage distributions on internal partition and external walls. Based on experimental values measured by (Guyot et al. 2016) on 23 heavy or wooden-structure houses, this previous study showed that we can obtain the same order of magnitude in the size of the path between a door undercut and internal partition wall airleakage. We took also into account moisture buffering effect using the boundary layer diffusion model in CONTAM (Walton et Emmerich 1994). Then simplified particles phenomena where implemented in CONTAM with a default penetration rate equal to 1; a deposition velocity using 0.65 m.h⁻¹ and 9,90 .10⁻⁷ h⁻¹ as indoor particles resuspension rate based on (Thatcher et Layton 1995) measured median values in a 4 residents housing.

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3.1.3 APPLICATION OF THE DEVELOPED METHOD TO A CASE STUDY

3.1.3.a) CASE STUDY

The case study is a low-energy house, a two-storey low-energy brick detached house, as shown on Figure 1. We assume being at the design stage of this house which must comply with a hypothetical regulation, code or label, requiring to calculate the proposed IAQ ventilation performance indicators according to the proposed method.

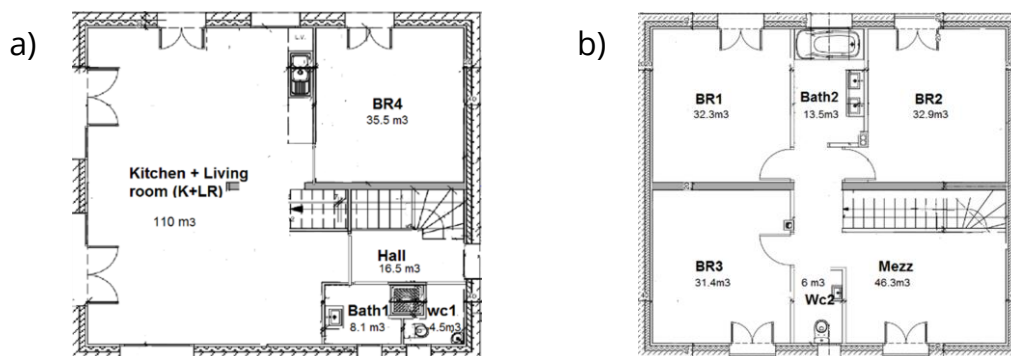


FIGURE 1 : PLAN OF THE HOUSE STUDIED (A) GROUND FLOOR (B) FIRST FLOOR

Airflows, relative humidity, CO₂ and formaldehyde concentrations are investigated using numerical modelling with CONTAM software. Each room is one zone, which accounts for 11 zones. We use a 10-min time step, with dynamic meteorological data of a typical year in Lyon (ASHRAE IWECC Weather file, 2001). The calculation is performed over the heating period, from October 15th 00:00 AM to April 14th 12:00 PM, accounting for 4366 simulated hours. The inside temperature is assumed to be 20°C during this period. The wind at the building is calculated from the weather data using a 0.3287 modifier factor, resulting from a power law used with factors from a suburban area and the house being 8.5 m in elevation. The pressure coefficients from the EN 15242 are used, assuming no barrier, i.e. +0.5 on the upwind facades and -0.7 on the downwind facades.

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3.1.3.b) DOORS AND AIRLEAKAGE DISTRIBUTION

Doors are assumed to be closed and the door undercuts are modelled through a single 1-cm-high crack as required by the French airing regulation, with a 0.65 flow exponent and a 0.6 discharge coefficient at a 10-Pa reference pressure. Airleakage is modelled by one path using the power-law at the centre of each external and internal partition wall of each zone, we use a case with uneven external and internal airleakage distribution, “d4 case” among the seven studied in (Guyot et al. 2019)

3.1.3.c) STUDIED VENTILATION SYSTEMS

We study several options for the ventilation system, which should be a whole house system complying with the French airing regulation (J.O. 1983):

1. An exhaust-only constant airflow ventilation system (EV)
2. A balanced constant airflow ventilation system (Extracted airflows are the same for 1 and 2) (BV)
3. An humidity based demand controlled ventilation (DCV) system, considered as a reference in France.

For our case study, a seven-room house with two bathrooms and two toilets, a constant-airflow ventilation system must provide $30 \text{ m}^3 \cdot \text{h}^{-1}$ in each bathroom, $15 \text{ m}^3 \cdot \text{h}^{-1}$ in each toilet, and $45 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen. A high-speed ventilation must also be able to provide $135 \text{ m}^3 \cdot \text{h}^{-1}$ in the kitchen during peak periods. As a result, the total extract airflow in the whole house is $135 \text{ m}^3 \cdot \text{h}^{-1}$ during basic mode and $225 \text{ m}^3 \cdot \text{h}^{-1}$ during peak mode. The basic mode accounts for an average dwelling air change rate of 0.4 h^{-1} .

The humidity DCV system adjusts the airflows according to the direct relative humidity (RH) measurement, through the extensions and retractions of a hygroscopic fabric modifying the cross-section of inlets and outlets (Jardinier et al. 2018). In our case study, this system includes:

- A kitchen exhaust ATD providing an airflow between 15 and $55 \text{ m}^3 \cdot \text{h}^{-1}$, and a peak airflow of $135 \text{ m}^3 \cdot \text{h}^{-1}$ for 30 minutes if activated by the user,
- Bathrooms exhaust ATD providing an airflow between 5 and $45 \text{ m}^3 \cdot \text{h}^{-1}$,
- Toilets exhaust ATD providing a constant airflow of $5 \text{ m}^3 \cdot \text{h}^{-1}$ which could be switched to $30 \text{ m}^3 \cdot \text{h}^{-1}$ for 20 minutes thanks to an occupancy sensor,
- A trickle ventilator in every bedroom and two in the living room, with an operating rate between $4 \text{ m}^3 \cdot \text{h}^{-1}$ and $31 \text{ m}^3 \cdot \text{h}^{-1}$ (reference pressure of 10 Pa).

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3.1.4 VENTILATION PERFORMANCE ASSESSMENT: RESULTS AND DISCUSSION

For each of the three scenarios (low/medium/high; formaldehyde and PM_{2.5}), defined in Table 1, the Figure 2 shows the performance of the three ventilation systems, assessed according to the five IAQ indicators calculation for this case study.

First, we can observe that none of these three-ventilation systems provides the best IAQ performance results. Indeed, the IAQ performance results from one system to another one are close depending on the indicators, no system is the most performant one for the five indicators. For example, the balanced ventilation system (BV) seems to provide better IAQ in terms of CO₂ (EV 1.17; DCV 1.16; BV **0.72**) and formaldehyde results (low/medium/high EV 0.52/1.06/1.88; DCV 0.53/1.09/1.94; BV **0.43/0.82/1.41**). Logically, the humidity-controlled ventilation system (DCV) provides better IAQ from the humidity-based indicators point of view $I_{RH70}^n/I_{RH30_70}^n$ (EV 0.89/0.58; DCV **0.55/0.51**; BV 0.71/0.85). The exhaust only ventilation system (EV) has almost the same performances than the DCV, except for the I_{RH70}^n where this system is less efficient than DCV. That is confirming the humidity-based ventilation strategy with DCV systems provides a clear benefice on EV, not compromising IAQ.

At last, the three systems responses are close together concerning the $I_{PM2.5}^n$ indicators and none reaches the acceptable thresholds (low/medium/high EV **1.21/1.76/2.31**; DCV 1.30/1.78/2.33; BV 1.24/**1.76/2.29**).

With this performance-based approach, applied to this study case, these 3-ventilation systems provide globally good IAQ performance with RH based indicators, close to the acceptable IAQ threshold with the I_{CO2}^n , but the performances are far from acceptable with the $I_{PM2.5}^n$ and I_{HCHO}^n , except for the low and medium formaldehyde emission scenario. That is reinforces the interest in this method taking into account other IAQ aspects than the traditional CO₂ and Humidity performance indicators, for a better IAQ consideration.

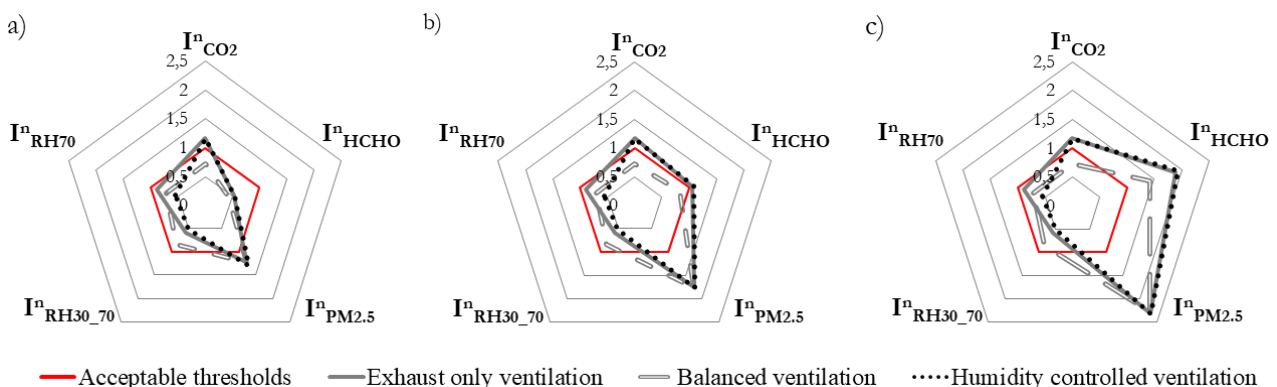


FIGURE 2 : VENTILATION PERFORMANCE, (A) LOW EMISSION SCENARIOS, (B) MEDIUM SCENARIOS, (C) HIGH SCENARIOS

3.1.5 CONCLUSION

We propose a performance-based method in order to assess ventilation performance, from an IAQ point of view, at the design stage of every new residential buildings. Then, we show that this method was applicable, applying it on a case study. This method allows to assess the IAQ performance through a radar scheme based on five relevant IAQ performance indicators, based on CO₂, formaldehyde and PM_{2.5} exposures, and RH-based indicators assessing both condensation and health risks.

This works show that it is possible to include in future regulations or labels performance-based approaches for ventilation at the design stage of buildings. It highlights the need for such methodologies to include multizone models for assessing ventilation and IAQ performance at the room scale, especially in bedrooms, not only at the whole building scale.

The formaldehyde emission scenario propositions of this paper should be considered as a first base in the presented IAQ performance approach, built on an in-situ measurement campaign that could be consolidated in the future by other data. The five indicators give a first evaluation of the ventilation systems performance tested. These results also highlighted the importance of taking into account other air pollutants than CO₂ and Humidity, for a better IAQ assessment, at least formaldehyde and PM_{2.5}. However, it is necessary to reduce the dependence of the indicators on emission rate scenarios by improving their reliability.

The proposed method should now be further investigated with several house geometries, several ventilation systems, including other smart ones, several envelope airleakage levels, etc. Performance indicators could also improved, depending on the countries and already existing methodologies. As a general perspective, to assess ventilation IAQ performance at the design stage, there is also a need for precise emissions for different pollutants: formaldehyde as well as particles, not only at the material scale but also at the room and dwelling scale. For this purpose, we propose in this paper to use a simplified method to calculate constant emission rates in future publication and works.

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3.1 DEVELOPMENT OF PERFORMANCE-BASED ASSESSMENT METHODS FOR CONVENTIONAL AND SMART VENTILATION IN RESIDENTIAL BUILDINGS (A FRENCH CASE STUDY)

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Design of residential ventilation systems using performance-based evaluation of Indoor Air Quality: application to a Danish study case

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Abstract

A Demand-controlled ventilation (DCV) has been recognized as a promising solution for decreasing energy consumption while ensuring good Indoor Air Quality (IAQ) in buildings. However, its application in the residential sector has increased first recently. Implementation of DCV systems brings the problem related to assessing their performance, not only in the view of energy savings but also in the ability to ensure IAQ. The objectives of this paper were to introduce a multicriteria performance-based approach for the evaluation of residential ventilation systems with CONTAM airflows simulations; illustrate its applicability to three DCV strategies in the context of renovated apartment buildings in Denmark and challenge the minimal background airflow requirements anchored in the Danish building code.

Our performance-based approach allows assessing ventilation performance regarding IAQ (CO₂, humidity, PM_{2.5}, and formaldehyde-based indicators), energy consumption, and ventilation heat loss.

Our results show that DCV strategies can improve IAQ while decreasing airflows. For example, application of DCV reduced the cumulative indicator of occupant exposure to formaldehyde, I_{HCHO} by 6 to 28 %, compared to the constant-airflow system. For humidity controlled mechanical exhaust ventilation, the heat loss can be reduced up 51%.

3.2.1 INTRODUCTION

The current pandemic has been highlighting the crucial role of ventilation. At the same time, ventilation impacts building energy consumption through ventilation heat loss and the electricity consumption of fan(s) and other components. Smart ventilation, especially demand-controlled ventilation (DCV) with variable airflows strategies, has been recognized as a promising solution for decreasing energy consumption while ensuring good Indoor Air Quality (IAQ) (Durier, Carrié, and Sherman 2018; G. Guyot, Sherman, and Walker 2018). In a Danish context, a study by Nielsen and Drivholm (2010) showed that 37% reduction of time at low airflow rates can lead to theoretical 35 % fan energy saving thanks to DCV based on CO₂ and humidity at the air handling unit level, without compromising the indoor air quality (IAQ).

Designing such smart ventilation strategies requires an optimisation task calling for a dynamic simulation to achieve the best IAQ with minimum energy demand, i.e. ventilate more where and when the needs are high and ventilate less where and when the needs are low. Even though the smart ventilation seems to represent obvious future solution, currently, there are still challenges to overcome. The two most important are:

1. Building regulations do not always allow decreasing airflows below certain minimum thresholds, for example a minimum background ventilation rate 0.3 l/s.m² in the Danish building code (Zukowska et al. 2020);
2. The requirements are prescriptive, based on constant airflows or constant air change rates, while for strategies with varying airflows a performance-based approach expressing the consequence of the control strategy expressed as suitable IAQ indicators is needed to exploit their potential.

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Some countries worldwide have introduced such performance-based approaches. Their limitation is that the used IAQ indicators are considering only CO₂ and humidity (G. Guyot, Walker, and Sherman 2018; G. Guyot et al. 2019). In this context, we defined the three main objectives of this paper:

1. To demonstrate the potential of smart ventilation strategies for improving IAQ and energy savings.
2. To introduce a performance-based approach using CONTAM airflow simulation to calculate a set of relevant IAQ and energy performance indicators and to illustrate their applicability in a case study, a typical Danish apartment building after renovation.
3. To demonstrate how minimum airflow requirements can be challenged by applying a simulation with reduced minimum airflows.

3.2.2 METHODS

Building renovation project usually represents a good opportunity to install or change the ventilation system to avoid building damages, save energy, and improve the provided IAQ. With a performance-based method, it is possible to compare the performances regarding provided IAQ, ventilation heat loss and energy consumption of several ventilation strategies. We decided to investigate five residential ventilation strategies:

1. mechanical exhaust-only ventilation with constant air volume (**MEV-cav**)
2. mechanical exhaust-only ventilation and humidity control (**MEV-rh**)
3. mechanical balanced ventilation with heat recovery and constant air volume (**MVHR-cav**)
4. mechanical balanced ventilation with heat recovery and humidity control at the apartment level (**MVHR-rh**)
5. mechanical balanced ventilation with heat recovery and CO₂ & humidity control at the room level (**MVHR-rb**).

These strategies will allow for a performance comparison between currently prevailing residential ventilation with constant airflows (reference) and smarter ventilation strategies with variables airflows.

Our performance-based approach allows to quantify the theoretical advantages and disadvantages for the compared ventilation strategies: provided IAQ (based on the calculation of CO₂, humidity, PM_{2.5} and formaldehyde-based indicators), energy consumption of ventilation system, ventilation heat loss. We used CONTAM multi-zone building simulation to calculate selected performance indicators. Simulations considered scenarios for inputs data, including pollutants emission rates (PM_{2.5} from cooking and formaldehyde from building) and occupant's emissions (CO₂ and water vapour).

We decided to demonstrate the potential of such a performance-based approach in a case study. We evaluated suitable airflows for the five mentioned ventilation strategies in two steps. The first step consisted of a performance evaluation of the strategies with the standards required airflows as a reference case (Danish Building Code (0.30 l/(s m²) heated floor area). Then a second step included simulations with reduced minimum airflows for MEV-rh, MVHR-rh, MVHR-rb strategies in the range of [0; 0.3] l/(s m²). We used the corresponding systems with constant airflows a reference system; i.e. MEV-cav was the reference for MEV-rh and MVHR-cav was the reference for MVHR-rh and MVHR-rb.

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3.2.2.a) PERFORMANCE INDICATORS

We evaluated the IAQ performance of the tested ventilation strategies using the previously developed method (Poirier, Guyot, Woloszyn, et al. 2021), which proposes a set of five IAQ performance indicators based on four relevant parameters and corresponding acceptable threshold (AT), with d the total duration of the period simulated:

- **I_{CO2}**: Maximum cumulative CO₂ exposure exceeding the reference value of 1000 ppm in bedrooms; AT = 1000. d (ppm.h)
- **I_{HCHO}**: Maximum occupant formaldehyde cumulative exposure; AT = 9. d ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$)
- **I_{PM2.5}**: Maximum occupant PM_{2.5} cumulative exposure; AT = 10. d ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$)
- **I_{RH30_70}**: Maximum percentage of time spent by the occupants with RH outside a range: [30%–70%] (health risk); AT= 14.4%
- **I_{RH70}**: Maximum percentage of time with RH higher than a threshold of 70% in all rooms (condensation risk); AT = 18% in bathroom, 10.8% in kitchen, 1.8% in other rooms

To complement the five indicators, we proposed two additional short term exposure indicators for PM_{2.5} and formaldehyde:

- **I_{PM2.5_short}** : the maximum occupant exposure on 24 hour average period according to (Cony Renaud Salis et al. 2017; HCSP 2013); AT = 25 $\mu\text{g}\cdot\text{m}^{-3}$
- **I_{HCHO_short}** : the maximum occupant exposure on one hour average period according to (Cony Renaud Salis et al. 2017; HCSP 2019; WHO 2010); AT = 100 $\mu\text{g}\cdot\text{m}^{-3}$

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As the second step focused on reducing the minimum airflow, we proposed in Equation 1 to complement those IAQ indicators with an energy indicator for ventilation systems based on the ventilation heat loss (Abadie et al. 2017):

$$Q_{load} = C_{p_m} \cdot q_m \cdot (1 - \varepsilon_{heat_{ex}}) \cdot (T_{in} - T_{ex})$$

EQUATION 1

With q_m the total exhaust mass airflows in $[kg.s^{-1}]$, C_{pm} the thermal mass capacity of air (we used $1 \text{ kJ}.kg^{-1}.^{\circ}C^{-1}$), $\varepsilon_{heat_{ex}}$ the heat exchanger efficiency (we used 0 for MEV and 0.8 for MVHR as a conservative value), T_{in} the zone temperature where the air is extracted, and T_{ex} the external temperature $[^{\circ}C]$. We assumed balanced airflows across the heat recovery. The capacity reduction due to frost formation was not considered.

Consequently, we performed the calculation of the fan power consumption according to ASHRAE Standard 90.1 (ANSI/ASHRAE/IES s. d.) :

$$P_{fan}(t) = P_{fan} \cdot P_{nom}$$

EQUATION 2

$$P_{nom} = Q_{max} \cdot SFP$$

EQUATION 3

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

EQUATION 4

$$PLR_{fan} = Q(t) / Q_{max}$$

EQUATION 5

With P_{nom} the nominal power of the fan, Q_{max} the maximal design airflow, SFP the specific fan power (supposed equal to $0.935 \text{ [W}.L^{-3}.s^{-1}]$) and $Q(t)$ the current total exhaust (or supply) airflow.

We assumed that the MEV systems used one fan while the MVHR systems used two equal fans for exhaust and supply.

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The MVHR-rb system represented so-called room-based ventilation (Smith and Kolarik 2019). In this system a main air handling unit delivered the airflow into a manifold equipped with three axial fans with continuous control of rotation speed. These fans provided airflow to particular rooms (a living room and bedrooms) based on the demand measured by IAQ sensors. We determined the power of the fans as:

$$P_{fan}(t) = (Q(t) / Q_{nom})^3 \cdot P_{nom}$$

EQUATION 6

With $Q_{nom} = 120 \text{ m}^3 \cdot \text{h}^{-1}$ and $P_{nom} = 18 \text{ W}$.

Finally the proposed total energy consumption indicator I_{EC} [Wh] for ventilation system (equation 7) was an aggregation over the entire simulation period of the instant heat loss from exhausted airflows and the instant fan power.

$$I_{EC} = \sum_{t=0}^d (Q_{load}(t) + P_{fan}(t)) \cdot dt$$

EQUATION 7

To present and compare the performance of the strategies in a radar graph, we normalized each IAQ indicator using its AT.

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3.2.2.b) INPUT SCENARIOS

We used detailed inputs scenarios for pollutant emissions and occupancy schedules, by Poirier, Guyot, Woloszyn, et al. (2021). These scenarios propose occupancy time spent in rooms for exposure calculation associated with bio-effluent emissions (CO₂ and moisture) from the occupants. Based on the occupancy time, we built daily schedules of rooms occupancy adapted for the three occupants (Table 1).

Moisture emission rates with the associated duration represented showering, cooking, and laundry. Then, we applied three scenarios a low, medium, and high level of emissions for the two remaining pollutants. We specified formaldehyde emission per m² of floor area as constant. We used data from in situ campaign, including ten recent French low-energy houses (Gaëlle Guyot et al. 2017; Poirier, Guyot, and Woloszyn 2020). Indeed there is a lack of exploitable data on variable formaldehyde emission rates from materials and furniture (Poirier, Guyot, Geoffroy, et al. 2021). For PM_{2.5}, we considered cooking activities producing most of the emissions. We used three scenarios corresponding to types of cooking ranging from the least emissive, such as boiled meals, to highly emissive dishes, such as grilled beef. We assumed a constant outdoor concentration of CO₂ at 400 ppm; 2.6 µg.m⁻³ for formaldehyde based on average concentration in European cities (Bruinen de Bruin et al. 2008) and 10.6 µg.m⁻³ yearly average concentration for PM_{2.5} in Copenhagen between 2015 and 2020 calculated from weather data measurement (« Annual AQ statistics » s. d.).

ROOM	OCCUPANT 1	OCCUPANT 2	OCCUPANT3	BIO-EFFLUENT	MOISTURE	HCHO	PM _{2.5}
Bedroom	21h00-6h20	21h00-6h20	21h00-6h20	By occupants in rooms based on occupancy schedules CO ₂ awake / asleep: 18 / 15 L.h ⁻¹ H ₂ O awake / asleep: 55 / 40 g.h ⁻¹	Breakfast / lunch / dinner: 1512 / 2268 / 2844 g.h ⁻¹ During 15 / 30 / 40 minutes	In each room 12 µg.h ⁻¹ .m ² (m ² floor area)	Cooking event: 1.91 mg.min ⁻¹ During 28 minutes
Bathroom	6h20-7h00	7h00-7h40	20h20-21h00				
Kitchen	7h00-7h20 12h00-12h40 19h00-20h10	6h20-6h40 12h00-12h40 19h00-20h10	6h20-6h40 12h00-12h40 19h00-20h10				
Livingroom	7h20-8h30 12h40-14h00 20h10-21h00	6h40-7h00 7h40-8h30 12h40-14h00 20h10-21h00	6h40-8h30 12h40-14h00 20h10-20h20				

TABLE 1 : OCCUPANCY SCHEDULES AND POLLUTANTS EMISSIONS SCENARIOS BY ROOM

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3.2.2.c) STUDY CASE PRESENTATION

The study case building for this application is a renovated apartment in a Danish building located in Copenhagen (Figure 1). The buildings of such type are very common in large Danish cities. They belong to a building type 1 (year of construction 1850-1890) according to Danish building typology (Danish Building Practice s. d.). According to Odgaard (Odgaard 2019), 25% of apartments in Danish residential building stock are situated in buildings constructed between 1850 and 1930. We investigated an apartment situated on the first floor. It had a ceiling height 2.6 m and heated floor area of 60.95 m². It had two bedrooms, a living room and separate kitchen. We assumed three occupants, based on the configuration of the dwelling with two persons in the “parent bedroom” (bedroom 1) and one in the second bedroom (bedroom 2).



FIGURE 1 : PLAN OF THE DANISH STUDY CASE APARTMENT

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3.2.2.d) MULTI-ZONE MODEL DESCRIPTION

The proposed simulation work is based only on airflows simulation with CONTAM multi-zone model which is scientifically validated (Dols and Polidoro 2015; Walton and Emmerich 1994). In this model the airflows between the zones are determined by pressure difference calculation. The CONTAM model has been chosen in order to take into account detailed air leakage distributions, several pollutant simulation (CO₂, water vapour/moisture, PM_{2.5}, HCHO in the method, but other can be added) and the possibility of modelling very different ventilation strategies. We used the modelling results such as pollutant concentration levels in zones or occupant exposure to calculate the IAQ performance indicators.

One limit of CONTAM is the absence of a thermal model, this means the temperature inside the zone is considered constant. However, in this performance approach for ventilation performance assessment, the simulation period is only during the heating period from October 15, 00:00 a.m to April 14, 12:00 p.m (Poirier, Guyot, Woloszyn, et al. 2021). The assumption of constant temperature in zones corresponds to a case where the heating demand is ideally covered by the heating system.

We modelled the airflows between zones with a leak having an equivalent leakage area (ELA) at 4 Pa of 0.01 m². (Filis, Kolarik, and Smith 2021). We considered infiltration to be pressure driven and described in CONTAM by a power-law model (Dols and Polidoro 2015)

$$Q = C \cdot (\Delta P)^n$$

EQUATION 8

With C the flow coefficient and n the characteristic exponent of the flow between 0.5 and 1 with here equal to 0.6 as the usual indicate flow exponent for typical infiltration (Dols and Polidoro 2015). We have determined the $C = 0.012 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{Pa}^n$ based on estimated airtightness of the building envelope of 2 L/s.m² (heated floor area) at 50 Pa distributed uniformly on the external surfaces (Smith and Kolarik 2019). We haven't applied any filtration coefficient to the air inlets in this study.

3.2.2.e) VENTILATION STRATEGIES DESCRIPTION

Mechanical ventilation systems used in the present paper represent a variability of solutions available on European market. Their use in practice is often determined by design traditions in particular countries, for example humidity-based exhaust only variable ventilation is widely used in France, while CO₂ based ventilation is used in Belgium. We selected ventilation systems and strategies based on available technical documentation and/or previous research projects (Poirier, Guyot, and Woloszyn 2020; Smith and Kolarik 2019):

Mechanical exhaust-only ventilation with constant air volume (MEV-cav) a mechanical ventilation system composed of air exhaust in the bathroom and kitchen with a one-hour boost during cooking events in the kitchen. This system does not directly conform with current Danish building regulations but can be eventually applied in project where installation of balanced ventilation with heat recovery is not possible due to lack of space or rentability issues.

Balanced mechanical ventilation with heat recovery with constant air volume (MVHR-cav) a system with the air exhaust in the kitchen and bathroom and air supply in bedrooms and living room. We assumed 60% of the total exhaust airflow through the kitchen (with additional 1-hour boosts during cooking events) and the remaining 40% of the exhaust airflow through the bathroom. Supply airflows were distributed proportionally to the floor area in the bedrooms and the living room.

Mechanical humidity-controlled exhaust-only ventilation (MEV-rh) a demand-controlled system with relative humidity (RH) as a controlled variable. The system adjusts the airflows according to the RH measurement, through the extensions and retractions of a hygroscopic fabric modifying the cross-section of inlets and outlets (Jardinier et al. 2018). We considered the air inlet in the bedrooms providing airflow rates between 4 m³.h⁻¹ and 31 m³.h⁻¹ (reference pressure of 10 Pa). The kitchen exhaust provided minimum airflow for RH < 23% and maximum airflow (55 m³/h) for RH > 55%, with a one-hour boost of 135 m³/h during cooking event. The bathroom exhaust provided minimum airflow for RH < 45% and maximum airflow (45 m³/h) for RH > 85% (Aldes 2018).

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Balanced, humidity controlled mechanical ventilation with heat recovery (MVHR-rh) a ventilation system with RH sensor integrated in the exhaust duct of the air handling unit. The system represents a commercially available system frequently installed in renovated apartments. The control is based on a combination of 24-hour running mean RH and the immediate rate of RH change (Nilan, s. d.). According to the control logic, the system works with three levels of airflow/ fan rotation speed (low, nominal, and high) see Figure 2. In the modelling we assumed that the high airflow is triggered for one hour during cooking event as same as the ventilation boost in the other studied systems.

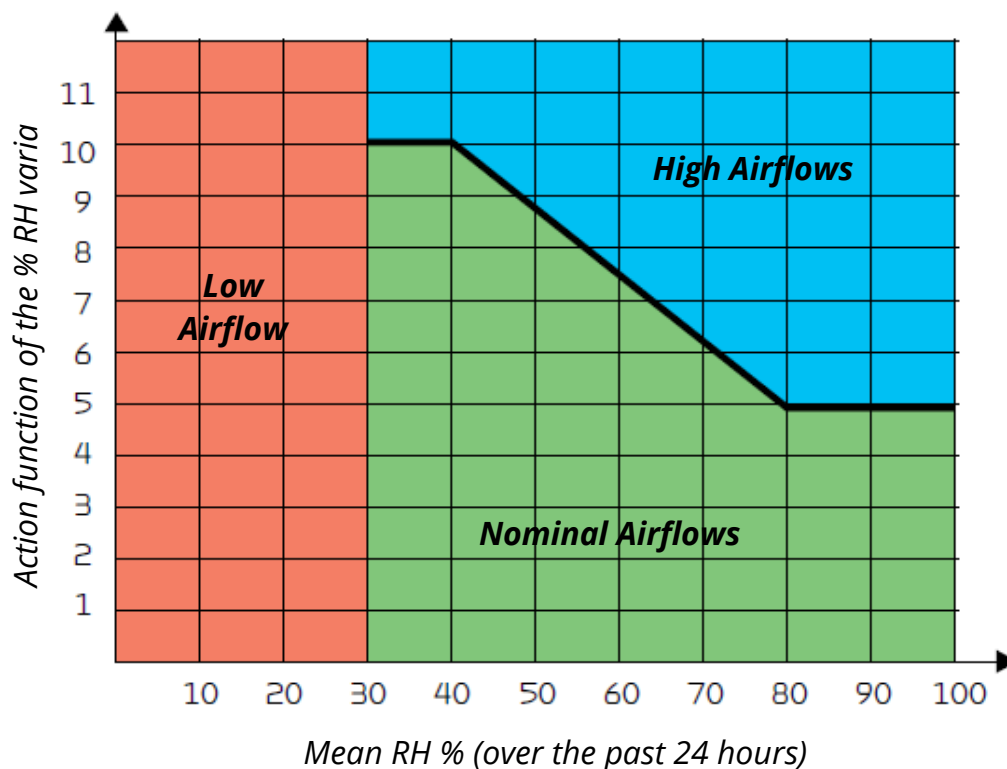


FIGURE 2 : MVHR-RH VENTILATION AIRFLOWS MODES DIAGRAM FUNCTION OF RH% LEVELS (MODIFIED FROM (NILAN, S. D.))

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Balanced mechanical ventilation with heat recovery with room-based control (MVHR-rb) an innovative ventilation system with ability for a separate control of airflow into each room. The room demand is specified by the IAQ sensor placed in the room. The modelled system considered measurements of RH and CO₂. A controller determined the airflow needs based on C_{co2} for bedrooms and the living room. For kitchen, the airflow was determined using C_{co2} and RH. The following setpoints were used:

- for lower limit C_{co2} < 800 ppm (RH < 57% at 21°C) the airflow demand was low
- for upper limit C_{co2} > 900 ppm (RH > 77% at 21°C) the airflow demand was high,
- the demand was proportional between lower and upper limit

When the humidity ratio between outdoor is 0.003kg_{H2O}/kg_{Air} higher than the indoor level, the demand stays low, to avoid additional moisture load from the outdoor air. (Smith and Kolarik 2019). As same as the other systems we assume a one-hour boost during cooking events in the kitchen

Airflows [m ³ /h]	MEV/MVHR-CAV		MEV-RH			MVHR-RH			MVHR-RB	
	Nominal	Max Qboost	Lower limit	Upper limit	Max Qboost	Lower limit	Nominal	Upper limit	Lower limit	Upper limit
Kitchen	39.5	108	49.4	55.0	108	39.5	73.7	108	39.5	108
Bathroom	26.3	26.3	16.5	45.0	45	26.3	49.20	72	26.3	72
Total	65.8	134.3	65.8	100.0	153	65.8	122.9	180	65.8	180
Total [l/s.m ²]	0.3	0.61	0.3	0.46	0.69	0.3	0.56	0.82	0.3	0.82

TABLE 2 : REFERENCE EXHAUST AIRFLOWS FOR SIMULATED SYSTEMS

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3.2.3 RESULTS AND DISCUSSION

To present and analyse the performances of the reference phase and optimisation phase we will focus only on the results of medium scenario for pollutants emissions rates.

3.2.3.a) REFERENCE PHASE

The Figure 3 presents the IAQ indicators determined for the studied ventilation systems. Firstly, the MVHR provide better IAQ when considering the CO₂ and HCHO. At the same time, none of the studied systems achieved good IAQ with respect to the exposure to PM_{2.5}. Regarding the I_{nRH70} indicator (exposure to the relative humidity over 70%), all studied systems yielded acceptable performance. The systems with variable airflows strategies outperformed the ones with the constant volume. On the opposite, no systems succeeded to keep acceptable humidity levels in the range [30%-70%], with however an advantage for the MEV (I_{rh30_70} in range [1.29;1.36]) on the MVHR (I_{rh30_70} in range [1.87;2.19]).

The absence of heat recovery in MEV systems led, as expected, to significantly higher (2 to 4.6 times) energy consumption in comparison to the MVHR systems. The reference ventilation systems with constant airflows had lower energy consumption efficient than systems with variable MEV-cav used 8.5% less compared to MEV-rh. MVHR-cav used up to 51% less than MVHR-rh. The reason for this is the possibility to increase the airflow over the level of constant airflows strategies when needed. But in return for higher energy consumption, system with variable airflows is improved IAQ regarding CO₂, RH >70% and HCHO.

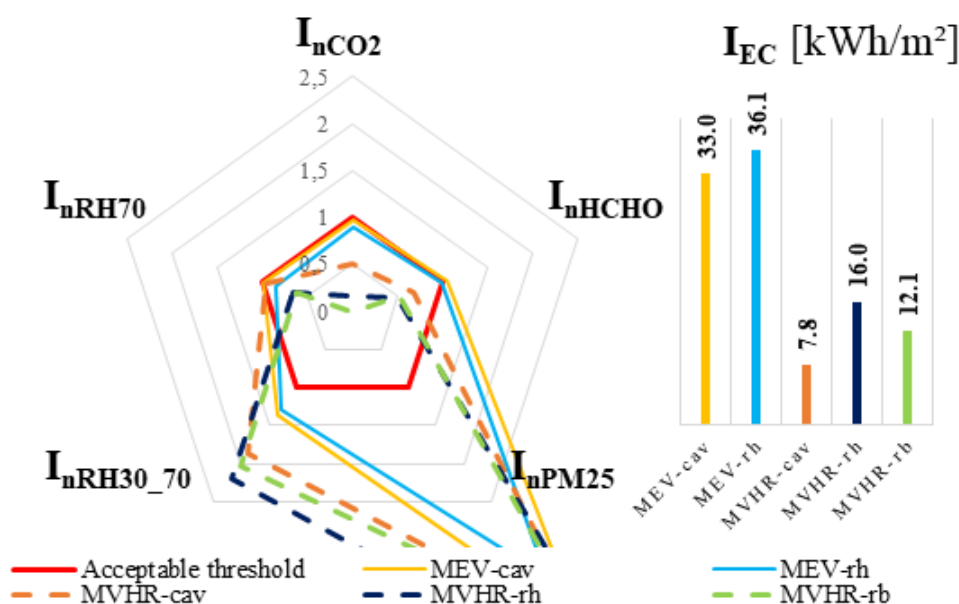


FIGURE 3 : PERFORMANCE RESULTS FOR THE REFERENCE PHASE

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3.2.3.b) REDUCED MINIMUM AIRFLOWS APPLICATION

The Figure 4 visualizes the relation between IAQ indicators and energy performance for investigated ventilation strategies. To complete the IAQ indicator results we also show the minimum airflows in relation to the total energy consumption. This is to highlight the relation between minimal control airflow and energy consumption.

As a general results, none of the tested ventilation strategies provided acceptable IAQ with respect to all indicators used. Especially for the $PM_{2.5}$ indicator, the results regarding short-term $PM_{2.5}$ are exceeded the acceptable threshold (1.69 up to 4.18), this was even more pronounced for long term exposure (3.43 up to 5.05). On the contrary the short-term indicator was close to 0 for formaldehyde. This means that the formaldehyde source used in the study was not posing any short-term exposure risk.

As result for the next analysis in this paper we propose to focus mainly on the I_{CO_2} ; I_{RH70} ; I_{RH30_70} ; I_{HCHO} which are more related to energy consumption than I_{PM25} , I_{PM25_short} , I_{HCHO_short} .

Regarding CO_2 exposure risk, majority of the systems provided the acceptable level. The MVHR-rb, showed the best performance with $I_{CO_2} = 0$ for all the tested minimal airflows, indeed this system was the only one with a control strategy based on CO_2 and moreover the control set point was 900 ppm that is lower than the acceptable threshold of I_{CO_2} (1000 ppm). For the two constant volume ventilation systems and the MEV-rh, lower minimal airflows could increase the CO_2 exposure and in some configurations lead to exposure over the acceptable threshold. This could play a role in the optimisation focused on trade-off between energy saving and increasing CO_2 level.

Almost the same conclusion can be done with the high humidity risk indicator I_{RH70} , all the systems provide acceptable performance. Concerning the performances for humidity levels between 30-70%, MVHR systems were exceeding the AT (between 1.9 and 2.19). Only the MEV-rh succeed to reach acceptable level on I_{RH30_70} even with lower energy consumption thanks to the reduction of the minimal airflows.

Finally the Figure 5, highlight that variable ventilation strategies with a minimal exhaust airflows equal to 0 l/s.m^{-2} can successfully provide IAQ performance equivalent to that obtained with 0.3 l/s.m^{-2} but with lower energy consumption.

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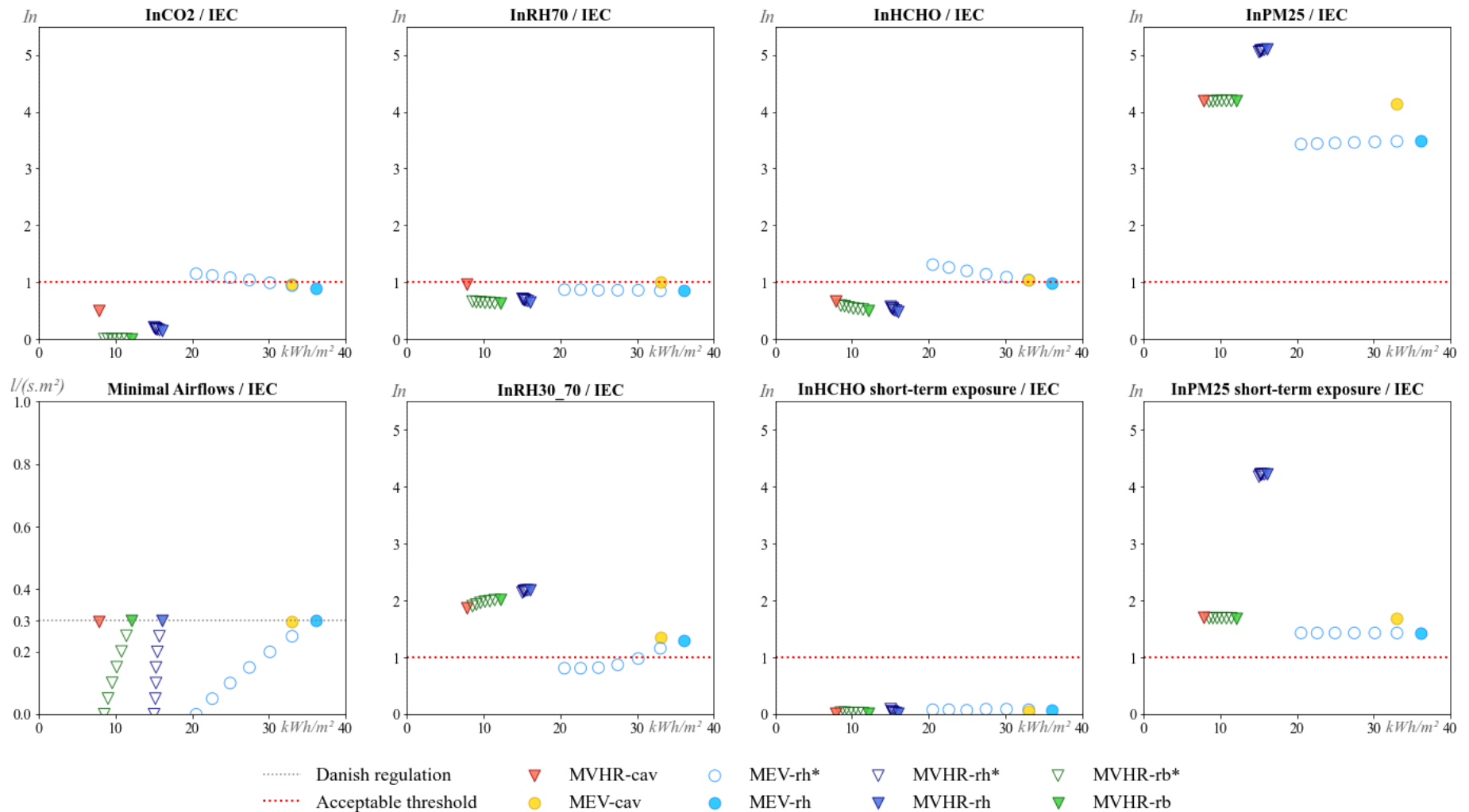


FIGURE 4 : PERFORMANCE RESULTS OF THE OPTIMISATION PHASE BY INDICATOR, *RESULTS WITH MIN EXHAUST AIRFLOWS FROM 0 TO 0.3 L/S.M⁻²

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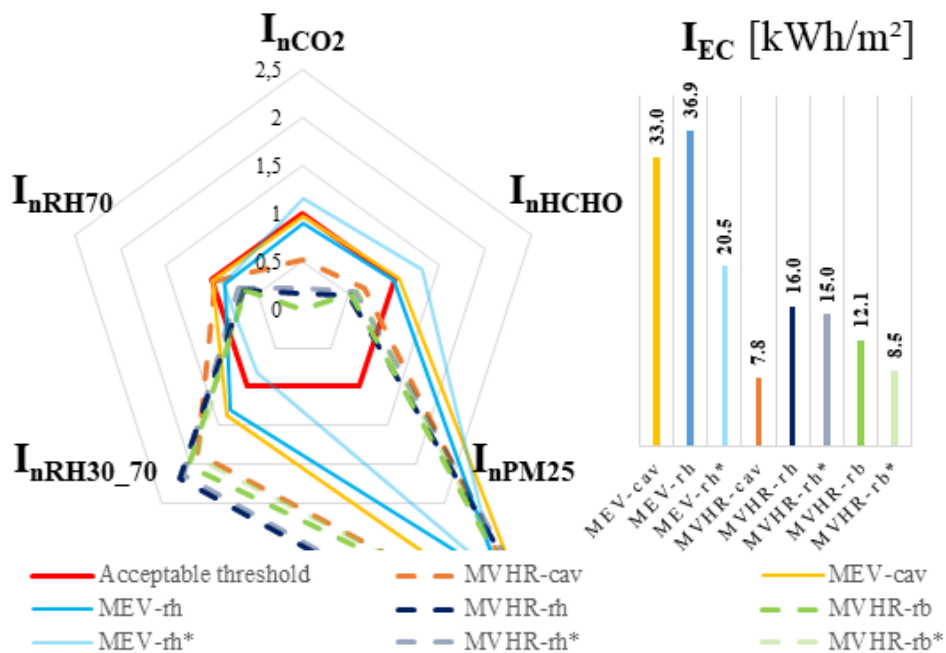


FIGURE 3 : PERFORMANCE COMPARISON BETWEEN, 0.3 L/S.M² REFERENCE EXHAUST AIRFLOWS AND 0 L/SM² AS LOWER AIRFLOWS

3.2.3.c) GENERAL DISCUSSION

In addition to assessing the IAQ and energy performance of the ventilation strategies tested, these results raised some points that could be discussed.

In this configuration, the results of the I_{RH30_70} exceeding the acceptable thresholds, while the performance of the I_{RH70} was achieved by all systems, showed dry air issue in the apartment. In general, with MVHR systems RH is low in modern houses, the heat recovery dries the outdoor air, especially at low outdoor temperatures and there is not enough humidity production to increase the RH. One solution could be heat recovery that recovers also moisture such as rotating heat exchanges which help to elevated the minimum relative humidity in rooms (Smith and Svendsen 2016). Regarding energy use, the lower minimal airflows improved the energy consumption of the MVHR-rb and which is now comparable to that of the MVHR-cav.

In addition to this comparable energy consumption, the MVHR-rb provides better IAQ performance on CO₂, HCHO and high humidity risk than the reference MVHR-cav. Lower airflows also present a significant benefit for MEV-rh with up to 51% energy saving compared to the MEV-cav, but this saving need to be balanced with a small degradation of the IAQ.

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We also paid attention to the results obtained with the I_{PM25} , which are well above the acceptable threshold, and which seem to be independent of ventilation strategies. This questions the emission scenarios used, but even with a low $PM_{2.5}$ emission scenario, the exposure reached over the AT as also pointed out in the description of the proposed performance approach (Poirier, Guyot, Woloszyn, et al. 2021). The high PM_{25} levels could also be explained by the apartment configuration due to the closed kitchen as it is a small volume so the concentration will increase, may be in future experiment a comparison with open kitchen can confirm this assumption.

Moreover, we simulated the exhaust airflow boost provided by the cooking hood, but the placement of the hood was not defined, thus the $PM_{2.5}$ entered the whole zone, which would not be the case in reality. A more precise modelling for the cooking hood would be needed to obtain more realistic $PM_{2.5}$ values on a zone level.

	INCO2	INHCHO	INPM25	INHCHOs	INPM25s	INRH30_70	INRH70	IEC [kWh]	AIRFLOW**
MEV-cav	0.97	1.05	4.14	0.06	1.69	1.36	1	2012	0.3
MEV_rh	0.89	0.99	3.49	0.08	1.43	1.29	0.85	2199	0.3
MEV_rh*	1.15	1.31	3.43	0.08	1.43	0.81	0.87	1251	0
MVHR-cav	0,51	0.68	4.19	0.02	1.7	1.87	0.97	478	0.3
MVHR-rh	0.16	0.49	5.1	0.02	4.22	2.19	0.66	976	0.3
MVHR-rh*	0.21	0.57	5.05	0.09	4.18	2.14	0.71	917	0
MVHR-rb	0	0.51	4.2	0.02	1.69	2.03	0.63	740	0.3
MVHR-rb*	0	0.59	4.18	0.03	1.69	1.9	0.66	521	0

TABLE 4 : NORMALISED INDICATORS PERFORMANCE RESULTS: ** TOTAL MINIMUM EXHAUST AIRFLOWS L/S.M⁻²

3.2.4 CONCLUSION

The results demonstrate the potential of smart ventilation strategies for improving IAQ, while maintaining, in case of MVHR-rb, or even improving energy performance in case of MEV-rh.

With variable airflow strategies of the smart ventilation systems (MEV-rh, MVHR-rh and MVHR-rb) it is possible and relevant to use lower exhaust airflows than the 0.3 l/s.m^{-2} required. Indeed, the provided IAQ with lower airflows down to 0 l/s.m^{-2} were comparable to the reference cases (MEV-cav and MVHR-cav) and even better depending of the strategy used.

Finally, the performance-based approach brings the possibility to directly evaluate consequences of reducing/variating airflows. On an example of the Danish case, we demonstrate that decreasing the ventilation rate does not necessarily mean compromising the IAQ. Thus, the code requirements asking for fixed minimum ventilation rates seems to be unnecessary when smart ventilation strategies are applied.

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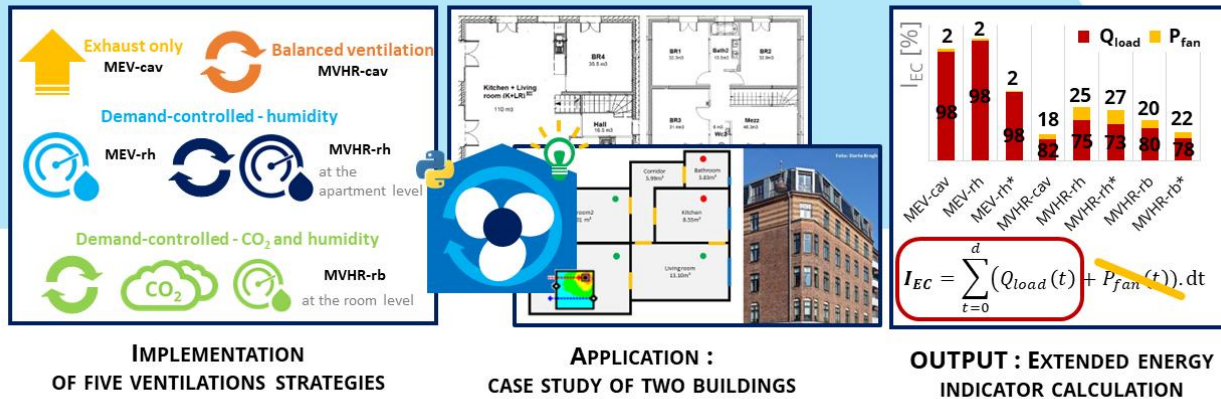
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PART 3



HIGHLIGHTS & LEARNINGS



In this part 3, we demonstrated the applicability of the MOPA in different contexts and for a diversity of ventilations strategies. We modelled two types of dwellings, a low energy detached single-family house and an apartment in a multi-family building. These two case studies provided a framework for the progressive development and implementation of the smart ventilation strategies in CONTAM. Such as a more advanced smart ventilation strategy based on CO₂ and humidity. This part also allowed to confirm the process of implementing the modelled ventilation systems from a previous project (a house) in another modelled building (an apartment). In addition, routines were developed with Python, for the variation of input and the extraction of output results, in order to prepare the implementation of sensitivity analysis tools in Part 4. That highlighted the benefits of the flexibility offered by the CONTAM airflows simulation tools for such research works.

In the two studies, the IAQ performance regarding PM_{2.5} was largely unacceptable. In the apartment case study, we observed worst PM_{2.5} performance indicators (between 3.5 up to 5 depending on the ventilation system for a threshold set at 1) than in the single house (between 1.5 and 2), for the same medium PM_{2.5} emission scenario from cooking. That is explained by the building configuration and modelled volumes. Indeed, in the apartment, the kitchen is closed and smaller in comparison with the house where the kitchen is open on the living room. In addition, for the Danish case study, a more precise modelling of the cooking hood would be needed to obtain more realistic PM_{2.5} values at the kitchen zone level. It could be done by integrating for example a sink model in CONTAM with a pollutant capture and filtering efficiency.

This is less relevant in the French context, where cooking hoods are not required and not encouraged by the thermal regulations for new buildings. This example shows that the need to adapt to the specificities of one country can influence the modelling assumptions in relation to the specificities of another country.

In the Danish case study, we developed and tested the short term exposure risk assessment to $PM_{2.5}$ and formaldehyde, with two short-term indicators $I_{PM_{2.5_short}}$, I_{HCHO_short} . However, the results were not conclusive. Indeed, the short-term $PM_{2.5}$ exposure does not give more information than its long-term equivalent ($I_{PM_{2.5}}$). For the formaldehyde, with the sources used in the study, we did not observe any short-term exposure risk. More specific studies on short-term exposure risk indicators for OPA should be performed on these pollutants or others. For this purpose, we decided to include these two short-term exposure indicators in the uncertainty quantification of the Part 4.

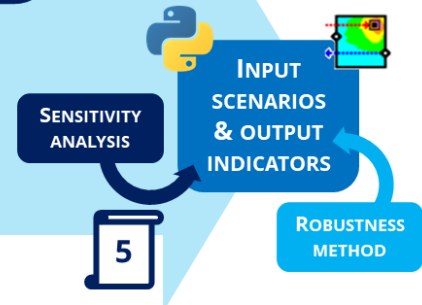
Moreover, the-Danish case study raises an issue of air dryness with the MVHR systems observed through high $I_{RH_{30_70}}$ values (time spent out of the 30-70% range), which were not observed in the French context. Indeed, the two types of outdoor climatic conditions, with different levels of outdoor relative humidity, have a different impact on the time spent by the occupant with an RH below than 30% (Annex III) This results in an increase in the indicator $I_{RH_{30_70}}$. This shows the role of differentiating between high humidity conditions, through the $I_{RH_{70}}$ indicator oriented towards the identification of the risk of moisture development in rooms; and the identification of conditions unfavorable to the health and comfort of occupants, including low humidity conditions, through the indicator $I_{RH_{30_70}}$. This highlights how those two IAQ indicators based on relative humidity are complementary.

Lastly, as part of the work on reducing the minimum exhaust airflows, the energy indicator (I_{EC}) has been extended to include the fan electric consumption (I_{epan}). We proposed in Annex III to detail the repartition between heat losses and fan consumption. In this additional analysis, the fan consumption represents 2% of the total energy calculated in I_{EC} for the MEV ventilation types, while it represents between 18% to 27 % of the total I_{EC} for the MVHR ventilation. This difference between MEV and MVHR ventilation systems can easily be explained because the MVHR has in absolute terms lower heat loss than the MEV thanks to the heat recovery, and an additional fan for air supply. For the MOPA, we propose to keep only the heat-loss part of the indicator I_{EC} . Indeed, we consider it more relevant to focus on the heat loss saving potential of variable (smart) ventilation strategies rather than on the energy consumption of the fan(s). Actually, we can assume that the operation of the fans is indirectly included in the I_{ewh} indicator through the exhausted/supplied airflows for the calculation of heat loss. This is because the instantaneous fan power is proportional to the exhaust/supply airflows. Thus, this part has also a reduced the number of indicator used for the MOPA.

All these issues raised and improvements in the application of these two case studies will then be pursued in the Part 4 with the uncertainty analysis and the robustness method for ranking the performance of the ventilation systems.

PART 4

A ROBUST METHOD WITH QUANTIFIED UNCERTAINTY



This last part of the manuscript mobilizes, in two sections, all the learnings from the previous parts with the application of the MOPA on five ventilation strategies for the same case study. Method reliability is checked by evaluating its sensitivity to the selected input parameters, the uncertainty on the final performance indicators and the verification of MOPA's robustness.

In the first section, the sensitivity analysis and uncertainty quantification of the method are developed in an article in submission process. Sensitivity analysis based on variance assessment was identified as a relevant method to evaluate influence of the variability of several input parameters on the output. With this sensitivity analysis, the aim is to quantify the impacts of the proposed occupancy and pollutants emission scenarios as input on the assessed performance with the OPA indicators as output. Moreover, some buildings modeling hypothesis were also included in the sensitivity analysis such as: the $PM_{2.5}$ resuspension and deposition coefficients; the film mass transfer (h) and the partition coefficient of the moisture buffering effect model; and the air leakage level through the building envelope. In addition, the uncertainty of the results was quantified.

In the second section, we propose an additional work on the robustness of the method. This is based on the performance results of the five ventilation systems simulated for the sensitivity analysis. For this purpose, the selected performance indicators were aggregated into a single indicator value calculated with a multicriteria aggregation method. This aggregated value is then used to rank the performance of the tested ventilation strategies and provide a robust criterion to assist in design decision making.

4.1 UNCERTAINTY QUANTIFICATION: FOR AN IAQ AND ENERGY PERFORMANCE ASSESSMENT METHOD FOR SMART VENTILATION STRATEGIES

Baptiste Poirier, Gaëlle Guyot, Monika Woloszyn

Abstract:

In new low energy buildings or old buildings after thermal refurbishment, the energy performance is improved thanks to the reduction of thermal losses and the decrease of the air leakage level of the envelope. But this high thermal performance of the envelope could have an impact on air renewal of the building and could decrease the indoor air quality of the building. In this context smart-ventilation systems with variable airflows could play a role in providing better IAQ and, at the same time, increasing the energy performance of the building.

However, some of these smart-ventilation strategies are quite recent, and their benefits need clearly to be quantified through performance assessment methods. Such methods at the design stage are still under development. In this article, we propose to quantify the uncertainty of a new performance assessment method, based on CONTAM modelling (Poirier et al., 2021b), using RBD-FAST sensitivity analysis. Indeed, the pollutant emissions scenarios (here moisture, formaldehyde and particle matter PM_{2.5} emissions), model input parameters and ventilation strategies could have an impact on the assessed performance; these variations need to be quantified.

For this sensitivity analysis, five ventilation systems were studied (2 with constant airflow, 1 humidity-based and 2 humidity/CO₂ based) on a low energy house located in France. 2500 simulations were performed to calculate 504 sensitivity indices (108 per ventilation strategy) across the 12 input variables and the 9 output performance indicators. The sensitivity indices analysis shows that occupant bio-effluent (CO₂-H₂O), formaldehyde and PM_{2.5} emissions rates are responsible for 11% to 87% of the uncertainty for the IAQ performance indicators. The PM_{2.5} deposition velocity parameter is responsible of 50% of the uncertainty on the PM_{2.5} indicator ($I_{nPM2.5}$), which was an unknown impact until now. In addition, this sensitivity analysis gives an extended demonstration of the potential of this method for ventilation performance assessment. Indeed, it highlights the benefits of humidity-based control (MEV-rh) ventilation regarding energy performance indicators, with heat-losses 20% less in average than the ones obtained with constant airflows ventilation (MEV-cav). Moreover, some smart-ventilation (MEV/MVHR-rb) strategy provides clear IAQ benefits without drastically increasing the energy demand.

4.1.1 INTRODUCTION

Indoor environments, where people spend from 60% up to 90% of their time (offices, school, homes etc.), have in general lower indoor air quality (IAQ) than the outdoor air. In buildings, after first reducing the sources of pollutants, ventilation systems could help to reduce pollution by air renewal and eventually reach a good IAQ level. On the other hand, ventilation systems are also a source of thermal loss from air renewal, in some cases accounting for a significant percentage of the total building energy consumption. With the emergence of smart-ventilation systems with variable airflow strategies there is a need for a robust method to evaluate their performance regarding IAQ and energy. Evaluating ventilation performance is essential to understand the benefits of these variable airflow strategies, which today are primarily based on indoor pollutant levels, or any possible future strategies based on other parameters, in comparison to historical constant airflow strategies.

A performance-based method in development gives a first overview of the possibility for IAQ performance assessment for different ventilation systems and strategies such as exhaust-only ventilation, balanced ventilation, and humidity demand-controlled ventilation (Poirier et al., 2021b). This method proposes five IAQ performance indicators (CO₂, PM_{2.5}, HCHO, Humidity health and condensation risk) calculated with the CONTAM building airflow model and input scenarios defined in (Poirier et al., 2021a) (occupant activities, pollutant scenarios, emissions). One result of this study showed that IAQ assessment depends upon the scenarios used (low, medium, or high emissions) and the selected indicator. Moreover, a study on air leakage modelling using some of these IAQ indicators showed the significant impact of a detailed envelope air leakage description on the CO₂, HCHO, and humidity indicators (Guyot et al., 2019), with a difference between even air leakage distribution and uneven distribution on the humidity indicator up to 29% for exhaust-only ventilation and down to -10% for balanced ventilation. This suggests that investigating several levels of envelope air leakage could also have an impact on performance results.

PART 4 : A ROBUST METHOD WITH QUANTIFIED UNCERTAINTY

4.1 UNCERTAINTY QUANTIFICATION: FOR AN IAQ AND ENERGY PERFORMANCE ASSESSMENT

METHOD FOR SMART VENTILATION STRATEGIES

As a consequence, the performance results of ventilation systems obtained with an assessment method may fluctuate depending on the inputs used and these fluctuations need to be characterised. This quantification of the uncertainty relations between inputs and outputs can be associated with the concept of sensitivity analysis (SA) methods which allow, among other things, the measurement of uncertainty. In the literature, several studies on building performance evaluation have applied sensitivity analysis methods to test the impact of inputs on outputs, such as the following non-exhaustive examples: architecture type, air permeability, PM_{2.5} deposition rate; emission rate; weather condition impacts on PM_{2.5} exposure, ventilation rate and heat loss (Molina et al., 2021); mass flow rate of domestic hot water, air change rate (ACH)

and occupancy schedule impacts on the solar thermal system production fraction for hot water production (Burhenne et al., 2022); the blind position of shading devices controlled by the occupants, window ratio, thermal load from electrical equipment impacts on thermal resistance and resilience against thermal stresses in low energy housing (Gondian et al., 2019). This illustrates the diversity of possible parameters examined using sensitivity analysis which are confirmed in a literature review study on sensitivity analysis methods in building energy analysis (Tian, 2013a) and the large potential of the SA methods for performance assessment with building simulation (Goffart and Woloszyn, 2021). These studies highlighted also the importance of the choice of inputs and outputs in order to properly address the desired outcomes of the methods.

In this context and based on previous studies (Poirier et al., 2022a, 2022b, 2021a), we have identified several groups of inputs as potentially influencing the proposed ventilation performance assessment method. Firstly, several inputs related to emissions scenarios, such as Bio-effluent emissions from occupants (H₂O, PM_{2.5}); emission rates from activities and furniture (H₂O, PM_{2.5}, HCHO); model parameters for PM_{2.5} and hygroscopic buffer effect should be investigated. Then the air leakage level of building envelope as well as the ventilation rates and strategy should also be assessed. The main objective of this article is to investigate and quantify the impact of input variability on the outputs (performance indicators) by performing a sensitivity analysis.

The first part of the study presents the methodology used for the sensitivity analysis, and the case study. The second part details the model inputs and tested outputs. The results are then presented with a discussion in the third part, followed by conclusion and perspectives.

4.1.2 METHODOLOGY

4.1.2.a) RBD-FAST AS A SENSITIVITY ANALYSIS TOOL

According to the detailed review by Tian (Tian, 2013b) on sensitivity analysis for building energy analysis, several methods exist and some are more relevant for building simulations. These range from local methods focusing on the sensitivity of inputs around a point with a low computational cost advantage, to global methods investigating the whole input space with a high computational cost such as Monte Carlo methods. Local methods changing one factor at a time in a reduced input space are not appropriate for the desired investigation of the sensitivity of the ventilation performance assessment method being tested. This is because the desired sensitivity analysis needs to be applicable to an extended input space among the pollutant emission scenarios, envelope permeability, ventilation strategies and modelling hypothesis. For this reason, we opted for a global method. There are several of these in existence such as the mainly-used Morris screening method which gives qualitative ranking of the most influential inputs on the selected output, or variance-based methods such as ANalysis Of Variance (ANOVA) approach computing the Sobol first order sensitivity index or ANOVA-FAST which give the variance of all the inputs on the output (Mechri et al., 2010; Tian, 2013b).

But a more recent method, EASI RBD-FAST (Goffart et al., 2015; Plischke, 2010) adapted from a combination of random balance design (RBD) (Tarantola et al., 2006) and Fourier amplitude sensitivity (FAST) (Saltelli and Bolado, 1998; Mara, 2009) seemed well suited to our objectives. Goffart's (Goffart and Woloszyn, 2021) work on sensitivity analysis demonstrated that the RBD-FAST method was more appropriate for building simulation and performance evaluation than the Morris method. The EASI RBD-FAST method is applicable independently of the model and its complexity, giving more information than the Morris screening method, such as quantified sensitivity indices, and uncertainty analysis over the inputs and outputs. It also has a lower computational cost than conventional variance based-methods and can easily be used for building simulations using SALib, a python sensitivity analysis toolbox (Herman and Usher, 2017; Iwanaga et al., 2022).

Based on the key steps for sensitivity analysis in building performance analysis presented in (Tian, 2013b), we designed the methodology presented in Figure 1. The inputs were first defined according to the objectives of the sensitivity analysis. Here, a total of 5 ventilation systems were modelled, 12 inputs being chosen with their associated variation range and classified by category dealing with:

- Occupancy pollutant emissions,
- Activity and furniture pollutant emissions
- CONTAM model parameters
- Ventilation systems and strategies

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The whole process was then automated with Python scripts for sampling, running the simulations and output data saving. The inputs were sampled before the simulations using Latin Hypercube Sampling (LHS) methods (Helton and Davis, 2003) following the sampling method recommended in the EASI RBD-FAST sensitivity analysis method (Goffart et al., 2015; Goffart and Woloszyn, 2021). This sampling was carried out with a Python function implemented in the SALib library.

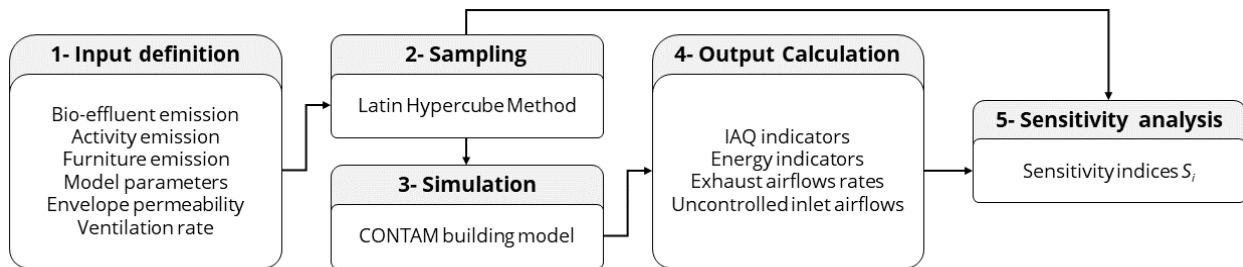


FIGURE 1: KEY STEPS FOR THE SENSITIVITY ANALYSIS

CONTAM airflow building model of a single family dwelling from previous studies (Poirier et al., 2022a, 2021b) was used for five tested ventilation systems detailed below in the section on ventilation system and strategy inputs. The simulation consisted of 500 CONTAM simulations per ventilation system giving a total of 2500 simulations. The simulations were performed over the heating period from October 15, 00:00 a.m., to April 14, 12.00 p.m., or 4466 hours, with 10min time steps according to the heating period defined in the ventilation performance assessment method (Poirier et al., 2022a). By using CONTAM, which has reasonable calculation costs, the simulation time was around 36h for the 2500 simulations, calculated with an Intel Core i5-7200U CPU @ 2.50GHz, 2712MHz, 2 core and 8 Go RAM.

The outputs selected for the sensitivity analysis were the 5 IAQ performance indicators of the ventilation performance assessment method, completed with a heat loss energy indicator. In addition, other aggregated results from the simulations (min, max, median) were included in order to understand other physical aspects such as: the air change rate, the total exhaust airflow and uncontrolled air leaks due to envelope air tightness defects.

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The number of 500 simulations per ventilation system was validated after convergence verification to be sure that enough iterations were performed to calculate the sensitivity indices. The convergence was verified on all the tested outputs with the cumulated mean and variance calculations over the 500 simulations. In the EASI RBD-FAST method used, the sensitivity indices (Equation 1) were the first-order indices from the popular Sobol method based on the variance decomposition of the model's output. (See (Tarantola et al., 2006; Plischke, 2010; Tissot and Prieur, 2012; Goffart et al., 2015) for more details).

$$S_i = \frac{V[E[Y|X_i]]}{V[Y]}$$

EQUATION 1

with X_i the input random variable sampled with the LHS method for $i = (1, \dots, k)$ the number of inputs; $Y = f(X_1, \dots, X_k)$ output of the model; S_i the first-order sensitivity indices of input i ; $E[Y|X_i]$ the conditional expectation of Y given X_i , and $V[-]$ the variance of a random variable (Plischke, 2010). The indices are between 0 and 1 and are the measure of sensitivity computed by the EASI RBD-FAST method. A high index indicates a strong relationship between the variation of X_i and the variation of the output Y . The total sum of S_i should be close to 1 and if it is significantly less than 1, this implies interactions between parameters (Goffart and Woloszyn, 2021).

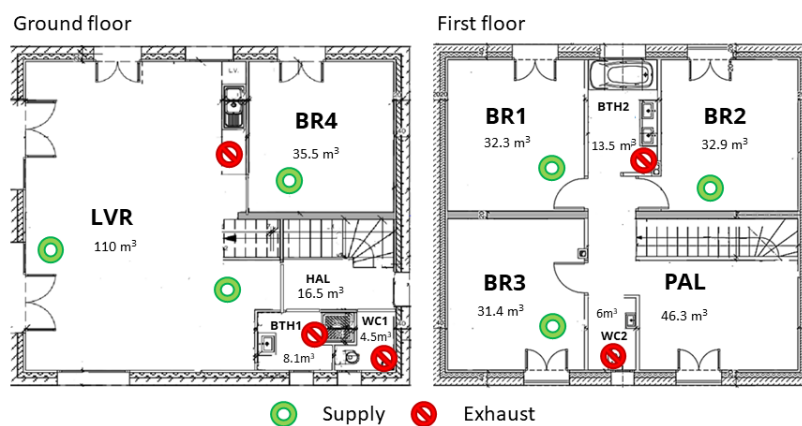
Finally, the S_i indices were calculated for all the tested outputs, to identify which outputs present the greatest uncertainty regarding the input's variations.

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4.1.2.b) CASE STUDY

The case study, shown in Figure 2, is a low-energy, two-storey house equipped with a mechanical ventilation with heat recovery (MVHR) system with constant airflows. The total occupied surface of the building is 135 m², with a ceiling height of 2.50 m. The house has 4 bedrooms (BR1, BR2, BR3, BR4), one bathroom per floor (BTH1, BTH2) and a kitchen open on the living-room (LVR/KTC).



**FIGURE 2 : PLAN OF THE CASE STUDY HOUSE;
SUPPLY AND EXHAUST LOCATION FOR MVHR; EXHAUST LOCATION ONLY FOR MEV**

According to the ventilation performance assessment method tested, the occupation of the house was taken to be 5 persons (one per bedroom and two in the parents' bedroom, here BR1). The associated schedules from (Poirier et al., 2021a) for occupancy with daily time spent by the occupants in rooms were used, with, for example, 2h10 in the kitchen, 9h20 in the bedroom, and occupancy state awake 14h40 per day. As mentioned earlier in the method, the building airflow model used was CONTAM, a multi-zone modelling software developed by the National Institute of Standards and Technology (NIST). It is used in a wide range of applications in the field of aerodynamics, such as IAQ analysis, ventilation flow management and smoke propagation, and has been widely validated (Walton and Emmerich, 1994).

The house is located in the peri-urban area of Chambéry, France and the weather data files used were for a typical year in Lyon, France (ASHRAE IWEC Weather file, 2001) the closest location available for this type of weather data file. We assumed a constant outdoor background concentration for formaldehyde and PM_{2.5}. For formaldehyde a constant value of 2.9 µg.m⁻³ based on measurements in a study on nursery schools in the same region as the house (DRASS Rhône-Alpes, 2007) was used. For PM_{2.5} we used a constant background level based on European weather measurement data between 2015 and 2020. In the Chambéry urban area using the closest available measured data the average PM_{2.5} concentration is 11.79 µg.m⁻³ and the median PM_{2.5} concentration is 9.40 µg.m⁻³. As a result, we used the median value of 9.4 µg.m⁻³ which is lower than the average and which could correspond to a conservative assumption in which a peri-urban area has a slightly lower concentrations of PM_{2.5} than an urban area.

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4.1.3 INPUT DEFINITION

4.1.3.a) BIO-EFFLUENT EMISSION RATES

The considered bio-effluents are CO₂ and H₂O, they are released into the room where the occupant is located. During the day an occupant may be awake or asleep, generating, according to the reference emission, the following values: 18 L.h⁻¹ when awake (15L .h⁻¹ when asleep) for CO₂ emission rates and 55 g.h⁻¹ / 40 g.h⁻¹ for H₂O emission rates. The current hypothesis assumes that all the occupants emit at the same level.

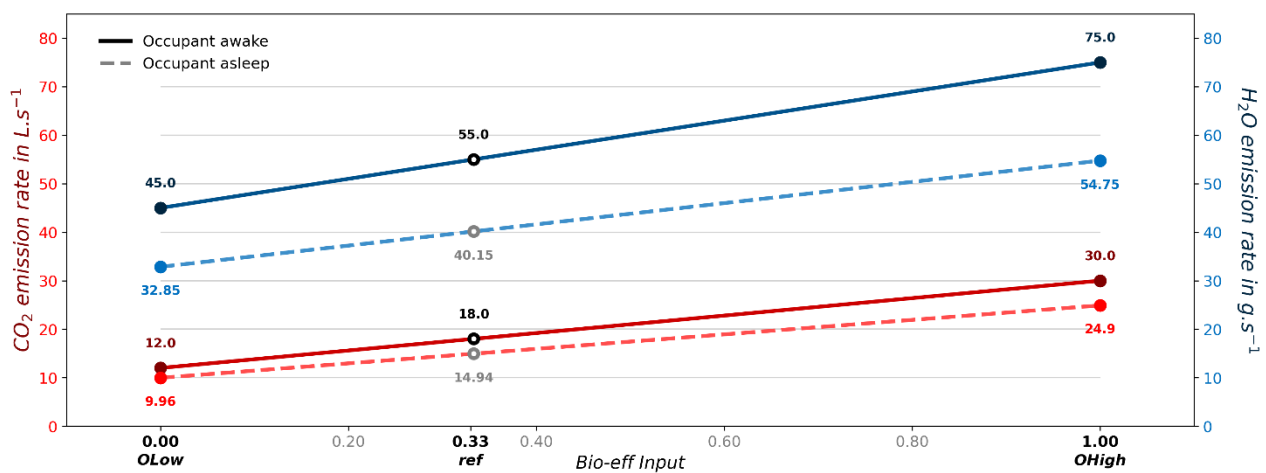


FIGURE 3 : OCCUPANT BIO-EFFLUENT PROFILES FROM LOW TO HIGH EMISSIVE; DEPENDING ON BIO-EFF INPUT

In order to assess the related uncertainty, we have firstly created two extreme occupant profiles: a low-emission occupant (OLow) and a high-emission occupant (OHigh). In the literature review used to build the occupant scenario the lowest values for awake H₂O emissions were 30 g.h⁻¹ (< 2 years) and 45 g.h⁻¹ (10-13 years) with 8 L.h⁻¹ and 12 L.h⁻¹ CO₂ emission rates respectively (Bienfait et al., 1992). The value of 45 g.h⁻¹ (12 L.h⁻¹) seems more representative for an adult as a OLow. The highest awake H₂O emission rate is then 70+ 5 g.h⁻¹ without the associated CO₂ emission rate according to (Bienfait et al., 1992).

This value of 75 g.h⁻¹ is kept as higher range (OHigh) with the hypothesis of a 30 L.h⁻¹ CO₂ emission rate calculated by linear extrapolation of the guidelines (Bienfait et al., 1992). To simplify the occupant profile and limit the number of variables for the sensitivity analysis we assume that CO₂ emission and H₂O are linearly correlated as shown in Figure 3. The ratio between the awake state and the asleep state is kept constant.

The resulting input is a float variable named **Bio-eff** varying within the range of 0 (for a low emission occupant) to 1 (for a high emission occupant).

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4.1.3.b) ACTIVITY AND FURNITURE EMISSION RATES

In the activity and furniture rates we include emissions of H₂O (cooking, shower, laundry, laundry drying), PM_{2.5} from the occupants' activity (cooking) and HCHO from furniture. These emissions are described in CONTAM by the constant coefficient Model (Equation 2):

$$E_{\alpha}(t) = G - Rm \cdot C_{\alpha}(t)$$

EQUATION 2

This models over time t a constant pollutant α source emission $E_{\alpha}(t)$ [kg_{α}/s], a function of the generation rate G [kg_{α}/s], the removal rate Rm [kg_{air}/s] and the pollutant α concentration in zone $C_{\alpha}(t)$ [kg_{α}/kg_{air}]. In the emission sources modelled we used a removal rate equal to 0 because we model the sink effect for PM_{2.5} and the buffering effect for H₂O as described below.

Input		Low			Ref			High
Acti-H ₂ O		0,7	0,8	0,9	1	1,1	1,2	1,3
H ₂ O g.h ⁻¹	Shower	1008	1152	1296	1440	1584	1728	1872
	Laundry	176.4	201.6	226.8	252	277.2	302.4	327.6
	Laundry dry	95.76	109.44	123.12	136.8	150.48	164.16	177.84
	Cooking breakfast	1058.4	1209.6	1360.8	1512	1663.2	1814.4	1965.6
	Cooking lunch	1587.6	1814.4	2041.2	2268	2494.8	2721.6	2948.4
	Cooking diner	1990.8	2275.2	2559.6	2844	3128.4	3412.8	3697.2

TABLE 1 : H₂O EMISSION RATES BY ACTIVITY; DEPENDING ON ACTI-H₂O INPUT

Activity and furniture emission rates variability range was defined based on literature and reasonable assumptions.

For H₂O, the emissions rates of all activities are assumed to be correlated and to vary from -30% to + 30% of the reference scenario. Consequently, the resulting input for the H₂O activity is a float variable named **Acti-H₂O**, varying in the range 0.70 (for -30%) to 1.30 (for +30%)

For PM_{2.5}, the emission rates from cooking activity will vary from the low-emission scenario (1.26 mg.min⁻¹) to the high-emission scenario (2.55 mg.min⁻¹) (Poirier et al., 2021a). We assume that cooking H₂O emissions are not correlated with PM_{2.5} emissions because the cooking H₂O value used in the reference scenario considers the whole process of meal preparation including dish washing and not only cooking food. Here, the resulting input for the PM_{2.5} activity is a float variable named **Acti-PM2.5** varying in the range 1.26 to 2.55 and referring to the PM_{2.5} emission rate due to cooking activities.

For HCHO, the emission rates per m² of floor area will vary from the lowest scenario of 4.5 mg.h⁻¹.m² to the highest scenario 23.6 mg.h⁻¹.m² (Poirier et al., 2022a, 2021a). Again, a float variable is introduced. It is named **Furn-HCHO**, and varies in the range 4.5 to 23.6, referring to the furniture emission rate.

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4.1.3.c) CONTAM MODEL PARAMETERS

HYGROSCOPIC BUFFER

Materials in buildings may have an influence on the humidity in air zones depending on the composition of walls, furniture, floor, etc. This is because materials can absorb and release moisture over time that corresponds to the hygroscopic buffer effect. In our model, the hygroscopic buffer effect is described with the boundary layer diffusion model in CONTAM as a source/sink element.

$$S_{\alpha}(t) = h \cdot d \cdot A_s [C_{\alpha}(t) - C_s(t)/k]$$

EQUATION 3

with h the film mass transfer coefficient over the sink [$\text{m}\cdot\text{s}^{-1}$], d the film density of air [$\text{kg}_{\text{air}}/\text{m}^3$], A_s the surface area of the adsorbent [m^2], C_{α} the vapor concentration in air [$\text{kg}_{\alpha}/\text{kg}_{\text{air}}$] C_s the concentration in the adsorbent, k the Henry adsorption constant or the partition coefficient [$\text{kg}_{\text{air}}/\text{kg}_{\text{surface}}$]. A previous calibration study (Guyot, 2018) determined the parameters to fit the CONTAM model (Axley, 1988, 1987) with the reference buffering model of Duforestel based on experimental measurements (Duforestel and Dalicieux, 1994). This work determined by numerical identification the following parameters in Table 2 for two types of room:

Parameters	Low-adsorbing room	High-adsorbing room
Film mass transfer (h)	0.0066 $\text{m}\cdot\text{s}^{-1}$	0.0051 $\text{m}\cdot\text{s}^{-1}$
Henry adsorption coefficient of the partition coefficient (k)	300 $\text{kg}\cdot\text{kg}^{-1}$	331.6 $\text{kg}\cdot\text{kg}^{-1}$
Surface mass (A)	2.4% of the room volume	12.3% of the room volume

TABLE 2 : PARAMETERS FOR THE BUFFERING MODEL IN CONTAM PROPOSED BY (GUYOT, 2018).

In order to test the impact of moisture buffering variability, intermediate values of k and h coefficients were implemented for the sensitivity analysis, From a low-adsorbing room to a high-adsorbing room the h film mass transfer parameter decreases from 0.0066 to 0.0051, whereas the k partition coefficient increases from 300 to 331.6.

We assumed a linear relation between the low and high parameters described in Equation 4 Equation 5 to calculate the h and k values as a function of an input value **Mbuff** as a float variable varying in the range 0 and 1, where $M_{\text{buff}} = 0$ corresponds to the reference low-adsorbing room and $M_{\text{buff}} = 1$ corresponds to the reference high adsorbing room described in Equation 4-5.

$$h = 0.0066 + M_{\text{buff}} \cdot (0.0051 - 0.0066)$$

EQUATION 4

$$k = 300 + M_{\text{buff}} \cdot (331.6 - 300)$$

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As in the base model the two types of room are used (high-absorption for bedrooms and living rooms, low-absorption otherwise), one Mbuff value for each room type is needed. Accordingly two inputs are used: **Mbuff-L** (for Model buffer in Low adsorbing rooms) and **Mbuff-H** (for Model buffer in High absorbing rooms), float variables varying respectively from 0 to 0.25 and 0.75 to 1.

PM_{2.5} DEPOSITION AND RESUSPENSION

To complement the source emission modelling of PM_{2.5} as described above in Equation 2 the phenomena of deposition and resuspension are implemented. This model is divided into two parts: first, deposition which models contaminant removals from the zone air by deposition onto a surface (Equation 6); and a second part which models a source emission via resuspension from the surface (Equation 7) (Dols and Polidoro, 2015).

$$D_{\alpha}(t) = v_d \cdot A_d \cdot \rho_{air}(t) \cdot C_{\alpha}(t)$$

EQUATION 6

$$R_{\alpha}(t) = r \cdot A_r \cdot L_{\alpha}(t)$$

EQUATION 7

with $v_d [m \cdot s^{-1}]$ the deposition velocity; $r [1/s]$ the resuspension rate; $A_d = A_r [m^2]$ the deposition and resuspension surface which we took to be equal together and to the zone floor area; $\rho_{air}(t) [kg_{air}/m^3]$ density of air in the source zone at time t ; $L_{\alpha}(t) [\mu g \cdot m^2]$ the concentration of contaminant α on the deposition surface at time t ; $C_{\alpha}(t) [kg_{\alpha}/kg_{air}]$ the concentration of contaminant α in zone air volume at time t .

As part of this sensitivity analysis, we decided to mainly focus on the deposition velocity v_d and r the resuspension rate. The deposition velocity for fine particles is variable depending on the diameter of the particle and the air change rate provided by the ventilation systems according to (He et al., 2005). We used two papers giving deposition velocity in $m \cdot s^{-1}$ (Fogh et al., 1997; Thatcher and Layton, 1995) that provide sufficiently accurate values of fine particle diameters to be used as a parameter. In addition, both references have the advantage of studying deposition velocity values in occupied houses, which is consistent with our study.

Regarding the characterization of the resuspension rate of fine particles few publications were found. A comprehensive study by (Qian et al., 2008) gives an estimate of the resuspension rate, but only for PM₁₀ ($1.4 \cdot 10^{-4} \cdot h^{-1}$). The only indoor resuspension rate values available for PM_{2.5} were those measured by (Thatcher and Layton, 1995) and corresponding to the indoor activities of 4 residents in a dwelling. These data are coupled to the deposition velocity values measured in this same study.

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As results, we have selected two **MPM25** inputs for the sensitivity analysis: the deposition velocity model **MPM25-*vd*** in the low and high range based on min (0.3 m.h⁻¹) and max (1.8 m.h⁻¹) values measured in houses with furniture in (Fogh et al., 1997; Thatcher and Layton, 1995), and the resuspension model **MPM25-*r*** varying within min (4.4 .10⁻⁷ h⁻¹) and max (1.8 .10⁻⁵ h⁻¹) values measured in (Thatcher and Layton, 1995). For both MPM25 inputs we propose to use the median as the reference value.

AIR LEAKAGE LEVEL

The air leakage through the envelope is in general described using the power law model (Equation 8). (Dols and Polidoro, 2015).

$$Q = C \cdot \Delta P^n$$

EQUATION 8

where Q is the volume flow rate [m³.h⁻¹], ΔP is the indoor-outdoor pressure difference [Pa], C is the air leakage coefficient [m³.s⁻¹.Pa⁻ⁿ], n is the flow exponent usually equal to 0.6-0.7(Dols and Polidoro, 2015; Carrié et al., 2006). The value of C can vary strongly, depending on building size and airtightness level. The C value can be fitted with the Q converted from the q4a measured at the scale of the building (Equation 9).

$$C = \frac{Q}{\Delta P^n} = \frac{q4a \cdot S_{dep}}{4^n}$$

EQUATION 9

The indicator q4a is widely used in France, to assess air leakage through the building envelope. It represents the total volume flow rate Q from air leakage at 4 Pa pressure difference between indoors and outdoors, divided by the loss surface area excluding the basement floor (*S_{dep}*).

According to data measured over 126,840 single family houses in France (116,847 with exhaust ventilation, 6,736 with balanced ventilation) the median q4a is around 0.4 h⁻¹ varying within the range 0.05 h⁻¹ to 0.9 h⁻¹ for extreme data (excluding outliers ±2.7 times the standard) (Mélois et al., 2019). Considering the size of the database, these values give a good overview of the possible permeability levels for a single-family house.

In our case n was taken equal to 0.65, the loss surface area to 232 m² and the *q4a* measured was 0.4 m³.h⁻¹.m⁻². As the result, C = 38 m³.h⁻¹.Pa⁻ⁿ for a total airflow rate from air leakage Q = 93 m³.h⁻¹ at 4 Pa pressure difference.

For the sensitivity analysis, we therefore propose a **Perm** input varying in the range [0.05; 0.9] corresponding to the q4a permeability level.

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4.1.3.d) VENTILATION SYSTEM AND STRATEGIES

Five different ventilation systems used in France and in Denmark were applied to our case study building to examine the impact of ventilation type. Two families of ventilation systems were modelled: Mechanical Exhaust Ventilation (MEV) and balanced Mechanical Ventilation with Heat Recovery (MVHR). Based on previous research projects (Poirier, Guyot, and Woloszyn 2020; Smith and Kolarik 2019), the MEV systems were examined in conjunction with 3 control strategies: Constant airflow ventilation (cav); Relative Humidity controlled ventilation (rh); and CO₂ and Relative Humidity room-based ventilation (rb). For reasons of time and development, the MVHR ventilation systems were only modelled with 2 control strategies: MVHR-cav and MVHR-rb.

CONSTANT AIRFLOWS (MEV-CAV; MVHR-CAV):

The MEV-cav for mechanical exhaust-only ventilation with constant air volume is a system with air exhaust distributed in the bathroom (30 m³.h⁻¹), toilet (15 m³.h⁻¹) and kitchen (45 m³.h⁻¹) with a one-hour boost (135 m³.h⁻¹) during cooking activities in the kitchen. In addition, self-regulated air inlets (trickle vents) providing 22 m³.h⁻¹ are modelled in bedrooms and the living room for fresh air supply from outside.

The MVHR-cav for mechanical ventilation with heat recovery with constant air volume is a ventilation system with the same exhaust airflows as the MEV-cav balanced with mechanical air suppliers in bedrooms and the living room. These two systems with constant airflow strategy could be considered as reference systems in comparison to the three following ones with smart control strategies.

HUMIDITY CONTROLLED AIRFLOWS (MEV-RH):

The MEV-rh for mechanical exhaust-only humidity-controlled ventilation is a system with demand control based on relative humidity (RH) for air exhaust in the kitchen and bathrooms. The system adjusts the exhausted airflows according to the RH level, through the extension and retraction of a hygroscopic fabric modifying the cross-section of the outlets (Jardinier et al., 2018). The kitchen exhaust provides a minimum airflow of 5 m³.h⁻¹ for RH < 23% and a maximum airflow of 55 m³.h⁻¹ for RH > 55%, with a one-hour boost of 135 m³.h⁻¹ during cooking activities. The bathroom exhaust provides a minimum airflow of 5 m³.h⁻¹ in BTH2 for RH < 45% (15 m³.h⁻¹ in BTH1 for RH < 20%) and a maximum airflow of 45 m³.h⁻¹ in BTH2 for RH > 85% (50 m³.h⁻¹ in BTH1 for RH > 55%) (Aldes, 2018).

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It should be noted that two variants of air supplies in bedrooms and living room can be associated with the extraction described above. The first one is called Hygro A, and has self-regulated air inlets ($22\text{m}^3\cdot\text{h}^{-1}$ same as MEV-cav). The second one, more recent, is called Hygro B and has hygroscopic trickle vents providing an airflow rate between $4\text{m}^3\cdot\text{h}^{-1}$ and $31\text{m}^3\cdot\text{h}^{-1}$ (at 10Pa reference pressure difference). Hygro B system is now the most common in new dwellings in France,

For the sensitivity analysis the Hygro A was selected, as a good compromise between modelling complexity and possibility of control. Even if no longer installed in new French dwellings, this system is still representative of existing variable control strategies used in Europe (commonly in France or with an equivalent based on CO_2 in Belgium) and is an intermediate solution between constant and smart system with more advanced control strategies.

ROOM-BASED, CO_2 AND HUMIDITY-CONTROLLED AIRFLOWS (MEV-RB; MVHR-RB)

The MVHR-rb for mechanical ventilation with heat recovery and room-based control, is an innovative balanced ventilation allowing for separate control of airflows in each room. A controller using an IAQ sensor calculates airflow requirements in each room based on CO_2 and RH for kitchen/living room and bathroom, whereas the airflow needs for bedrooms are based on CO_2 . This system was modelled with the same exhaust and supply location as the MVHR-cav. The following setpoints for control are used:

- a minimum airflow rate of $5\text{m}^3\cdot\text{h}^{-1}$ in all rooms (except $15\text{m}^3\cdot\text{h}^{-1}$ in BTH1) for lower limit $C_{\text{CO}_2} < 800\text{ppm}$ (RH $< 57\%$ at 21°C)
- a maximum airflow rate of $135\text{m}^3\cdot\text{h}^{-1}$ in the kitchen ($50\text{m}^3\cdot\text{h}^{-1}$ in BTH1; $45\text{m}^3\cdot\text{h}^{-1}$ in BTH2) for upper limit $C_{\text{CO}_2} > 900\text{ppm}$ (RH $> 77\%$ at 21°C)
- the rate is linear between the lower and the upper limits

When the outdoor humidity ratio is $0.003\text{kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{Air}}$ higher than the indoor level, the demand stays low, to avoid additional moisture load from the outdoor air (Smith and Kolarik 2019). As with the other systems, we assume a one-hour boost (maximum airflow of $135\text{m}^3\cdot\text{h}^{-1}$) in the kitchen during cooking activities.

The MEV-rb is a fictive adaption of the MVHR-rb with the same control but with exhaust-only airflows instead of balanced airflows. It is modelled based on the MEV-cav model with exhaust in the kitchen, toilet, and bathrooms. The exhaust is then controlled proportionally by the kitchen and bathroom requirements and then by the bedrooms requirements if the needs are low in kitchen and bathroom. The airflow in the toilet is kept constant for both MVHR-rb and MEV-rb.

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As CONTAM does not have an energy model, the heat recovery for MVHR systems is not modelled directly in CONTAM but a theoretical constant efficiency coefficient is applied for heat-loss calculation from exhaust airflows (output indicator described below).

Choices for sensitivity analysis

To build inputs that can be applied to all the tested ventilation strategies for the sensitivity analysis, we decided to focus on the impact of varying the exhaust airflows.

We propose a variation range for these airflows of -30% to + 30% to test the two extreme situations. The -30% could represent the case when ventilation airflows are deliberately reduced to evaluate the potential for energy heat loss saving from air renewal; or even represent reduced airflows from performance decrease because of lack of maintenance after the building has been in use for a long time. The +30% situation explores the impact of ventilation airflow oversizing; from a deliberate increase by an attempt to design an IAQ improvement or an involuntary increase from a modelling error during the performance assessment process. Both decreased and oversized airflow tests would serve to explain the impact of a discrepancy between a real effective airflow and the theoretical designed airflows.

In detail, for the sensitivity analysis we propose to create two inputs varying in range [0.7; 1.3] focused on the exhaust airflows that could be adapted to the five ventilation systems modelled. The first one, **Q-exh**, is a constant multiplier coefficient to modify the total exhaust airflow and is applied to all exhaust paths in the CONTAM model (kitchen, bathrooms, toilet). The second input, **Q-max**, is a constant multiplier coefficient applied only to the maximum airflow Max/Qboost control value (see in Table 4). For MVHR systems the supply airflows were adjusted to correspond to the **Q-exh** or **Q-max** edited exhaust airflows, in order to keep the balance between exhaust and supply.

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MEV/MVHR-cav						
<i>Airflows [m³.h⁻¹]</i>	<i>Min (Q-exh)</i>			<i>Max (Q-max)</i>		
<i>Input Q-exh / Q-max</i>	<i>Low</i>	<i>Ref</i>	<i>High</i>	<i>Low</i>	<i>Ref</i>	<i>High</i>
KIT/LVR	31,5	45	58,5	94,5	135	175,5
BTH1	21	30	39	21	30	39
BTH2	21	30	39	21	30	39
WC1 / WC2	10,5	15	19,5	10,5	15	19,5
Total	94,5	135	175,5	157,5	225	292,5

MEV-rh									
<i>Airflows [m³.h⁻¹]</i>	<i>Min* (Q-exh)</i>			<i>Max** (Q-exh)</i>			<i>Max (Q-max)</i>		
<i>Input Q-exh / Q-max</i>	<i>Low</i>	<i>Ref</i>	<i>High</i>	<i>Low</i>	<i>Ref</i>	<i>High</i>	<i>Low</i>	<i>Ref</i>	<i>High</i>
KIT/LVR	3,5	5	6,5	38,5	55	71,5	94,5	135	175,5
BTH1	10,5	15	19,5	35	50	65	35	50	65
BTH2	3,5	5	6,5	31,5	45	58,5	31,5	45	58,5
WC1 / WC2	3,5	5	6,5	3,5	5	6,5	3,5	5	6,5
Total	24,5	35	45,5	112	160	208	168	240	312

*for RH<20% in BTH1 / for RH<45% in BTH2 / for RH<23% in KIT/LVR
**for RH>55% in BTH1 / for RH>85% in BTH / for RH>55% in KIT/LVR

MEV/MVHR-rb						
<i>Airflows [m³.h⁻¹]</i>	<i>Min* (Q-exh)</i>			<i>Max** (Q-exh) / Max (Q-max)</i>		
<i>Input Q-exh / Q-max</i>	<i>Low</i>	<i>Ref</i>	<i>High</i>	<i>Low</i>	<i>Ref</i>	<i>High</i>
KIT/LVR	3,5	5	6,5	94,5	135	175,5
BTH1	10,5	15	19,5	35	50	65
BTH2	3,5	5	6,5	31,5	45	58,5
WC1 / WC2	3,5	5	6,5	3,5	5	6,5
Total	24,5	35	45,5	168	240	312

*for Cco2 < 800 ppm or RH<57% independently by room
** for Cco2 < 900 ppm or RH>77% independently by room

TABLE 3 :SUMMARY OF THE EXHAUST AIRFLOWS BY ROOMS (AND TOTAL) FOR SIMULATED SYSTEMS

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4.1.4 OUTPUT DEFINITION

The aim of this sensitivity analysis is to find the most important inputs and to evaluate the uncertainty of the method for ventilation performance assessment developed in Poirier (Poirier et al., 2021b). Naturally, the first selected outputs were five IAQ performance indicators (I_{CO_2} , I_{HCHO} , $I_{PM_{2.5}}$, $I_{RH_{70}}$, $I_{RH_{30_70}}$) of the method. These five indicators were then extended with two additional IAQ indicators for formaldehyde and $PM_{2.5}$ short-term exposure risks (I_{HCHO-s} , $I_{PM_{2.5-s}}$) and one energy indicator evaluating the thermal heat loss from supply airflows and uncontrolled infiltration ($I_{E_{wh}}$). All these IAQ and energy indicators are proposed with an associated acceptable threshold (AT) representing a reference limit of acceptable performance not to be exceeded. For results analysis the indicators were normalised by their AT and referenced with the notation [I_n -]. Moreover, the average values of pollutant concentration and ventilation airflow rate were aggregated on the scale of the building. In the results analysed, the S_i sensitivity indices were calculated only for the following normalized outputs (I_{nCO_2} , I_{nHCHO} , $I_{nPM_{2.5}}$, $I_{nRH_{70}}$, $I_{nRH_{30_70}}$, $I_{nHCHO-s}$, $I_{nPM_{2.5-s}}$, $I_{nCO_{2v}}$, with the exception of $I_{E_{wh}}$) and a few other physical values were used for general or additional performance analysis.

4.1.4.a) INDOOR AIR QUALITY INDICATORS

CO_2 is generally not considered as a pollutant: in an indoor environment the concentration levels are commonly in the range 450–2000 ppm (Kirchner and et. al., 2007). This is because in this range CO_2 does not cause any damage to health apart from headache, fatigue, or sleepiness in some cases. However, occupants are the main source of CO_2 in buildings which makes CO_2 concentration a good indicator related to occupant bio-effluent emissions. Lastly, some smart-ventilation strategies based their ventilation rates on CO_2 (Guyot et al., 2018). The proposed performance indicator in the method is I_{nCO_2} the maximum cumulative CO_2 exposure over 1000 ppm in the bedrooms (ppm.h) normalized by $AT = 1000 \cdot d$ (ppm.h with d the duration of the simulated period in hours). In addition, for the sensitivity analysis a variant of I_{nCO_2} was tested, with a variable exposure threshold based on a complementary input **Tco2**. This variant was referenced as $I_{nCO_{2-v}}$ the maximum cumulative CO_2 exposure over Tco2 ppm in the bedrooms, with Tco2 included in the sampled variable input varying in the range [800; 1200].

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The next two IAQ outputs were based on formaldehyde and PM_{2.5} pollutant exposure with: I_{nHCHO} the maximum cumulative HCHO exposure among all the occupants, normalized by $AT = 9.d$ ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$); I_{nPM25} the maximum cumulative PM_{2.5} exposure among all the occupants, normalized by $AT = 10.d$ ($\mu\text{g}\cdot\text{m}^{-3}\cdot\text{h}$). These two indicators were used respectively in a short term exposure version $I_{nHCHO-s}$ and $I_{nPM2.5-s}$ which were described and tested in a previous study (Poirier et al., 2022b), with $I_{nHCHO-s}$ the maximum occupant formaldehyde exposure over a one hour average period according to (Cony Renaud Salis et al., 2017; HCSP, 2019; World Health Organization, 2010), normalized by $AT = 100 \mu\text{g}\cdot\text{m}^{-3}$; $I_{nPM2.5-s}$ the maximum occupant PM_{2.5} exposure over a 24-hour average period according to (Cony Renaud Salis et al., 2017; HCSP, 2013) and normalized by $AT = 25\mu\text{g}\cdot\text{m}^{-3}$.

The last IAQ outputs were based on relative humidity, with I_{nRH70} the maximum percentage of time with RH higher than 70% in all the rooms, focusing on the condensation risk, the AT varying as a function of the room evaluated, AT = 18% in the bathroom, 10.8% in the kitchen, and 1.8% in other rooms. The second indicator I_{nRH30_70} was proposed for the occupant comfort aspect, as the maximum percentage of time spent by the occupants with RH outside the range: [30%–70%] with AT= 14.4%.

4.1.4.b) ENERGY INDICATOR

For the energy performance aspect, we propose to focus on the heat losses from air renewal as described in Equation 10. This energy indicator was tested in a previous study and is inspired from an earlier method in the French thermal regulations (*RE-2020 ANNEXE III*) and other studies (Abadie et al., 2017; Molina et al., 2021). The amount of heat loss due to the ventilation airflows can be easily calculated with an airflow model using exhaust airflows and temperature difference between inside and outside:

$$I_{Ewh} = H_{th} = \frac{C_{pm}}{3600} \cdot (1 - \varepsilon_{heat_{ex}}) \int q_m(t) \cdot [T_{in}(t) - T_{ex}(t)] \cdot dt$$

EQUATION 10

with I_{Ewh} the energy indicator resulting directly from H_{th} , the heat losses from exhausted air [*kWh*], q_m the total exhaust mass airflows in [*kg.s⁻¹*], C_{pm} the heat capacity of air (we used $1 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{°C}^{-1}$), $\varepsilon_{heat_{ex}}$ the heat exchanger efficiency assumed to be ideal and constant. A constant theoretical efficiency of 0.8 can, for example, be used for MEVHR and 0 with no heat recovery. T_{in} is the zone temperature where the air is exhausted, and T_{ex} the external temperature [*°C*].

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4.1.4.c) SUMMARY OF INPUTS AND OUTPUTS

As shown in Table 4-5, 12 inputs were selected with their associated range of variation and 9 outputs were selected for the sensitivity analysis. The reference column, X_{ref} , gathers reference or average values for all inputs, in particular: the reference occupant bio-effluent emissions; the medium activity and furniture pollutant emissions; the reference parameter values used in the deposition/resuspension model; the median permeability of the envelope representative of single-family houses in France, and the theoretical design ventilation airflow. For the result analyses, this X_{ref} input was used as a comparison point to assess whether the use of these reference inputs is relevant and representative enough to generalise the ventilation performance assessment.

Inputs	Description	Low	Reference	High
Bio-eff	occupant CO ₂ and H ₂ O emissions	0	0.333	1
Acti-H ₂ O	moisture emissions from activities	0.7	1	1.3
Acti-PM _{2.5}	emissions from cooking activities	1.26	1.91	2.55
Furn-	HCHO formaldehyde emissions from furniture	4.5	12	23.6
Mbuff-L	buffer effect for low adsorbing room	0	0	0.25
Mbuff-H	buffer effect for high adsorbing room	0.75	1	1
MPM _{2.5-vd}	Deposition velocity	0,3	0,65	1,8
MPM _{2.5-r}	Resuspension rate	$4.4 \cdot 10^{-7}$	$9.90 \cdot 10^{-7}$	$1.8 \cdot 10^{-5}$
Perm	Permeability level based on a q4a	0.05	0.4	0.9
Q-exh	Total exhaust airflow multiplier	0.7	1	1.3
Q-max	Maximum airflow M/Qboost multiplier	0.7	1	1.3
TCo ₂	Variable CO ₂ exposure AT for I _{nCO_{2-v}} calculation	800	1000	1200

TABLE 4 : SUMMARY OF THE PROPOSED INPUTS FOR THE SENSITIVITY ANALYSIS

Outputs	Description	AT
I _{nCO₂}	Maximum cumulative CO ₂ exposure over 1000 ppm	1000 .d (ppm.h)
I _{nCO_{2-v}}	Maximum cumulative CO ₂ exposure over T _{Co₂} ppm	T _{Co₂} d (ppm.h)
I _{nHCHO}	Maximum cumulative HCHO exposure among all the occupants	9.d (µg.m ⁻³ .h)
I _{nHCHO-s}	Maximum occupant HCHO exposure over a one-hour average period	100 µg.m ⁻³
I _{nPM₂₅}	Maximum cumulative PM _{2.5} exposure among all the occupants	10.d (µg.m ⁻³ .h)
I _{nPM_{25-s}}	Maximum occupant PM _{2.5} exposure over a 24-hour average period	25 µg.m ⁻³
I _{nRH70}	Maximum percentage of time with RH > 70% among all the rooms	18%; 10.8%;1.8%
I _{nRH30_70}	Maximum percentage of occupant time spent with RH outside the range [30-70%]	14.4%
I _{Ewh}	Heat losses from total exhaust airflows	-

TABLE 5 : SUMMARY OF THE OUTPUTS FOR THE SENSITIVITY ANALYSIS

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4.1.5 RESULTS

4.1.5.a) GENERAL PERFORMANCE RESULTS

Before analysing the sensitivity index results in detail, we give here a general overview of the indoor environment pollutant levels and ventilation airflows involved over the 500 simulations for each ventilation strategy.

First, in Figure 4 the results of three reference simulations with the low inputs (Ref_{low}), reference inputs (Ref) and high inputs (Ref_{high}) are presented for each system (MEV-cav, MEV-rh, MEV-rb, MVHR-cav, MVHR-rb). For each graph the reference simulations was plotted in full line and the space between Ref_{low} and Ref_{high} was coloured with following associated colours:

- The building average CO_2 concentration in red
- The building average relative humidity in blue.
- The total exhausted airflow in yellow, light-blue, green, orange, purple function of the ventilation system.

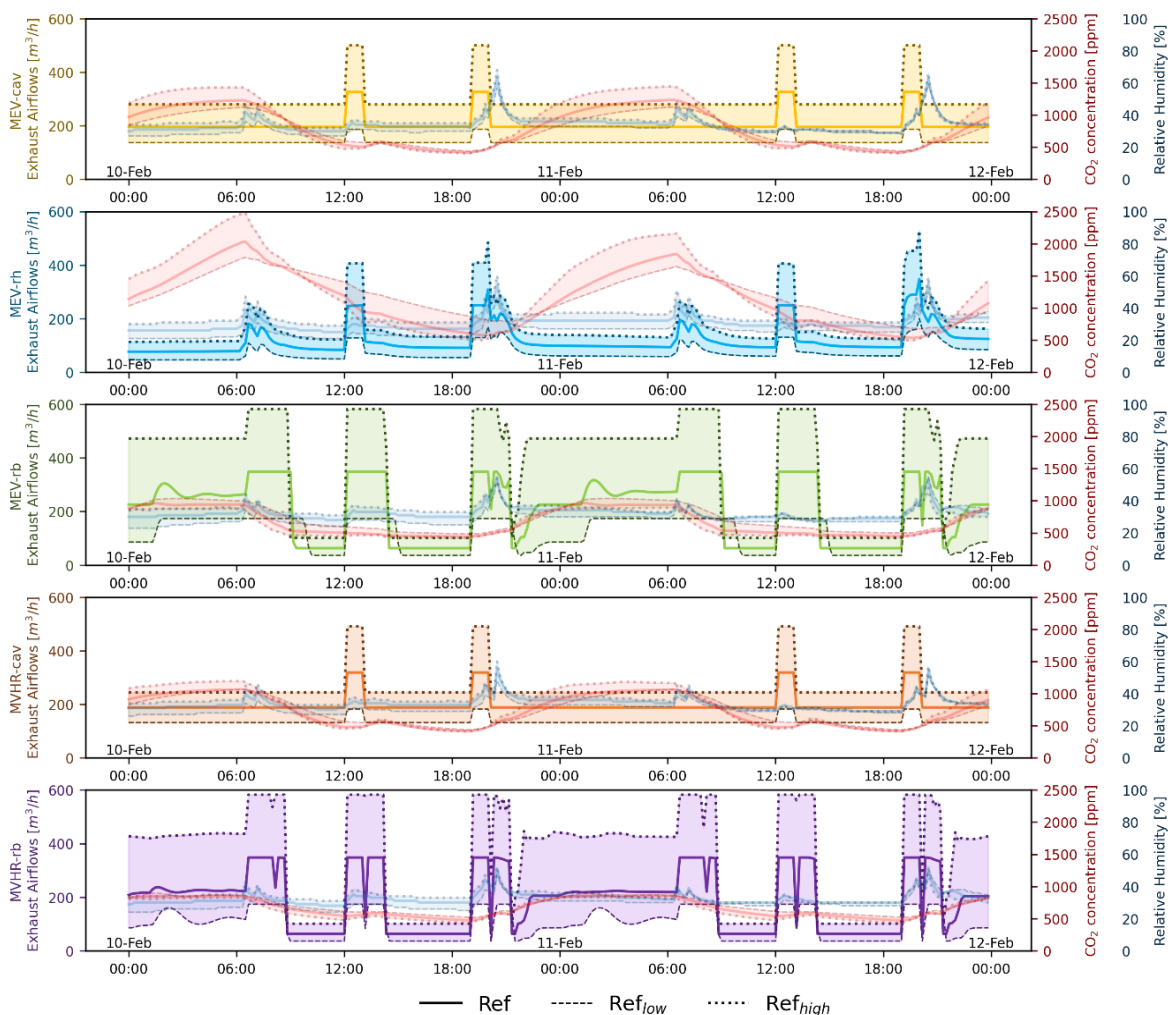


FIGURE 4 : TOTAL EXHAUST VENTILATION AIRFLOWS FOR THE 5 STRATEGIES; CO_2 AND RH[%] AVERAGE ON THE SCALE OF THE BUILDING ; FOR THE REFERENCE AND EXTREME INPUTS

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To display this more clearly, we showed only two days in February which are representative of the simulated heating period. The two constant-airflow ventilation strategies (MEV-cav, MVHR-cav) have similar airflow profiles with lower CO₂ and humidity levels for the MVHR-cav in comparison to the MEV-cav. Whereas the other three strategies undergo more significant change in their airflows over the days. For *rh* and *rb* strategies, an airflow peak can be observed in the morning in addition to the two others from controlled cooking boost observed for all systems. This shows that humidity spikes due to cooking and morning showers do trigger additional high airflows for variable ventilation control strategies. Moreover, for the two room-based strategies (MEV-rb, MVHR-rb) higher airflows during the night and lower airflows during the day were observed. This shows that the *rb* strategy provides additional higher airflows in response to the CO₂ bio-effluent emissions during occupancy periods. The MEV-rh systems had comparatively lower airflows during the night and day and the CO₂ concentration clearly increases during the occupied periods. These differences illustrate the specificity of each ventilation strategy from a constant conventional one to the smartest based on CO₂ and humidity.

To complete these time series, the Figure 5 shows boxplots of total average exhausted airflows and average representative parameters of the indoor environment (CO₂, H₂O, HCHO, PM_{2.5}), on the whole simulated period over the 500 simulations. The boxplots represent first quartile (q1) at the bottom of the box, the median in the middle and the third quartile (q3) at the top of the box; with the whiskers extend from the box by 1.5x the inter-quartile range (IQR) and the remaining outliers are represented by grey crosses.

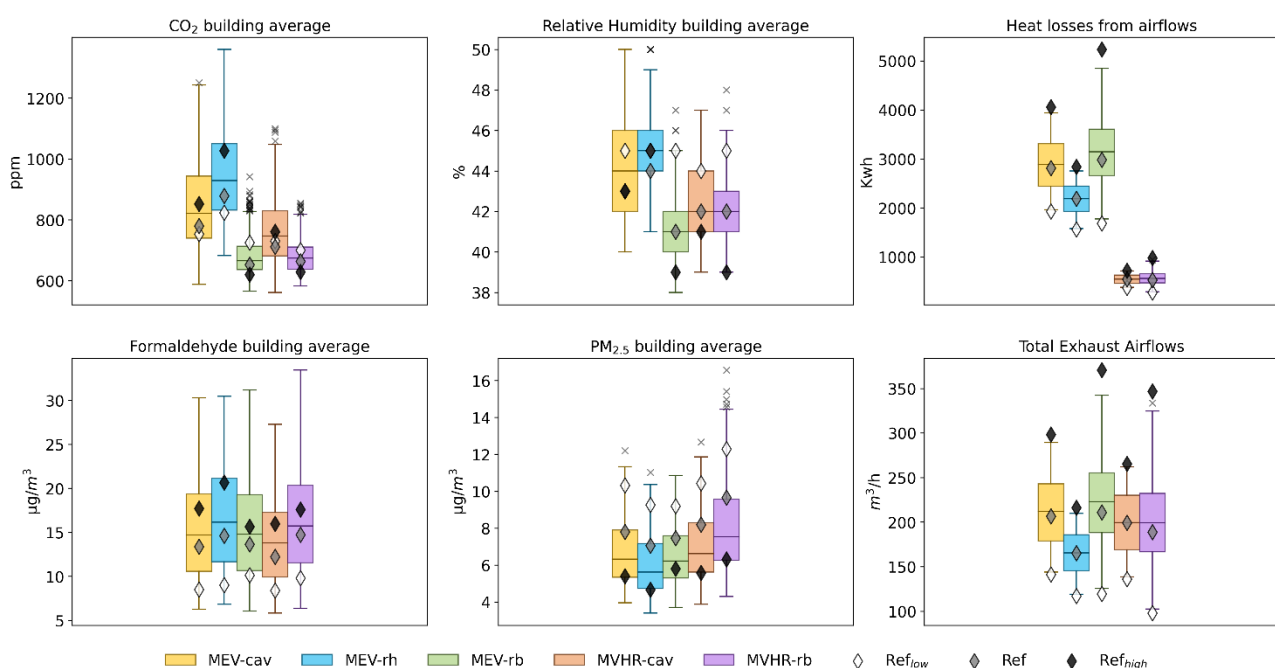


FIGURE 5 : INDOOR ENVIRONMENT AND VENTILATION AVERAGE DATA ON THE HEATING PERIOD BOXPLOT OVER THE 500 SIMULATIONS FOR THE 5 VENTILATION STRATEGIES

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According to the total exhaust airflows boxplot shown in Figure 5 the Ref_{low} and Ref_{high} cover the extremum values for the exhaust airflow variation range, while the Ref scenario is close to the median value of the 500 simulations. These 3 reference simulations are less representative for the CO_2 concentration and RH [%]. Indeed, the reference simulations results are not always in the q1, q3 box of the boxplot (Figure 5).

The CO_2 boxplot in Figure 5 confirms the previous observations that room-based control and MVHR ventilation have on average lower CO_2 concentrations than MEV-cav and MEV-rh. With these three strategies (MEV-rb, MVHR-rb, MVHR-cav) the air is on average also dryer $\pm 3\%$. The average formaldehyde concentration is relatively similar for all strategies, with concentrations mainly between $10 \mu g.m^{-3}$ and $20 \mu g.m^{-3}$. The same is true for $PM_{2.5}$ with concentrations between $5 \mu g.m^{-3}$ (q1 for MEV-rh) and $9 \mu g.m^{-3}$ (q3 for MVHR-rb). Regarding the airflows, MEV-rh had lower airflows than the other strategies and MEV-rb had slightly higher airflows in comparison with its heat recovery equivalent MVHR-rb (the same was observed for MEV-cav and MVHR-cav).

The representation of the Ref , Ref_{low} , Ref_{high} inputs shows that low, medium or high pollutant scenario emissions do not always give the lowest, the median or the highest response. This appears to be quite relevant for formaldehyde where the distance between $Rref$, Ref_{low} and Ref_{high} are almost the same for all the strategies but always lower than q3, median and q1. In contrast, for $PM_{2.5}$ the Ref_{low} corresponds to the highest $PM_{2.5}$ concentration, the Ref_{high} to the q1 concentration and the Ref_{medium} to the q3 concentration.

Figure 6 shows as boxplots all the performance indicators calculated over the 500 simulations per strategy. In a global analysis, the differences between the strategies regarding IAQ performance seem relatively small and dependent on pollutant. Whereas the energy benefits show significant differences .

As previously observed with CO_2 concentrations in Figure 4, the I_{nCO_2} indicator confirms the good performance of MEV-rb, MVHR-rb and MVHR-cav, whereas the I_{nCO_2} remains mostly under the acceptable threshold. For MEV-cav and MEV-rh the situation is different: in some simulations (eg. for some inputs) the indicator value is below the threshold while in other cases it is above it. This position around the acceptable threshold as a function of the inputs' values is also observed for I_{nHCHO} , I_{nRH30_70} , I_{nRH70} . For $PM_{2.5}$ performance no strategy reaches the acceptable thresholds except in some outlying configurations. The outliers also show that the association of specific inputs could generate in most cases a factor 3 between the lowest and the highest values. In some cases, it could even generate huge performance assessment difference, with up to 14 times the acceptable threshold for MEV-rh on the I_{nRH70} .

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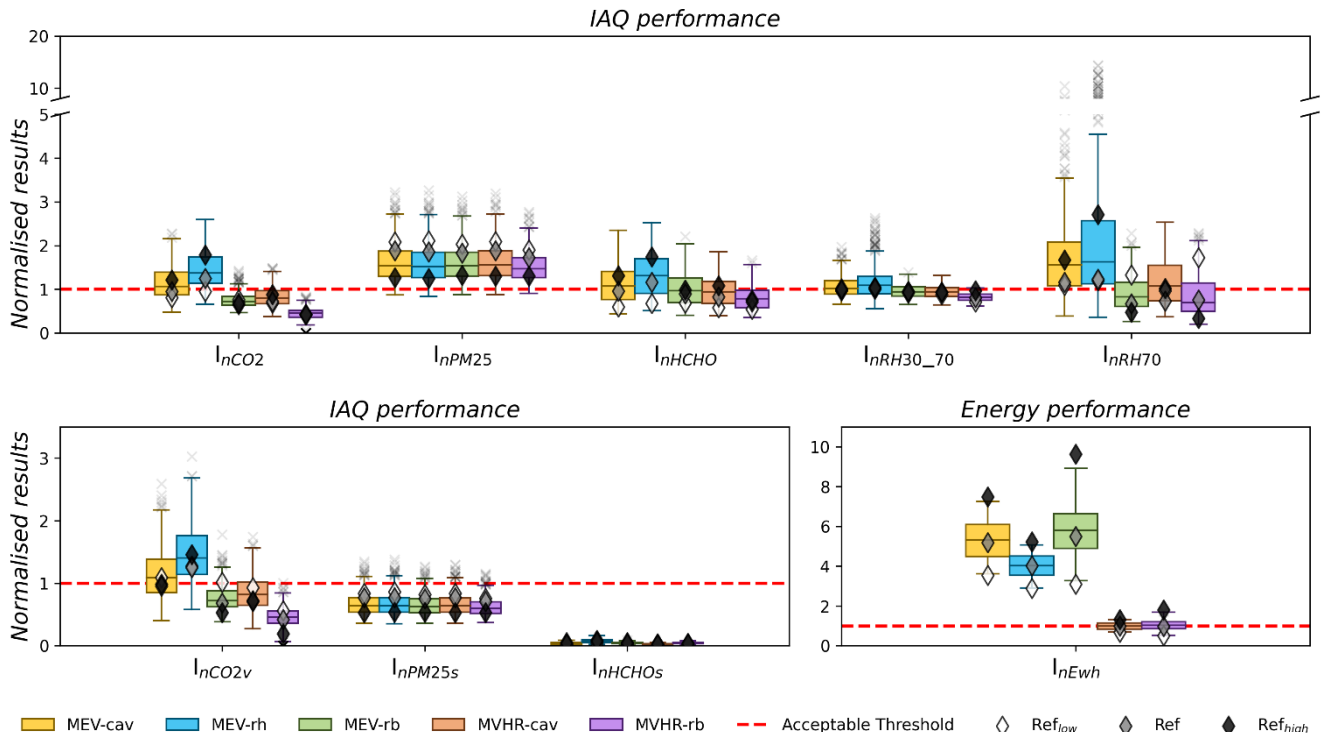


FIGURE 6 : BOXPLOT OF NORMALIZED INDICATOR PERFORMANCE RESULTS OVER THE 500 SIMULATIONS FOR THE 5 VENTILATION STRATEGIES

The additional IAQ outputs for short term exposures $I_{nHCHO-s}$ and $I_{nPM25-s}$, for this case study and with the inputs tested, provide almost the same information as their long-term equivalent. In these cases, the risk from formaldehyde was mostly close to 0, which means that the problem of formaldehyde in the indoor environment seems to be related to long-term and background exposure rather than to the peak exposure. For the $PM_{2.5}$ short term risk, with the exception of a few outliers, the q1, q3 and median values are below the acceptable thresholds; the chosen duration of the 24-hour average period for short-term exposure may not be appropriate to capture the maximum exposure risk. The use of a variable threshold between, 800 and 1200 ppm for CO_2 exposure calculation I_{nCO2-v} also gives the same information as I_{nCO2} , with 1000 ppm. This means in this configuration that a lower (or higher) limit for CO_2 exposure does not significantly increase (or reduce) the assessed exposure of the occupants.

Finally, to normalise the energy heat loss indicator I_{Ewh} we decided to use the MVHR-cav strategies as a reference for comparison and used the median performance result obtained over the 500 simulations, with the median I_{Ewh} of the MVHR-cav equal to 543 kWh (4.02 kWh.m⁻²). This normalization therefore shows that the energy needs from thermal heat losses are for the 3 MEV strategies (MEV-cav, MEV-rh, MEV-rb) between 3 times and 10 times higher in comparison with MVHR-cav strategy heat losses. But the comparison between MEV and MVHR is not particularly relevant: the main amount of energy saving derives from the theoretical heat recovery efficiency of 0.8.

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However, it still highlights the fact that that MEV-rh had lower energy losses than MEV-cav and MEV-rb, for IAQ equivalent performance to MEV-cav as discussed above, but without the benefit on CO₂ provided by MEV-rb. In this case, if energy saving is encouraged, the use of MEV-rh could be relevant in comparison with MEV-cav. In contrast if IAQ is prioritized on energy, the use of MEV-rb could be more relevant. Lastly, MVHR-rb, in some configurations, could be lower or higher than MVHR-cav, but had mostly equivalent energy performance, with the added advantage on all IAQ indicators over MVHR-cav and other MEV strategies.

4.1.5.b) SENSITIVITY ANALYSIS RESULTS

In this sensitivity analysis a total of 540 sensitivity indices (108 per ventilation strategy) were calculated across the 12 input variables and the 9 output indicators. Faced with the challenge of displaying the information from so many S_i , we built what we called a "flower graph" which groups all these 540 indices by ventilation strategy in Figure 7.

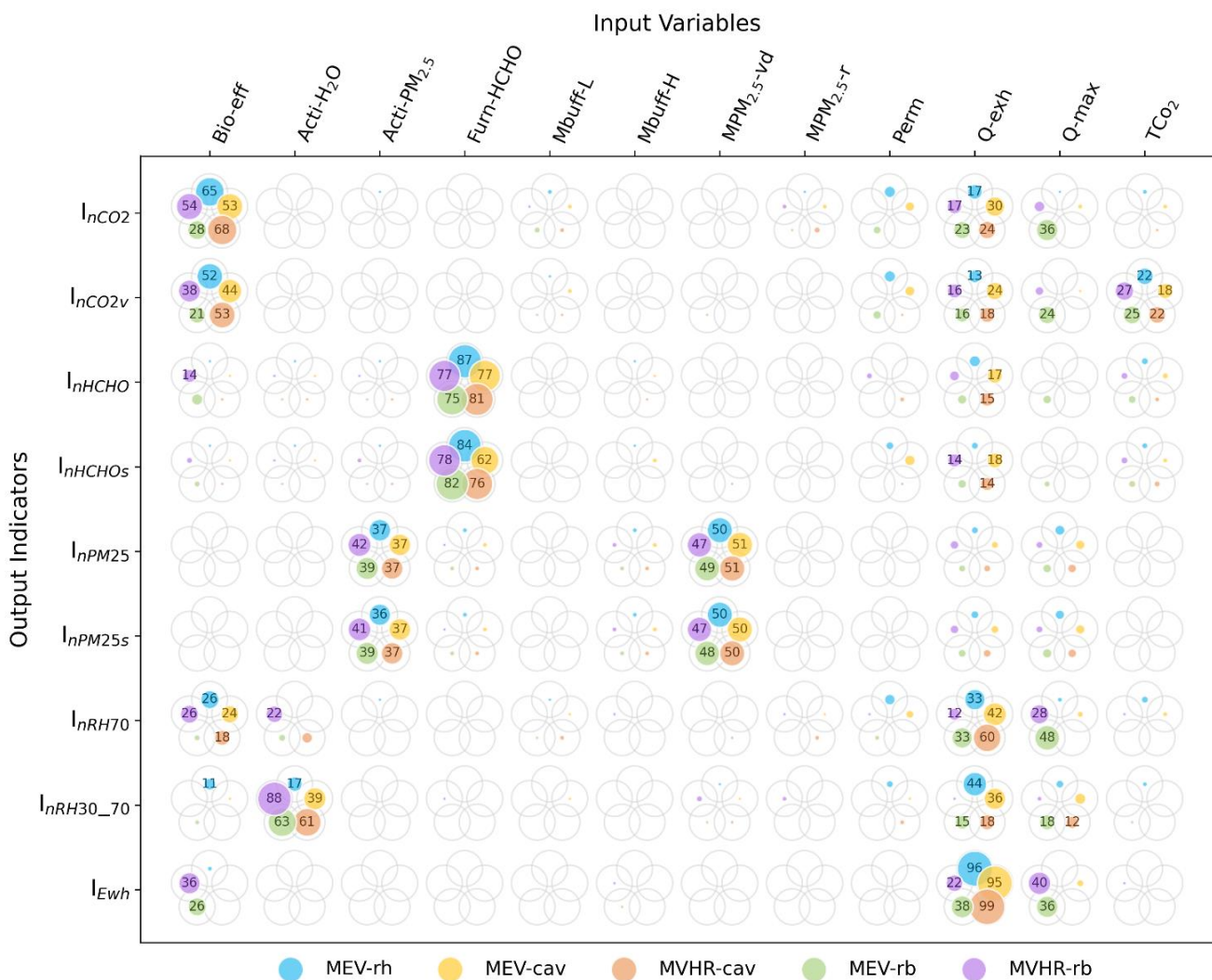


FIGURE 7 : DISPLAY OF THE SENSITIVITY INDICES CALCULATED FOR THE 5 VENTILATION STRATEGIES

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On this graph each row represents the output indicator and each column the input variable. Each of the 108 "flowers" has 5 circles, one for each ventilation strategy. The grey circle represents the maximum possible S_i , with a coloured circle sized proportionally to its real value. Each colour representing one system. In addition, the percentage value ($S_i\%$) is added if the indices start to be significant ($S_i > 0.1$) and the indices are not represented if $S_i < 0.05$. In other words, an empty flower means that for all ventilation systems the impact of the corresponding input variability on the output variability is insignificant, while coloured petals indicate important impact.

At first sight, the Mbuff-L, Mbuff-M, MPM_{2.5-r} and Perm input variables present little or no influence on the outputs for all the strategies (empty flowers on corresponding columns). Acti-H₂O, Acti-PM_{2.5}, Furn-HCHO, MPM_{2.5-vd} and TCO₂ influence one or two outputs, related to the pollutant associated with the specific input. The last inputs Bio-eff, Q-exh influence several outputs and the Q-max has strong impact on both room-based strategies MVHR-rb and MEV-rb. The Q-max influence on room-based strategies could be explained by the way the Q-max value was implemented in CONTAM for these *rb* strategies. Indeed for these two systems the max Q-exh (high humidity or CO₂) and the Q-max (ref 135 m³.h⁻¹ cooking boost) are equal and not dissociable. Whereas for MEV-cav; MVHR-cav; MEV-rh the Q-max (cooking boost) airflows were effective only during the cooking boost and are much higher than max Q-exh. (For example, the max Q-exh for high humidity in the kitchen equals to 55m³.h⁻¹ at reference. Whereas, for *rb* strategies max Q-exh can reach 135 m³.h⁻¹ in the case of high CO₂ concentrations and high moisture level.



FIGURE 8 : S_i SORTED BY ORDER OF SIGNIFICANCE; FOR THE 9 OUTPUT INDICATORS (INDICES < 0.1 WERE REMOVED)

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Figure 8 gives a detailed presentation of the sensitivity indices S_i per output and order of significance. I_{nCO_2} and $I_{nCO_{2v}}$ are impacted mainly by the Bio-eff inputs; from 0.28 to 0.68 for I_{nCO_2} and from 0.21 to 0.53 for $I_{nCO_{2v}}$ depending on the strategy. Additionally, I_{nCO_2} is also impacted by Q-exh with sensitivity indices from 0.17 to 0.3 depending on the strategy. $I_{nCO_{2v}}$ is the only output influenced by TCO_2 with sensitivity indices between 0.18 - 0.27 depending on the strategy, but Bio-eff is still the most influential on the I_{nCO_2} indicator. This confirms that in our case the use of variable thresholds for CO_2 exposure is not necessarily useful and does not provide any additional information. Regardless the ventilation strategy, the formaldehyde indicator I_{nHCHO} is not surprisingly influenced by Furn-HCHO as it is the only formaldehyde source input. The same could be true for Bio-eff impact on the CO_2 indicator, as Bio-eff is the only input varying the CO_2 emission source from the occupants. More unexpectedly, Bio-eff has also some impact on formaldehyde indicator I_{nHCHO} ($S_i=0.14$), and this for MVHR-rb system only. This can be explained by the ventilation control strategy for MVHR-rb based on CO_2 which is related to the occupant but also impacts formaldehyde concentrations. For constant ventilation airflows (cav) the Q-exh value also has some influence on I_{nHCHO} , which can be explained by varying airflow rates. For the $PM_{2.5}$ indicators the 5 systems are almost equally impacted by the particle emission rates (Acti- $PM_{2.5}$, S_i in [0.47-0.51]) and the deposition velocity (MPM $_{2.5}$ -vd, S_i in [0.37-0.42]) but not by the resuspension rate (MPM $_{2.5}$ -r, $S_i < 0.05$). This result highlights the need to focus on the deposition velocity for the $PM_{2.5}$ model, as implemented in CONTAM, as its impact on the $I_{nPM_{2.5}}$ indicator is even higher than the impact of emission rates (sensitivity indices of 47 to 51 % for deposition velocity and 37 to 42% for emission rates).

Regarding humidity-based indicators, $I_{nRH_{70}}$ is more impacted by occupants emissions (Bio-eff), while $I_{nRH_{30-70}}$ is more impacted by activity emissions (Acti- H_2O). This result is quite unexpected; indeed, moisture emissions from activities were expected to impact $I_{nRH_{70}}$. Moisture emissions from activities are more intense and intermittent and, as peak emissions, should have an impact on high humidity levels ($RH > 70\%$). But this has not been observed in the sensitivity results. In addition, $I_{nRH_{70}}$ is strongly impacted by the exhaust airflows Q-exh and Q-max.

Lastly, for the heat loss indicator $I_{nE_{wh}}$, its variability is influenced by Q-exh for MEV-cav, MEV-rh and MVHR-cav. While for the systems with the most complex control strategy (MEV-rb and MVHR-rb), $I_{nE_{wh}}$ are almost equally impacted by the Bio-eff, Q-exh and Q-max. The presence of Bio-eff for *rb* strategies could again be explained by the CO_2 control for the room-based systems. Surprisingly, inputs related to moisture sources (Bio-eff and Acti- H_2O) have no impact on the energy performance for humidity-based control systems (MEV-rh and MVHR-rh)..

Overall, the variability of each output is significantly impacted only by 1 to 4 tested inputs, other inputs having only a negligible influence.

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Finally, the highest values of S_i show the inputs that appear frequently as the most impacting. Sensitivity analysis provided a better view of the method sensitivity for several ventilation strategies. The results highlight the fact that attention should be paid firstly to the inputs related to CONTAM model $MPM_{2.5-vd}$, $Acti-PM_{2.5}$, $Furn-HCHO$, and secondly to $Bio-eff / Acti-H_2O$ as very influential on I_{nCO_2} / I_{nRH30_70} . Of course, the airflow rate values are also very important.

4.1.6 CONCLUSION

Five ventilation strategies in a low-energy dwelling were modelled with CONTAM to quantify the sensitivity of a proposed ventilation performance assessment method. Nine performance indicators were evaluated with the RBD-FAST sensitivity analysis method, by varying 12 inputs of the model over 2500 simulations. In addition, these results make it possible to present IAQ and energy ventilation performance assessment over a large range of tested scenarios, instead of the more usual reduced set of minimum, medium and maximum scenarios.

In the case examined, the smart ventilation room-based system offered an additional IAQ benefit over CO_2 but with greater heat losses if the system does not have a heat recovery. The mechanical exhaust-only humidity-controlled ventilation seems to be a good alternative to mechanical constant exhaust ventilation for energy saving. The comparison of these results with the Ref , Ref_{low} , Ref_{high} inputs showed that the use of these 3 scenarios is representative of the extreme and the median values for the energy performance indicator, but for the IAQ performance assessment this seems less relevant. We also showed that the use of the constant mechanical ventilation with heat recovery as a reference strategy to normalize the I_{Ewh} indicators allow easy comparison of the other strategies regarding energy performance assessment. However, the use of variable thresholds for CO_2 exposure or short-term exposure indicators does not provide more information than their originals proposed in the performance assessment method (I_{nCO_2} ; I_{nHCHO} ; I_{nPM25}).

In this sensitivity analysis, the influence of the $Bio-eff$, $Acti-PM_{2.5}$, $Acti-H_2O$, $Furn-HCHO$ and $MPM_{2.5-vd}$ inputs on the indicators confirmed the need to pursue research into parameters for pollutant emission scenarios. These results showed that some identified inputs, M_{buff-L} , M_{buff-M} and $MPM_{2.5-r}$ could be set to default values, as their variability is not impacting the performance indicators.

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To extend this sensitivity analysis, additional simulations could be focused on a more detailed scenario. For example, bio-effluent emission rates could vary independently for each occupant or different “family types” could be tested. For Acti-PM_{2.5} the cooking emission scenario may be varied by differentiating between days or types of meals cooked throughout the week, to test “cooking type habits” and additional PM_{2.5} sources could be added in other rooms. The activities brought together in Acti-H₂O could also be varied independently to obtain greater accuracy and identify which activities have more impact on relative humidity.

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In addition to the quantified uncertainty from the sensitivity analysis, we propose to extend the performance-based approach with a methodology to rank the systems performance. Such methodology could be used in a decision-making tool for ventilation systems in buildings at the design stage. Indeed, with the work proposed in the 4.1 section, the performed simulations allow to obtain a relative range of the theoretical performances, which should be achieved for each tested ventilation strategy. Nevertheless, it does not allow to rank the ventilation systems performances and to choose the most relevant one from global performance point-of-view. According to the previous results presented in section 4.1, the difference of the performances among the ventilation systems will vary depending on the selected indicators. For example, differences between the ventilation systems were clearly identifiable for the indicators: I_{nCO_2} , I_{nRH70} or I_{nEwh} . On the contrary, the performances were almost the same or very close for other indicators like I_{nPM25} , I_{nHCHO} , I_{nRH30_70} . It clearly raises the question of how to aggregate these indicators and what method to use to rank the calculated performance of several ventilation systems. This could be used to determine at the design stage the most relevant ventilation system for a given building.

4.2.1 METHODOLOGY

We propose, in the next paragraphs, a simplified approach in 3 keys steps to achieve a robust ranking of the systems based on performance assessment results, to help in decision making (Figure 1). These steps are based on some relevant studies on existing robust assessment methods adapted to building sector (Kotireddy et al., 2018; Velasquez and Hester, 2013; Hoes et al., 2009; Sharma and Bhattacharya, n.d.) that seem relevant for application in the context of MOPA development.

The first step consists in performance assessment by simulations of the different design options (D_{opt}) to be tested. In building design, several parameters could be tested, such as thermal envelope materials, compactness ratio, external shadings, building orientation, heating systems, photovoltaic panels surface, etc. (Hoes et al., 2009; Kotireddy et al., 2017; Mechri et al., 2010). In the present work, the design options are the ventilation systems (MEV-cav, MEV-rh, MEV-rb, MVHR-cav, MVHR-rb), which have been tested with several sets of input parameters in the previous study on sensitivity analysis (*Part 4.1*). We propose to reuse the performance assessment results from the 500 simulations per ventilation system and focus on the following performance indicators: $I_{nCO_2}^n$, I_{nHCHO}^n , I_{nPM25}^n , I_{nRH70}^n , $I_{nRH30_70}^n$ and I_{nEwh}^n .

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In addition, the three reference scenarios (Ref_{low}, Ref, Ref_{high}) were also used for robustness assessment. The objective was to compare the ranking based on the OPA calculated with the set of 500 input scenarios and the ranking based on the OPA calculated with the reference and the two extreme input scenarios. This is to assess whether the three reference scenarios are sufficient to obtain a relevant ranking of ventilation systems or if more simulations are needed to achieve this goal.

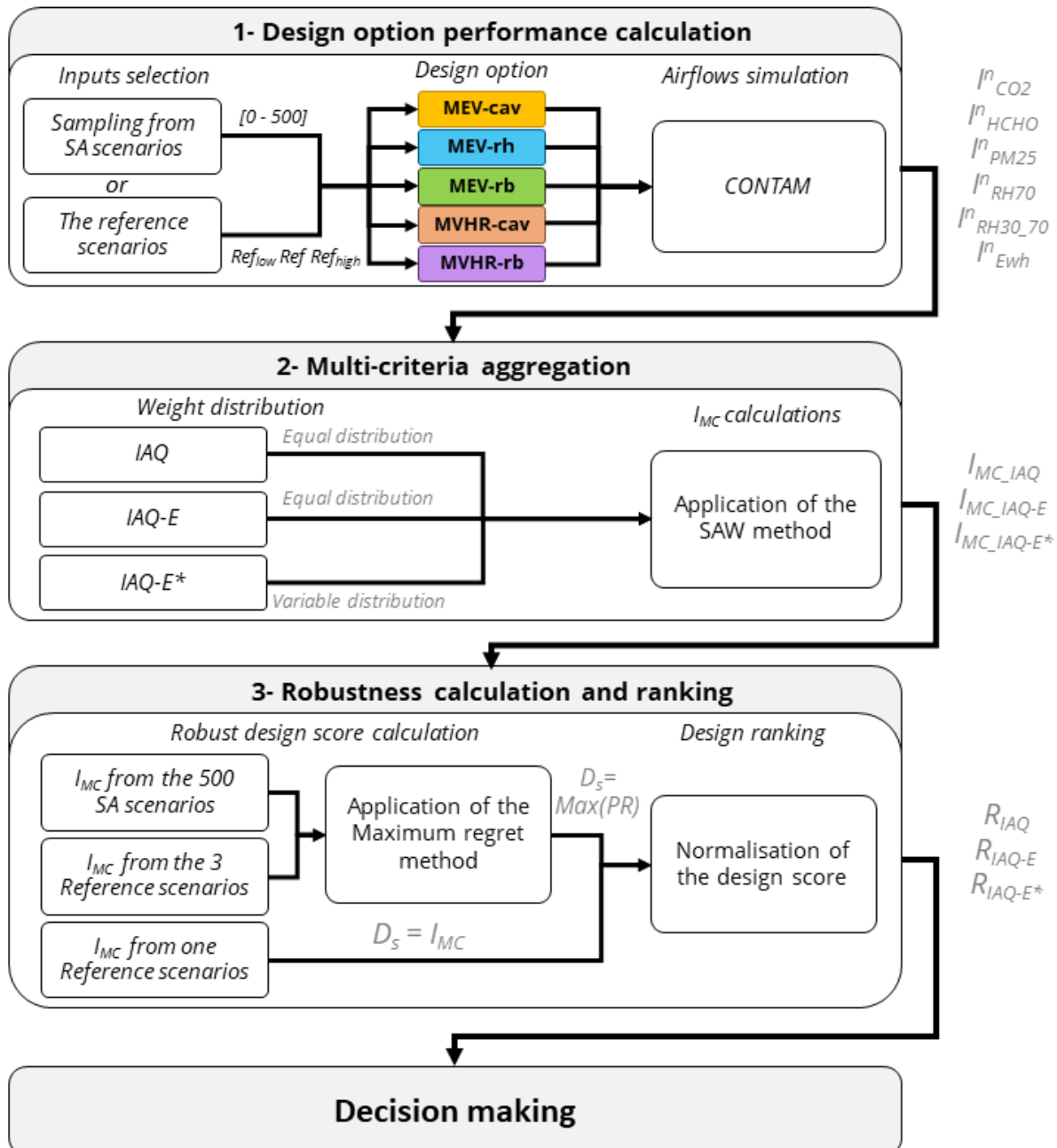


FIGURE 1 : METHODOLOGY FOR ROBUSTNESS CALCULATION AND RANKING FOR DECISION MAKING

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4.2 A ROBUST METHOD FOR PERFORMANCE ASSESSMENT

4.2.1.a) MULTI-CRITERIA AGGREGATION

The second step focuses on the method to be used to regroup the performance results from the six indicators to one aggregated value for each simulation. In the literature, the aggregation of several indicators for decision making could be found under the notion of *methods for "multi-criteria decision-making"* (MCDM)(Kotireddy et al., 2018; Namin et al., 2022; Velasquez and Hester, 2013). These methods generally propose a formulation to aggregate the multiple criteria for the tested design option under one value (here the performance indicator). We propose to name this aggregated value I_{MC} for Multi-Criteria Indicator.

According to the literature, there are numerous methods of MCDM, with for example at least 10 different methods identified in a recent review on MCDM (Namin et al., 2022). As the purpose of this work is not to test or compare all the possible methods; we decided to use the Simple Additive Weighting (SAW) method. This method is a common MCDM method widely used and seems relevant to our problem. Indeed, this method is a classical method consisting of adding up the indicators with a weighting coefficient to give more or less importance to certain indicators over others. The proposed calculation of I_{MC} with the SAW method (Equation 1) has been realised and adapted from the method described in (Podvezko, 2011).

$$I_{MC} = \sum_i \omega_i \cdot I_i$$

EQUATION 1

Where ω_i is the weighted normalized value ($\sum \omega_i = 1$) of the indicator I_i in [$I_{CO_2}^n$, I_{HCHO}^n , $I_{PM_{2.5}}^n$, $I_{RH_{70}}^n$, $I_{RH_{30_70}}^n$, I_{Ewh}^n].

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The weighted values can be set in several ways depending on the priority given to the indicator by the decision maker. To show the impact of weight arrangement priority on the I_{MC} calculation we build three weight distributions to calculate an associated I_{MC} (Table 1):

- **I_{MC_IAQ}** , corresponding to decision-making based only on the IAQ indicator, with the weight equally distributed over the five IAQ indicators ($I^{n_{CO_2}}$, $I^{n_{HCHO}}$, $I^{n_{PM_{2.5}}}$, $I^{n_{RH70}}$, $I^{n_{RH30_70}}$) and 0 for $I^{n_{Ewh}}$.
- **I_{MC_IAQ-E}** , corresponding to decision-making for overall performance assessment based on IAQ and Energy aspects, with the weight equally distributed on the six indicators. However, this distribution gives globally an advantage to the IAQ aspect as energy aspect is represented only by one indicator against five indicators for IAQ.
- **$I_{MC_IAQ-E^*}$** corresponding to a decision making for overall performance assessment based on IAQ and Energy aspects, but with variable and unequally distributed weight on the six indicators in comparison with I_{MC_IAQ-E} . This distribution was built to have an equal proportion between IAQ and energy. Consequently, the weight of $I^{n_{Ewh}}$ is set equal to 0.5. In addition, the IAQ aspects were differentiated to give more weight to the indicators $I^{n_{PM_{2.5}}}$ and $I^{n_{HCHO}}$. Their weight is doubled in comparison to the remaining IAQ indicators. This distribution for IAQ indicator could correspond to the assumption that moisture and CO_2 have less impact on the health in comparison with $PM_{2.5}$ and formaldehyde.

Distribution For I_{MC} calculation	Weight ω_i					
	$I^{n_{CO_2}}$	$I^{n_{RH70}}$	$I^{n_{RH30_70}}$	$I^{n_{PM_{2.5}}}$	$I^{n_{HCHO}}$	$I^{n_{Ewh}}$
I_{MC_IAQ}	0.2	0.2	0.2	0.2	0.2	0
I_{MC_IAQ-E}	0.16	0.16	0.16	0.16	0.16	0.16
$I_{MC_IAQ-E^*}$	0.071	0.071	0.071	0.143	0.143	0.5

TABLE 1 : WEIGHT DISTRIBUTION FOR I_{MC} CALCULATION

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4.2.1.b) ROBUSTNESS CALCULATION AND RANKING

Lastly, the robustness calculation step consists in integrating into one design score (D_s) all the individual performance indicators I_{MC} across the tested scenarios. Then this robust design score can be used for performance comparison of each design option (D_{opt}).

According to the comparative study for robustness method assessment of Kotireddy (Kotireddy et al., 2019); several methods exist for robustness calculations. In this study three robustness assessment methods were implemented -max-min method, best-case and worst-case method, and minimax regret method - and compared with the widely used Taguchi method.

The Max-Min method evaluates the performance spread (PS) between the maximum performance ($A_{D_{opt}}$) and the minimum performance ($B_{D_{opt}}$) of each design strategy across all the scenarios. The most robust design is the design with the smallest PS.

$$PS = A_{D_{opt}} - B_{D_{opt}}$$

EQUATION 2

The best-case and worst-case method evaluates the performance deviation (PD) between the maximum performance ($A_{D_{opt}}$) and the minimum performance of all design strategies (D_{min}). The most robust design is the design with the smallest PD.

$$PD = A_{D_{opt}} - D_{min}$$

EQUATION 3

The minimax regret method evaluates the performance regret (PR), with the difference between the performance indicators value and the minimum performance of each scenario across all designs (C_s). The performance regret is calculated for each design strategy D_{opt} across all the scenarios s . Then the MPR is the maximum performance regret of each design, and the most robust design is the design with the smallest MPR

$$PR = I_{MC,D_{opt},s} - C_s ; \text{ with } C_s = \text{Min}_s(I_{MC(all_D_{opt}),s})$$

EQUATION 4

$$MPR = \text{Max}_{D_{opt}}(PR)$$

EQUATION 5

The Taguchi method evaluates the robustness of the design strategies based on the mean and standard deviation of the performance indicators over all the scenarios. The most robust design is the design with the smallest mean and standard deviation (mean \cap std) (Hoes et al., 2009)

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The max–min, best-case and worst-case, and minimax regret robustness methods for design score provide a better integration of the uncertainty across all the scenarios in comparison with the Taguchi method. That could facilitate the decision-making process by reducing the gap between simulated performance at the design stage and the real performance (Kotireddy et al., 2019).

All four methods presented above were tested for the calculation of the robust design score. Finally, we selected the minimax regret method for design score calculation and the final ranking. Indeed, the minimax regret method has been identified as a less conservative approach to design decision making when risk can be accepted as a trade-off (Kotireddy et al., 2019). This is relevant for MOPA as compared to the other three methods which are more conservative. Moreover, the use of these three other methods had little impact on the final ranking, as presented in the *Annex IV*.

Finally for the results analysis we calculated the design score by applying Equation 5 with the I_{MC} from the 500 SA scenarios on one hand and with the I_{MC} from the 3 Reference scenarios on the other hand. The last case is the reference scenario, when the design score is directly the I_{MC} . Then this design scores were normalized In [%] by $\sum_{D_{opt}}(D_s)$ the sum of all the design scores. That facilitating the ranking and comparison between the weight distribution and the number of scenarios.

4.2.2 METHOD ANALYSIS AND RANKING RESULTS

The first step of the proposed robustness method consists in design option performance calculation. Here, the results of 500 simulations per design option used for SA are exploited. They were already presented and discussed in previous section 4.1. The following sections next result analyses are focused on the second step (multi-criteria aggregation) and the third step (robustness design score calculation) for robust ranking.

4.2.2.a) MULTI-CRITERIA AGGREGATION

In the Figure 2, we represent by boxplot the aggregate I_{MC} calculated with the three weight distributions (IAQ, IAQ-E, IAQ-E*) on the 500 simulated scenarios for each design option. The three reference scenarios are represented by small grey diamonds. The boxplots represent first quartile (q1) at the bottom of the box, the median in the middle and the third quartile (q3) at the top of the box; with the whiskers extend from the box by 1.5x the inter-quartile range (IQR) and the remaining outliers are represented by grey crosses.

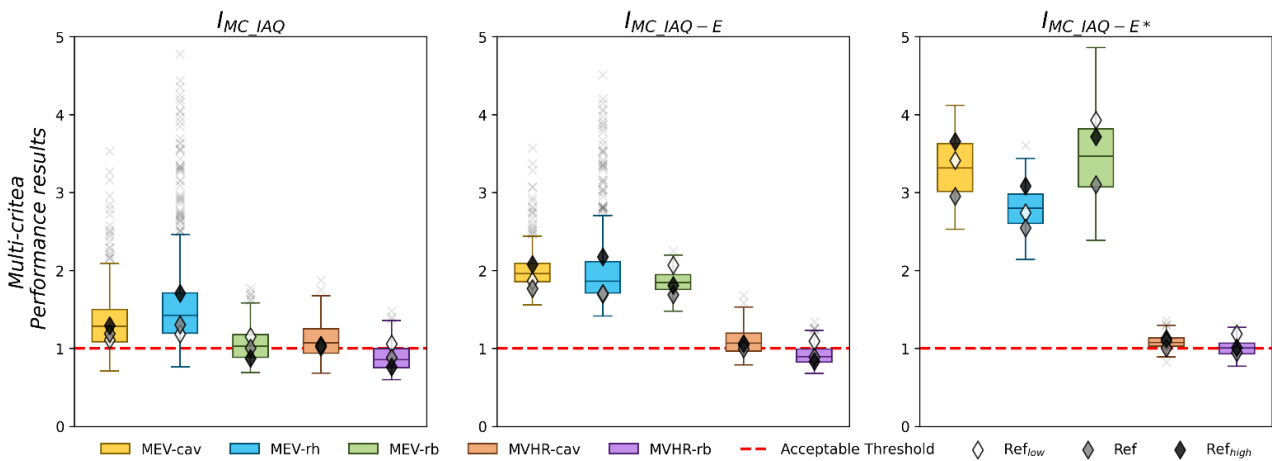


FIGURE 2 : MULTI-CRITERIA PERFORMANCE RESULTS OF THE FIVE DESIGN OPTION TESTED BY WEIGHT DISTRIBUTION

This representation gives a general overview of the I_{MC} results depending on the proposed weight distribution. For the first weight distribution, including only the IAQ indicators, the aggregated performance ($I_{MC_{IAQ}}$) results in values mainly between 1 and 2 for MEV-cav and MEV-rh. For the MEV-rb and the MVHR-cav the results are centred around the acceptable threshold of 1. ; only the MVHR-rb gives the values mostly lower than 1, meaning an acceptable performance. The outliers for MEV-cav and MEV-rh can be explained by the outliers on I_{RH70}^n for these two systems, already discussed in previous sections. For this first case, with constant weight distribution over IAQ only, there is no clear gap between the systems in comparison with the two others weight distribution results ($I_{MC_{IAQ-E}}$, $I_{MC_{IAQ-E*}}$). Similar unclear difference regarding the IAQ performance indicator results was already observed in the previous section 4.1. Such results may question the exclusive use of these IAQ indicators to rank the ventilation systems.

PART 4 : A ROBUST METHOD WITH QUANTIFIED UNCERTAINTY

4.2 A ROBUST METHOD FOR PERFORMANCE ASSESSMENT

The introduction of the energy indicator in I_{MC_IAQ-E} underlines the difference between MEV and MVHR systems. Indeed, the values of I_{MC_IAQ-E} are distributed around the acceptable threshold of 1 for MVHR. On the opposite, the values for I_{MC_IAQ-E} are much higher than the acceptable threshold, being distributed around the value of 2 for all three MEV systems. In detail, a higher energy performance of MEV-rh (meaning lower I_{Ewh}) raised its global performance (lower I_{MC_IAQ-E} median value) in comparison with the two other systems without heat recovery (MEV). This compensates a slightly lower IAQ performance for MEV-rh. Whereas the higher I_{Ewh} of the MEV-rb increased its I_{MC_IAQ-E} value in comparison with the two other MEV. As a result, the three MEV systems have now comparable median values of I_{MC_IAQ-E} . Regarding the two MVHR systems, there is no significant change and the MVHR-rb still performs slightly better than MVHR-cav, thanks to its better IAQ performance. Thus, the distribution of IAQ-E weights highlights the energy benefit of heat recovery from MVHR systems, this smoothed out the other differences observed I_{Ewh} in section 4.1.

In the last case IAQ-E*, with variable weight distribution, the differences between all systems are even more pronounced. Now, the MEV performance results are worse ($I_{MC_IAQ-E^*}$ range between 2.5 and 4). In addition, the differences between the three MEV systems are similar to the ones observed with the I_{Ewh} indicator, already discussed in section 4.1. On the opposite, both MVHR systems exhibit performance indicator close to 1, with a narrow distribution range.

The comparison of these three weight distributions shows that the weight distribution is a clear leverage to increase the differences between systems on the final aggregated performance results. However, the uncertainty distribution from the 500 simulations performed and presented with boxplots doesn't make systematically the ranking of the systems obvious. Moreover, in practice the use of weight distributions that voluntarily increase the difference between systems to facilitate the ranking could lead to a wrong extrapolation of the simulated performance results. For example, this may question the ranking based on the IAQ-E* where the differences are mainly related to the initial pronounced differences on the I_{Ewh} .

That confirms the need of the robust design score calculation of the next step, considering uncertainty, to finalize the ranking process for decision-making.

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4.2.2.b) ROBUST DESIGN SCORE CALCULATION AND RANKING

Figure 3 regroups, for the three tested weight distributions, the normalised design score [%] calculated with different scenarios. According to the methodology described above, the design score with 500 simulations and the three reference scenarios were calculated with the minimax regret method. The design scores for Ref_{low} , Ref , Ref_{high} , plotted in the figure, are directly the I_{MC} of each individual scenario. Then, for ranking, the best design option ($n^{\circ}1$) is the one with the lowest design score and the last ($n^{\circ}5$) is the highest design score.

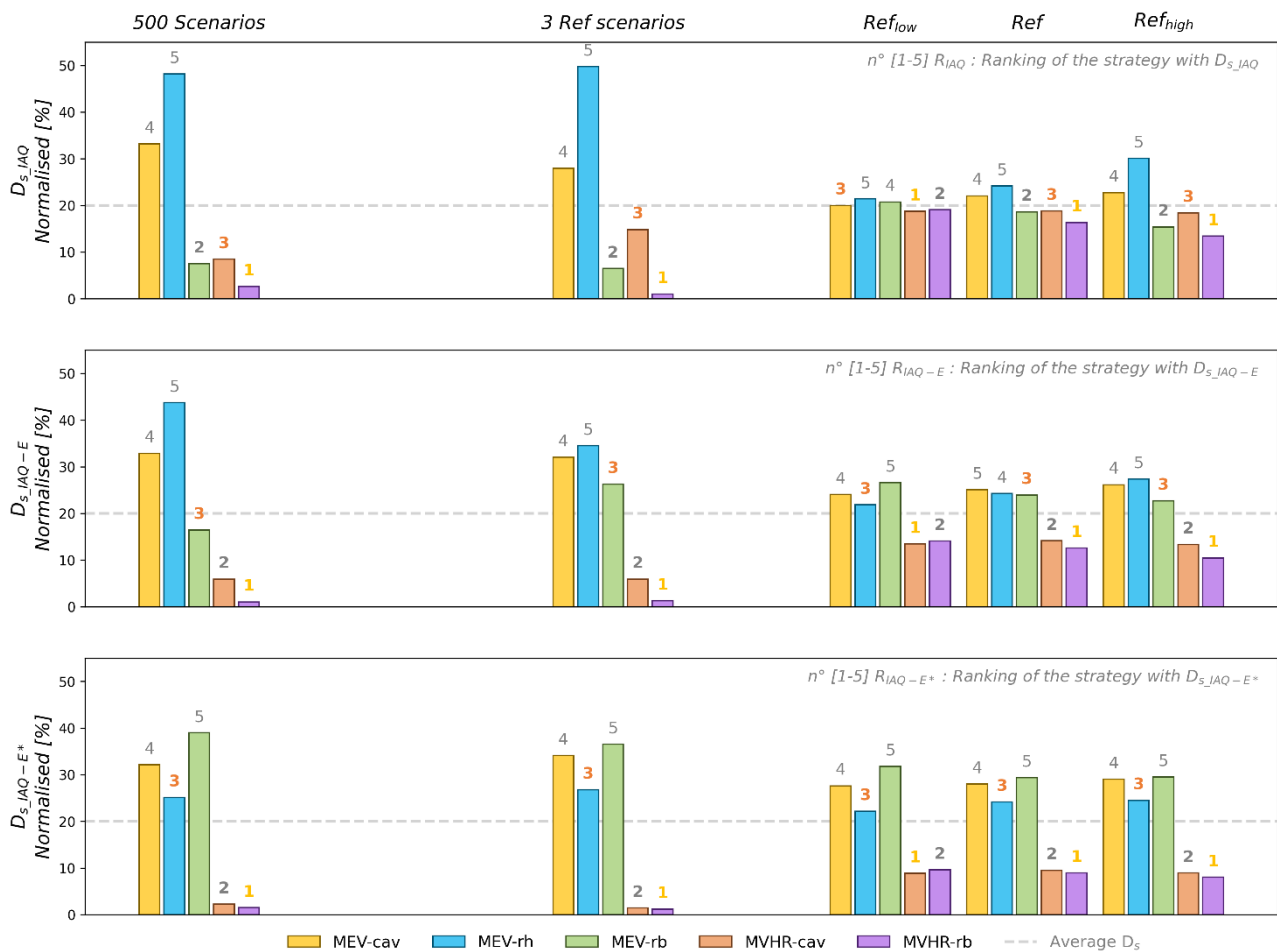


FIGURE 3 : ROBUST DESIGN SCORE AND RANKING, MINMAX REGRET METHOD.

DIFFERENT WEIGHT DISTRIBUTIONS ARE PRESENTED: EQUAL IAQ (TOP), EQUAL IAQ AND ENERGY, IAQ-E (MIDDLE), AND ENHANCED ENERGY AND HEALTH IAQ-E* (BOTTOM).

DIFFERENT SCENARIOS ARE PRESENTED: 500 PER SYSTEM USING UNCERTAINTY DISTRIBUTION ON INPUT PARAMETERS (LEFT), THREE PER SYSTEM: HIGH/REF/LOW (MIDDLE), AND ONE PER SYSTEM, SEPARATING HIGH/REF/LOW (RIGHT).

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At first, the ranking order calculated from the design score is the same with 500 simulations and the 3 ref simulations. This confirms previous observations made on Figure and in section 4.1, with the reference scenarios (grey diamonds) located inside the q1-q3 box. It means that the use of these 3 references scenarios for design score calculation and ranking provides the same information as the one obtained with 500 simulations design score calculation and ranking.

In detail, the ranking with design score calculated from each individual scenario (right plots), changes sometimes depending upon the weight distribution and the scenario used. For example, the ranking is inversed between MEV-cav and MEV-rh with the Ref scenario depending upon weight distribution. Another exemple is the Ref_{low} scenario, where ranking inversion is observed between the MVHR-cav and MVHR-rb as compared to all the other cases. In general, with Ref_{high} scenario the differences between design scores are more identifiable than for the Ref_{low} scenario.

Based on these results and the analysis made on Figure 2 we propose to :

- exclude the Ref_{low} scenarios from design scores for ranking. The risk is the loss of the uncertainty aspects, as this Ref_{low} ranking does not match with the ranking results obtained with the 500 simulations.
- keep the Ref scenario design score for an “optimistic performance ranking”, indeed the I_{MC} performance results of this reference scenario are mainly close to the q1 value and the ranking.
- keep the Ref_{high} scenario design score for a “conservative performance ranking”, indeed the I_{MC} performance results of this high reference scenario are mainly close to the q3 or the median value.

Associated together, the I_{MC} from Ref and Ref_{high} mainly cover the q1-q3 interquartile space (or at least the q1-mean). This allows to keep part of the uncertainty information and to calculate the design score with a ranking in accordance with the ranking of the 500 simulations.

Secondly, the impact of weight distribution on ranking is clearly identifiable with the design score. Indeed, the normalized design score is highly impacted for the MEV-rh from almost 50% (D_{S_IAQ}) to 25% ($D_{S_IAQ-E^*}$). An opposite evolution can be observed for the MEV-rb from almost 8% (D_{S_IAQ}) to 40% ($D_{S_IAQ-E^*}$). On the other hand, the results are only slightly impacted by the weight distribution for the MEV-cav (scores remaining around 32%), MVHR-cav (from 8% to 2%) and MVHR-rb (3% and lower). In all cases, MVHR-rb is ranked first and MEV-cav is ranked fourth, whereas MVHR-cav moves from third to second place due to the change in the ranking of MEV-rb.

This shows the importance of the weight given to the energy indicator and the priority balance between IAQ and energy. For instance, with the IAQ indicators only, the MEV-rb provides the second-best ventilation performance when it provides the worst one with the IAQ-E* distribution. Indeed, with the D_{S_IAQ-E} , the better IAQ performance of the MEV-rb is penalized because of its higher energy consumption; this explains the swapping between change MEV-rb and MVHR-cav, the latter performing much better in energy consumption (thanks to heat recovery) for a slightly worse IAQ performance. On the opposite, the MEV-rh is by far the worst with IAQ performance only but it can reach a good third position with the IAQ-E* distribution. In this case, the 50% weight given for the energy indicator in the $I_{MC_IAQ-E^*}$ calculation valorizes the energy benefits of MEV-rh in comparison with the two other MEV systems which certainly provide a better IAQ.

4.2.3 CONCLUSION

To conclude, we propose a three-step method to rank different ventilation design systems and we have tested it on five ventilation systems. We confirmed that the performance indicators aggregation with the SAW method is relatively accurate compared to the performance observed individually by each indicator in section 4.1. Then, the calculation of the design score with the minimax regret robustness method offers a clear advantage to highlight the difference between the ventilation systems, in order to rank them by including the uncertainty of several simulations.

In addition, we show that the use of the three reference scenarios could be sufficient to obtain a relevant ranking of the ventilation systems, in comparison with the ranking obtained with 500 simulations. However, if the number of simulations is limited, we propose to perform in priority the reference scenario (Ref), if the decision making needs an “optimistic performance ranking”, or the reference scenario with the highest emission rates (Ref_{high}) for a “conservative performance ranking”. Nevertheless, if there are no constraint, we encourage the decision maker to simulate at least the three reference scenarios and ideally 500 scenarios or more. The latter reinforces the validity of the calculated design score and ranking by including the uncertainty on input parameters.

For the MOPA, we do not retain the IAQ weight distribution as it doesn't include energy aspect for OPA. We propose to use at this stage the IAQ-E distribution in a conservative approach with balanced distribution across the six selected performance indicators. However, the IAQ-E* present a strong interest for a decision maker that would need a strictly equal proportion between IAQ and energy aspects. In future work it could be relevant to perform a more detailed sensitivity analysis on the weight distribution and then elaborate an adapted weighting selection method specifically for the six indicators (or more if added). Other MCMD could also be tested for indicators performance aggregation.

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In our case, the MVHR systems presented the best overall performance with an IAQ benefit of the smart ventilation strategy (MHVR-rb). Then, depending on the decision maker priorities, the third most performant system could be the MEV-rb if IAQ is favored, or the MEV-rh or if the energy savings are more essential. In both cases the variable smart ventilation strategies present a benefit over the constant MEV-cav.

Lastly, this ranking of the ventilation strategies shouldn't be considered as general performance ranking valid in all buildings. Indeed, the method has been applied only on one case study to demonstrate the relevance of the proposed methodology as a robust performance assessment decision-making tool for ventilation systems in buildings at the design stage.

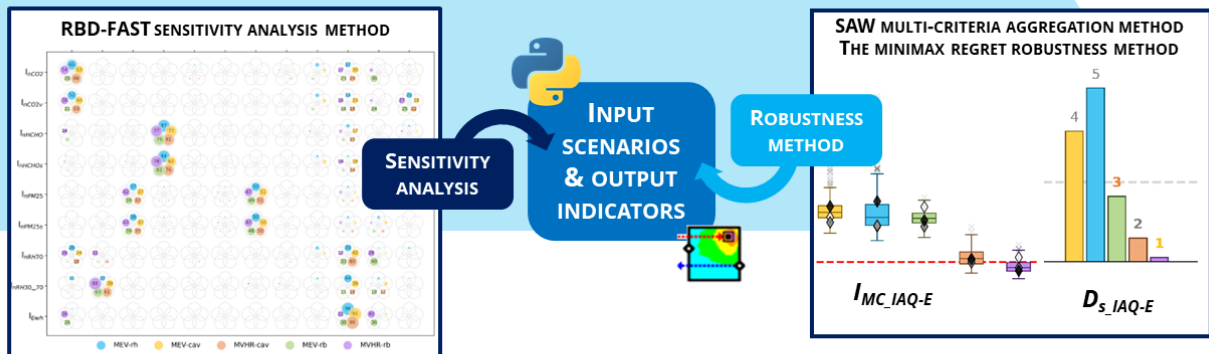
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PART 4



HIGHLIGHTS & LEARNINGS



INPUT - OUTPUT : UNCERTAINTY QUANTIFICATION AND DETERMINATION OF INFLUENTIAL PARAMETERS

OUTPUT: A THREE-STEP METHOD FOR DESIGN SCORE CALCULATION AND RANKING

In this last Part, we performed an uncertainty analysis on the single-family house case study by applying the RBD-FAST sensitivity analysis method. This method consists in varying inputs over a large number of simulations to calculate the Sobol indices, which allow the quantification of the sensitivity of the output to the variation of input. The method was tested on five implemented ventilations systems from constant airflows strategies to smart ventilation strategies. In each analysis, we varied 12 inputs of the model over 2500 simulations and studied the impacts on 9 output parameters.

The main influential input parameters identified were the bio-effluents, the $PM_{2.5}$ and moisture activities emissions, the formaldehyde emissions from furniture, the $PM_{2.5}$ deposition velocity, and the airflows rate values input. That confirmed the need to pursue research into parameters for pollutant emission scenarios. To simplify the assumption of the MOPA, moisture buffering effect, and $PM_{2.5}$ resuspension rate could be set to default values, as their variability is not impacting the performance indicators. Regarding the air leakage through the envelope, the reference value can be use if actual building value is unknown, as it appears to not be an influential parameter. However, it might be relevant in a future work to perform a detailed sensitivity analysis by testing higher air leakage levels focusing on the distribution of air leakage around the envelope (see detailed idea in Annex IV). Indeed, the tested range for $q4Pa$ [0.05; 0.9] was adapted on new buildings with high energy performance and airtight envelope. If the method is applied on renovation, old buildings could have four to ten times higher air leakage combined with unbalanced air leakage distributions which could have an impact on the performance indicator.

The additional IAQ output for short term exposures $I_{nHCHO-5}$ and $I_{nPM25-5}$, provide almost the same information as their long-term equivalent. Therefore, we decided not to retain these two indicators in the MOPA and to keep the reduced set of five IAQ indicators. We also propose to keep the use of the MVHR-cav as a reference strategy to normalize the I_{Ewh} indicators that allow easier comparison of other strategies in energy performance evaluation.

Lastly, we build and presented an application of a three-step method for robust design score calculation and ranking of the system. The first step consisted in performance calculation of the tested ventilation systems. For this step, we based our application on the performance results calculated for the sensitivity analysis. Then, we used the SAW method for the multi-criteria aggregation step, that is a simple aggregation weighting method which regroups the 5 IAQ indicators and the energy indicators under one value that we named I_{MC} for “multi-criteria” indicator. The third step provided a robust design score calculation in order to rank the ventilation systems. For MOPA, such a robust design score calculation presents the advantage of integrating the uncertainty of all the simulations performed (here 500 per system) in the ranking. Indeed, beyond 3 tested ventilation systems with several calculated performance indicators and many input scenarios, it becomes complex to identify the best performing systems compared to each other.

All these learnings from the sensitivity analysis and robustness method calculation allowed to refine the modeling assumptions input, the selected output performance indicators and this facilitate the ranking between the ventilations systems.

SYNTHESIS METHOD FOR OVERALL PERFORMANCE ASSESSMENT

FINAL MOPA

1 Scenarios
2 Simulations
3 Indicators
4 Robustness

To demonstrate that we have met the objectives of this PhD work as far as possible, we have presented in Figure 1 a synthesis of the developed MOPA-Method for Overall Performance Assessment, illustrated by a final application result in Figure 2.

These results show the improvement of the assessment method for overall performance of ventilation systems at design stage. Indeed, the work started in Part 1 with five IAQ indicators that now have been completed with energy indicators and a design score for ranking.

Then, in this MOPA, we propose three level of input scenarios that could be employed depending on the level of uncertainty quantification needs. If no uncertainty is needed, only one scenario can be used. For a partial uncertainty quantification, the three-reference scenarios can be used. Lastly, for a complete uncertainty quantification, a large range of scenarios for sensitivity analysis must be performed (in this application we performed 500 input scenarios). The CONTAM airflows simulation is proposed for modeling the ventilation systems design options, but another airflows simulation or building model could be used. We retain to weighting distribution for multi-criteria performance indicators aggregation, but another distribution could be used depending the need of the decision maker. Finally, the design score can be calculated with the minimax regret robustness method and normalized for ranking.

To explore the potential of performance-based approach as a decision-making tool for ventilation systems in building design, we applied this final OPA on the five ventilations systems studied in Part 4, with in addition the MEV-RhB system from Part 1 & 3.

The complete uncertainty level was selected with 500 new scenarios sampled with the Latin hyper cube method. Here were varied only the reduced sets of influential inputs parameters identified in Part 4 (summarized in Table 1). The air leakage level of the building was considered unknow and fixed with a q4a at $0.4 \text{ m}^3 \cdot \text{h} \cdot \text{m}^{-2}$ according to the recommended reference value in the national French building regulation. The $\text{PM}_{2.5}$ resuspension rate was also set at the reference value pending further work on this parameter.

SYNTHESIS

A METHOD FOR OVERALL PERFORMANCE ASSESSMENT

Inputs	Description	Low	Reference	High
Bio-eff	occupant CO ₂ and H ₂ O emissions	0	0.333	1
Acti-H₂O	moisture emissions from activities	0.7	1	1.3
Acti-PM_{2.5}	emissions from cooking activities	1.26	1.91	2.55
Furn-	HCHO formaldehyde emissions from furniture	4.5	12	23.6
Q-exh	Total exhaust airflow multiplier	0.7	1	1.3
Q-max	Maximum airflow M/Qboost multiplier	0.7	1	1.3

TABLE 1 : SUMMARY OF THE VARIABLES INPUTS FOR THE FINAL APPLICATION

Outputs	Description	AT
I_{nCO2}	Maximum cumulative CO ₂ exposure over 1000 ppm	1000 .d (ppm.h)
I_{nHCHO}	Maximum cumulative HCHO exposure among all the occupants	9.d (μg.m ⁻³ .h)
I_{nPM25}	Maximum cumulative PM _{2.5} exposure among all the occupants	10.d (μg.m ⁻³ .h)
I_{nRH70}	Maximum percentage of time with RH > 70% among all the rooms	18%; 10.8%;1.8%
I_{nRH30_70}	Maximum percentage of occupant time spent with RH outside the range [30-70%]	14.4%
I_{Ewh}	Heat losses from total exhaust airflows	-

TABLE 2 : SUMMARY OF THE OUTPUTS FOR THE FINAL APPLICATION

To illustrate the impact of the decision maker choices in weighting distribution, we calculated the multi-criteria indicator I_{MC} with both the IAQ-E and the IAQ-E* proposed distributions in Part 4, resulting in two robust design scores and rankings. This gives us two robust design scores and rankings.

Figure 2 presents the performances of each system, as it could be presented in a dashboard of a design support or decision-making tools. The developed representation for IAQ performance combines a radar graph and a boxplot, with the median value in solid line and the q1-q3 envelope in a light-colored background. The IAQ radar is completed with the I_{Ewh} boxplot. At the bottom are regrouped the I_{MC} and design score for the two tested weighting distributions.

In a short results analysis of the final application of the MOPA, according to the design score, the two MVHR ventilation systems have still the highest performance regarding both IAQ and energy. Followed by the MEV-rhB or MEV-rb depending on the chosen weighting priority, which also showed interesting IAQ and energy performance among the MEV systems. With its third position, the MEV-rhB seems to have a slight advantage over the MEV-rb which is penalized by less good results concerning energy. In fifth place, the MEV-cav system maintains a stable design score that confirms its role as a reference for MEV systems.

With its first position in this final application the MVHR-rb confirmed the potential of smart ventilation for providing acceptable IAQ performance coupled with some energy savings.

SYNTHESIS

A METHOD FOR OVERALL PERFORMANCE ASSESSMENT

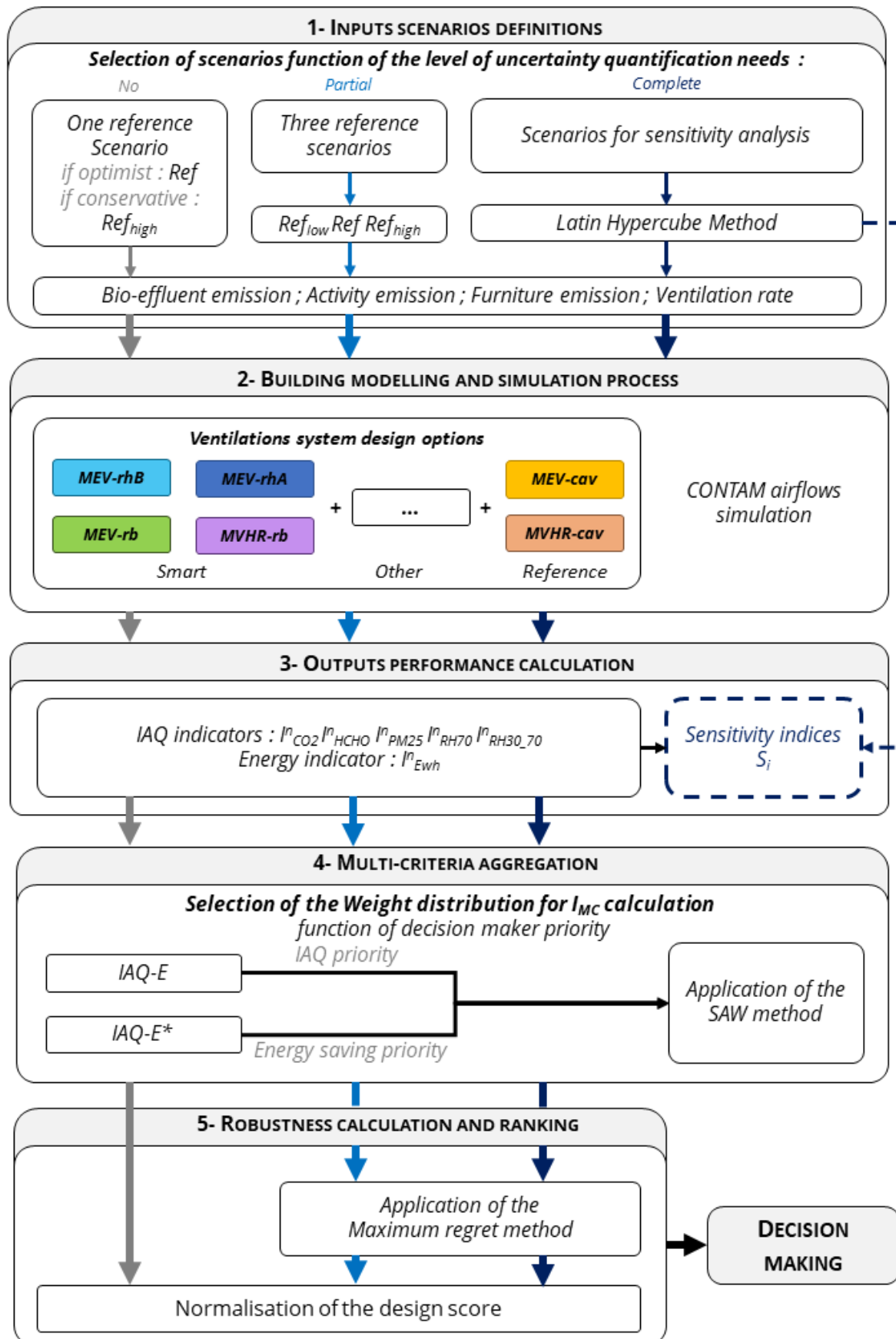


FIGURE 1 : SYNTHESIS OF THE PROPOSED OVERALL PERFORMANCE ASSESSMENT METHOD FOR VENTILATION SYSTEMS

SYNTHESIS

A METHOD FOR OVERALL PERFORMANCE ASSESSMENT

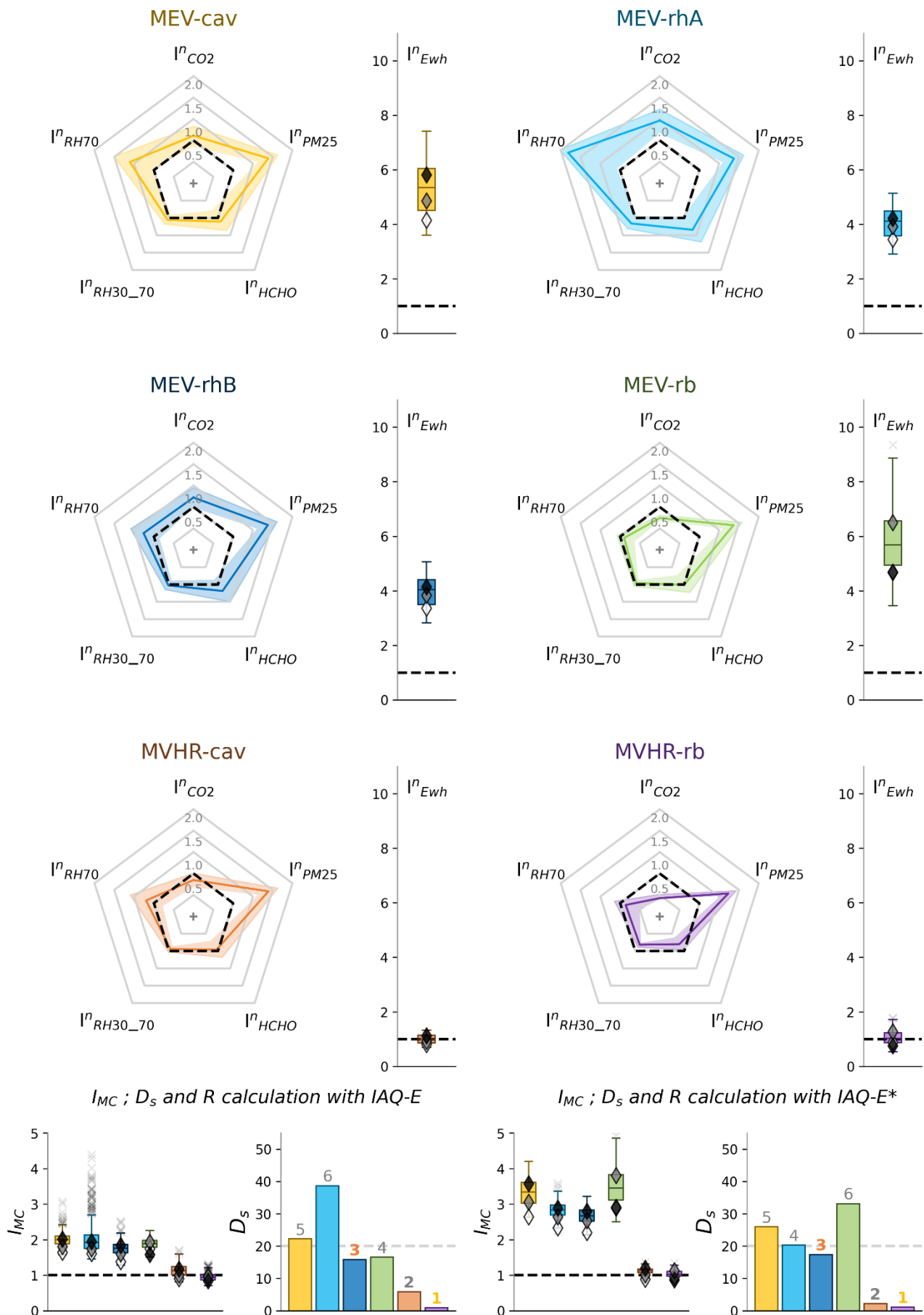


FIGURE 2 : OVERALL PERFORMANCE RESULTS, DESIGN SCORE AND RANKING FOR THE 6 VENTILATION SYSTEMS TESTED

CONCLUSION

ANSWERS TO THE RESEARCH QUESTIONS & PERSPECTIVES



To conclude this PhD work developed in four parts, we detail how we answer to the research questions dressed at the beginning of the work.

The first part was dedicated to the presentation of the overall performance method oriented first on IAQ performance. That was realized through two review articles published in the Journal of Building Engineering.

The second part focused on the energy indicator development and questioned the need of energy simulations for such performance assessment method. The energy simulation performed with DOMUS allowed to test several temperature control strategies and we developed the basis of a co-simulation between DOMUS and CONTAM. This work would never been possible without the long collaboration with the LST laboratory of the PUCPR University, Curitiba, Brasil. However, the potential publication in this part has been limited by the difficulties in the co-simulation implementation on a full case study.

The third part detailed two case studies applications with different building types and contexts, which have been valorised in two conferences. The first study based on a French single-family low energy house was presented in 2022 at the ASHRAE – AIVC conference in Athens. It was also a great opportunity to attend and present this work in a meeting of the IAE-EBC Annex 86. The second study on the Danish apartment in multi-housing building was developed during an international mobility at DTU Denmark during 4 months in 2021 and presented in 2022 at the IBPSA: BuildSim Nordic conference (By J. Kolarik because of inability to be present at the conference).

The last part regrouped all the learnings aggerated in the previous parts and during the PhD to perform a sensitivity analysis for uncertainty quantification. This work aims to be valorised in a journal article. In addition, an exploratory work on robustness method for ranking the performance of the ventilation systems finalized the proposed Method for Overall Performance Assessment-MOPA.

ANSWERS TO THE RESEARCH QUESTIONS



WHAT ARE THE RELEVANT EXISTING IAQ INDICATORS? HOW TO COMPLETE THEM WITH ENERGY PERFORMANCE INDICATORS ?

The relevant IAQ indicators are a set of 5 indicators which have been proposed in the Part 1: I_{CO_2} , I_{HCHO} , $I_{PM_{2.5}}$, $I_{RH_{70}}$, $I_{RH_{30-70}}$. These indicators are normalised by their associated acceptable thresholds. Indicators lower than 1 mean the performance is achieved and the ones higher than 1 mean the performance needs to be improved. In addition, the use of normalised indicators facilitates the results visualisations and analysis, as demonstrated through the various performance results representation in this work, such as radar graphs, boxplots, or scatter plots.

We decided to exclude at this stage the short-term exposure indicator as they provide almost the same information as their long-term equivalent. This to maintain a reduced number of IAQ indicators.

Lastly, this first performance results on the case study application highlighted the importance of taking into account IAQ parameters other than the traditional CO_2 and humidity, for a better consideration of IAQ in buildings.



HOW TO DEFINE, MODEL AND CHARACTERISE THE ENERGY SAVING ACHIEVED BY VENTILATION SYSTEMS; IN ORDER TO BUILD AND VALIDATE A NEW SET OF PERFORMANCE INDICATORS COUPLING ENERGY AND IAQ?

To define and characterize the energy saving achieved by ventilation systems, the composition of heat losses for exhausted airflows and fan energy consumption under one energy performance indicator could be the most precise indicator. But such precision may not be necessary for the OPA to provide the correct order of magnitude of energy savings potential. As with the constant temperature assumption in the CONTAM airflow simulations, discussed in Part 2, we proposed that no additional energy simulation is needed, if this method is applied during the heating period.

As a consequence, we propose to keep only the heat-loss part of this I_{EC} . Indeed, we consider as more relevant to focus on the heat losses saving potential from variable ventilation strategies instead of the energy consumption of the fans, as the instant power of the fan is only proportional to the exhaust/supplied. That also allows to maintain a reduced number of indicators used for the MOPA.

CONCLUSION

ANSWERS TO THE RESEARCH QUESTIONS



HOW TO CORRECTLY ESTIMATE AND CHARACTERIZE THE EMISSION OF A POLLUTING SOURCE FROM DIVERSIFIED EXISTING MATERIALS, PRODUCTS AND ACTIVITIES IN A BUILDING; IN ORDER TO BUILD RELEVANT EMISSIONS SCENARIO AT THE HOUSING SCALE?

As highlighted in Part 1, it is difficult to build scenarios from the material, product, and activity scale to the dwelling scale.

For occupancy schedules and moisture activities from the occupants (shower, cooking, laundry drying), we used detailed data from the French IAQ national observatory assuming two occupants in one bedroom and one in each of the others.

For the formaldehyde, we accordingly suggest using data gathered on French low-energy homes to calculate average in-situ loads at the dwelling scale.

For the PM_{2.5} emission rate scenarios, from our first literature analysis, we retained only emissions from cooking activities to build a low, a medium and a high emission rate scenario.

We proposed an illustration regrouping all the proposed emission rates scenarios that could be use as toolbox and should be adjusted by the modeller based on the case study and its local context.



WHAT ARE THE IMPACTS OF HYPOTHESES AND PARAMETERS USED IN THE MODELLING OF THESE POLLUTANTS SOURCES REGARDING THE LACK OF AVAILABLE DATA AND THE DIFFICULTIES TO EXTRAPOLATE THEM AT THE SCALE OF THE BUILDING ?

The results comparison in Part 3 highlights that cooking hood, cooking boost and kitchen volume zone could explain a part of the reason for high PM_{2.5} concentration.

The sensitivity analysis work in Part 4 confirmed the need to pursue research on the parameters for pollutant emission scenarios. To simplify the assumptions of the MOPA, we showed that the moisture buffering parameters and the PM_{2.5} rates could be set to default values, as their variability is not impacting the performance indicators. But a specific focus on the PM_{2.5} deposition velocity parameter implemented in CONTAM is need as it is responsible of about 50% of the sensitivity impact on the PM_{2.5} indicator.

CONCLUSION

ANSWERS TO THE RESEARCH QUESTIONS



WHAT IS THE UNCERTAINTY AND WHAT ARE THE MAIN INPUT PARAMETERS IMPACTING THE ASSESSED PERFORMANCE ?

Based on Part 4 results on uncertainty quantification, the main influential input parameters identified were the Bio-effluent emission; the PM_{2.5} cooking emission, the moisture activities of the occupants, the formaldehyde furniture emission rate and the PM_{2.5} velocity deposition. That confirmed the need to pursue research on all these parameters.

In addition, exhausted airflows and maximum cooking airflows are the main contributors to the uncertainty on the energy indicator; and also present in a more moderate way regarding the uncertainty on IAQ performance.



HOW TO BALANCE IAQ AND ENERGY PERFORMANCE ASSESSMENT TO PROVIDE A ROBUST RANKING OF THE VENTILATION SYSTEMS ?

To balance the IAQ and energy performance assessment, we proposed in the Part 4 to regroup the IAQ and energy indicators in one unique aggregated indicator I_{MC} that reflect the overall performance of the ventilation systems.

The proposed method is the simple aggregation weighting method, and the weighting distribution could be adjusted function of the decision marker priority. Then based on I_{MC} , the robustness minimax regret method can be used for the calculation of a design score which is normalized for ranking the ventilation systems performance.

PERSPECTIVES

We summarized the possible improvements and future works identified in the following points :

- **Improve scenarios and models for pollutants emissions** : as highlighted in the sensitivity analysis, the main influential parameters were the Bio-eff, Acti-PM_{2.5}, Acti-H₂O, Furn-HCHO, MPM_{2.5}-vd . The number of occupants and their bio-effluent emissions profiles could be mixed to evaluate if such more detailed occupants models have an impact on the assessed performance or if the reference assumptions are sufficient. The same approach could also be used with the cooking emission scenarios by mixing the low, medium, high type of cook over the week. Then the impact of additional PM_{2.5} sources needs to be quantified in order to evaluate if our assumption to use only the cooking activity is enough representative or if it underestimates the PM_{2.5} exposure. A specific work on PM_{2.5} velocity deposition parameter in CONTAM model should also be performed. Moreover, the impact of the outside pollutant concentrations and infiltration rates could also be relevant to explore other smart ventilation strategies based on the level of outdoor pollution.
- **An in-situ measurement declination of the method** : The five IAQ Indicators and the energy indicator could be calculated based on in-situ measurement instead of simulation results. However, that questions the feasibility to measure in each room all the IAQ parameters and the exhausted airflows over the total heating period. Some simplification may be explored such as :
 - **A shorter period**, but the uncertainty from this period reduction should be quantified. That could be done by airflows simulations and measurement comparison on a week period, similar to the comparison made on C1 and C2 campaign in Part 2. But with a larger number of tested period and with extended comparison analysis.
 - **Reduction of the studied parameters for in-situ measurement**: At this stage, 4 indoor environment parameters are used to calculate the IAQ and energy indicators (CO₂, relative humidity, formaldehyde and PM_{2.5}). However, these parameters may have correlation between each other. If such correlation can be characterized, the number of parameters could be then reduced. Moreover, such correlations could have been calculated and deepened with the sensibility analysis simulations results.

This *in-situ* measurements declination could help to assess the performance of ventilation systems at commissioning to quantify the gap between designed performance and real performance. This could also be used to measure the performance guarantee in time.

- **Testing other short-term exposure indicators :** *The short-term exposure indicator implemented in Part 3 and 4 but not retained were based on the short-term exposure indicators available in the literature. However, few proposals were available in the literature, and we showed that they were not suitable for OPA. Indeed, the 24-hour average for PM_{2.5} may not be suitable for the indoor environment and peak exposure of peak emissions from activities (such as cooking in this work but others in general). Where for the formaldehyde the one-hour period may not be the most relevant as we modelled here formaldehyde with a background constant emission. A sensitivity work on the ideal period, the threshold and the emissions sources variations could be relevant to build a specific short-term indicator to be integrated in the MOPA.*
- **Energy simulations for extended energy performance indicators :** The energy indicator was limited to only the heat losses from ventilation as we were focusing only on the heating period. But an improved energy performance indicator could include other aspects such as night cooling potential, summer comfort impact. That is even more relevant with the smart ventilation systems which could be specifically designed to provide passive cooling in summer. In this case, the use of energy simulation tools will be necessary to overcome the inter-seasonal and summer period limitations of the constant temperature assumptions highlighted with CONTAM in Part 2.
- **DOMUS-CONTAM co-simulation:** the initiated work for the coupling between DOMUS and CONTAM with the LST of PUCPR Curitiba will be pursued to overcome the difficulties of the co-simulation process implementation. With the aim to valorize this development by a successful case study application.
- **Sensitivity of the multicriteria aggregation method :** the method used for multicriteria aggregation was the SAW method with weighting distribution. The impact of the weight distribution needs to be clearly explored in order to propose a distribution adapted to the IAQ and energy indicators used. But also, to be able to propose more declinations adapted to several profiles of decision-making priority. Moreover, other multicriteria aggregations could be tested and may be more relevant for the overall performance assessment of ventilation.
- **Sensitivity of the robust design score calculation method :** the method used for the design score calculation and ranking was based on the minimax regret method as it appears the most relevant. However other methods exist and the number of simulations used for the design score calculation or the number of ventilation strategies design tested may have an impact on the final ranking. This needs to be quantified on other case studies to be generalized.

CONCLUSION

PERSPECTIVES

Finally, this MOPA is a proposition for overall performance assessment method that highlighted the potential of performance-based approach for ventilation systems OPA. This provides answers elements to the research questions asked in this PhD work, but it also open the discussion on how to generalize such a method at design stage and on the entire life cycle of ventilations systems in a building. Indeed, we should keep in mind that it has been tested only on few case studies based on simulations and several more applications on different houses geometries and ventilation systems needs to be studied before to be generalized.

RÉSUMÉ LONG EN FRANÇAIS

ÉVALUATION DE LA PERFORMANCE GLOBALE DE LA VENTILATION INTELLIGENTE EN LOGEMENT BASSE CONSOMMATION

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INTRODUCTION

QUALITÉ D’AIR INTÉRIEUR, ÉNERGIE ET VENTILATION INTELLIGENTE

Le secteur résidentiel représente 28% de la consommation totale d'énergie finale dans les pays de l'Union européenne (Direction générale de l'énergie (Commission européenne), 2022). De plus, en 2019 en France, le secteur du bâtiment était responsable de 25 % des émissions nationales de carbone (RE2020 dossier de presse, 2021). Ainsi, le bâtiment est un secteur présentant d'importantes sources d'économies d'énergie et de réductions des émissions carbone. Pour soutenir la transition énergétique dans ce secteur, des objectifs européens ambitieux (Directive EPBD, 2003:2010.) visent à généraliser les bâtiments à haute efficacité énergétique. En France, la nouvelle réglementation thermique RE2020 poursuit les objectifs de réduction de la consommation énergétique des bâtiments en diminuant de 30% les besoins bioclimatiques Bbio par rapport à la précédente réglementation thermique (RT2012) (Bbio, est un indicateur traduisant les besoins énergétiques du bâtiment dans la réglementation RE2020). (RE2020 : Arrêté du 4 août 2021 - Légifrance ; RE2020, 2021).

Pour atteindre ce niveau de performance énergétique, des améliorations ont été apportées à l'étanchéité à l'air et à l'isolation des bâtiments afin de réduire les déperditions thermiques. Ces gains de performance permettent de réduire les besoins de chauffage ou de climatisation. Cependant, la ventilation dans les bâtiments, pour le renouvellement de l'air intérieur reste une source de déperdition et de consommation d'énergie. Avec l'avènement des nouveaux bâtiments à faible consommation d'énergie, les systèmes de ventilation prennent alors une part croissante de la consommation globale du bâtiment à l'intérieur (Walker et al., 2014).

Or, l'air intérieur est un environnement dans lequel on trouve un plus grand nombre de polluants que dans l'air extérieur et à des concentrations plus élevées. Sachant qu'un Européen passe en moyenne 60 à 90 % de son temps à l'intérieur, l'exposition quotidienne à ces polluants peut donc être importante et avoir un fort impact sur la santé. En France, la mauvaise qualité de l'air intérieur (QAI) est responsable de 30 000 décès et représente un coût socio-économique estimé à plus de 19 milliards d'euros par an (Bayeux et al., n.d.). Les systèmes de ventilation jouent alors un rôle clé dans l'évacuation et la dilution des polluants.

La ventilation, est donc à la croisée des enjeux énergétiques et des enjeux de qualité d'air intérieur dans le bâtiment. Pour les aspects énergétiques, la performance de la ventilation est souvent intégrée dans les calculs énergétiques exigés par les réglementations thermiques. Cependant, les critères de performance de la ventilation sont encore en cours de développement pour les aspects liés à la qualité de l'air intérieur. Ainsi, l'évaluation de la performance de la ventilation doit être développée dans une démarche de performance globale combinant la performance énergétique et la performance de la QAI pour répondre à ces deux enjeux.

Dans ce contexte, les systèmes de ventilation intelligents, en plein essor mais encore peu abordés dans la littérature scientifique, sont de bons candidats pour répondre à ce besoin de performance globale. En effet, les systèmes de ventilation intelligents sont caractérisés par des débits de fonctionnement variables qui peuvent être adaptés aux conditions de pollution intérieure, aux scénarios d'occupation, voire aux pics de pollution extérieure. Cette flexibilité donne la possibilité d'optimiser les périodes de renouvellement d'air pour réduire les pertes de chaleur, améliorer la QAI et limiter la consommation énergétique des systèmes. Une définition récente est donnée par l'AIVC (Durier et al., 2018) :

"LA VENTILATION INTELLIGENTE EST UN PROCESSUS VISANT À AJUSTER CONTINUUELLEMENT LE SYSTÈME DE VENTILATION DANS LE TEMPS, ET ÉVENTUELLEMENT EN FONCTION DU LIEU, AFIN DE FOURNIR LES AVANTAGES EN QAI SOUHAITES TOUT EN MINIMISANT LA CONSOMMATION D'ÉNERGIE, LES FACTURES ET D'AUTRES COÛTS HORS QAI (TELS QUE L'INCONFORT THERMIQUE OU LE BRUIT) [...]."

Ainsi, l'ajustement continu du débit de ventilation est la caractéristique principale d'un système de ventilation intelligent. Par exemple, les systèmes de ventilations hygroréglables qui sont couramment utilisés en France ; sont des systèmes de ventilation mécanique contrôlée qui ajustent en permanence leurs débits d'air en fonction de l'humidité de l'air intérieur. Par conséquent, ce type de ventilation contrôlée par l'humidité peut être considéré comme un système de ventilation intelligent. Plus généralement, un système de ventilation qui ajuste en permanence ses débits pour remplir une ou plusieurs fonctions tout en étant sensible à son environnement est un système de ventilation intelligent.

La revue de plusieurs études de 2018 à 2022 (détaillé dans l'introduction du manuscrit de thèse en anglais) montre le potentiel des stratégies de contrôle innovantes pour l'amélioration de la QAI et les économies d'énergie. Mais pour cela il est nécessaire d'établir une méthode pour évaluer leur performance effective par rapport aux stratégies traditionnelles de débit d'air constant.

LE BESOIN D'UNE APPROCHE PERFORMANCIELLE POUR LA VENTILATION

Les réglementations nationales relatives aux systèmes de ventilation dans les bâtiments résidentiels ont peu évolué au cours des 30 dernières années. Les réglementations actuelles sur la ventilation proposent généralement *une approche prescriptive* préconisant, par exemple en France (JOFR, 1982), des débits d'extraction d'air vicié à respecter en fonction de la taille de la maison et du type de pièce.

Or il serait préférable de se concentrer sur des niveaux de qualité d'air à atteindre plutôt qu'uniquement sur des débits d'air à respecter. Ceci dans le but de garantir à la conception la performance fournie par le système de ventilation en termes de QAI. Cette approche visant un des niveaux de QAI à respecter est *une approche performancielle*. Dans le domaine du bâtiment ce concept de méthode pour une conception basée sur des exigences de performance, peut être illustrée par la définition de la commission CIB W60 (Gibson, 1982) fréquemment citée dans la littérature :

"LA PRATIQUE QUI CONSISTE À PENSER ET À TRAVAILLER EN TERMES DE FINS PLUTÔT QUE DE MOYENS [...] EN FONCTION DE CE QU'UN BÂTIMENT OU UN PRODUIT DE CONSTRUCTION DOIT FAIRE, ET NON PAS EN FONCTION DE LA MANIÈRE DONT IL DOIT ÊTRE CONSTRUIT".

Les approches performanciennes peuvent au-delà des aspects énergétiques et de la QAI s'appliquer à toutes les parties d'un projet de construction. Idéalement, elle pourrait inclure le confort acoustique, le confort visuel, l'accessibilité, la sécurité, la maintenabilité, la durabilité ou de nombreux autres aspects du cycle de vie complet du bâtiment.

Pour la ventilation, une approche performancielle globale, incluant la qualité de l'air intérieur, le confort et la performance énergétique, permettrait d'éviter les conflits entre ces éléments, tels que les économies d'énergie par rapport au risque de moisissure (Ginestet et al., 2020). De telles réglementations utilisant des approches performancielle pour la ventilation des bâtiments doivent encore être développées. Ainsi les enjeux d'approche performancielle pour la ventilation sont au cœur de ce travail de thèse, où nous nous concentrons sur les aspects liés à la QAI et à l'énergie pour l'évaluation de la performance globale (*OPA pour overall performance assessment*) des systèmes de ventilation intelligents.

QUESTIONS DE RECHERCHE ET OBJECTIFS

Avant de proposer une méthode d'évaluation de la performance globale (MOPA pour Method for Overall Performance Assessment et OPA pour Overall Performance Assessment) pour la ventilation intelligente, il est nécessaire de s'appuyer sur les approches performanciennes existantes dans le cadre de la ventilation. Celles-ci se concentrent essentiellement sur la QAI avec entre autres l'approche basée sur la performance appliquée aux stratégies de ventilation à débit d'air constant proposée par Guyot (Guyot, n.d.). Ces recherches antérieures sur les systèmes de ventilation à débit d'air constant constituent le point de départ de cette thèse. Elles ont permis : de valider le niveau de détail approprié nécessaire à l'étude des polluants de l'air intérieur ; de confirmer l'importance d'une modélisation précise de la perméabilité à l'air des parois intérieures ; d'identifier les indicateurs de performance de la QAI les plus pertinents.

Dans la continuité de ce travail, il est néanmoins nécessaire de compléter ces indicateurs avec des indicateurs de performance énergétique pour répondre aux enjeux de performance globale. Le second enjeu est d'étudier la sensibilité de la méthode, de confirmer sa robustesse et de s'assurer de son applicabilité aux systèmes de ventilation intelligents.

DES INDICATEURS DE PERFORMANCE GLOBALE

La caractérisation de la performance globale de la ventilation est un sujet émergent qui, pour être bien traité, doit combiner la caractérisation de la performance de la QAI et la caractérisation de la performance énergétique.

Tout d'abord, dans la littérature scientifique disponible, la plupart des études qui traitent de la performance de la QAI sont axées sur la concentration de CO₂ ou le niveau d'humidité comme paramètres pertinents pour la QAI. De plus, parmi la diversité de ces études de cas, aucune méthode unifiée de calcul et de caractérisation de la performance de la QAI n'émerge. Ainsi, la caractérisation de la performance de la QAI est toujours en cours de développement, car la QAI ne se limite pas aux seuls niveaux de CO₂ et d'humidité.

Le travail de recherche de doctorat précédent a permis d'identifier et de proposer un premier ensemble d'indicateurs pertinents de la QAI et d'initier le développement d'une méthode pour caractériser la performance de la ventilation en matière de QAI (Guyot, n.d.). Cependant, ces indicateurs n'ont été appliqués qu'à des systèmes de ventilation à débit constant et leur pertinence doit être confirmée dans le cas de débits d'air variables avec une application de ventilation intelligente. Avec, entre autres, des questions sur la méthode utilisée pour calculer les indicateurs de performance en matière d'énergie et de QAI. La simulation des flux d'air fournit-elle des résultats suffisamment bons pour évaluer la performance énergétique dans le bon ordre de grandeur ? Avons-nous besoin d'une simulation énergétique supplémentaire ou d'une co-simulation pour être réalistes dans l'évaluation de la performance énergétique ?

Ainsi, la caractérisation de la performance énergétique des systèmes de ventilation, tout comme les indicateurs de QAI, est traitée dans la littérature sans grande convergence dans la méthode utilisée. Enfin, la caractérisation de la performance globale de la ventilation intelligente peut être abordée par les questions de recherche suivantes :



QUELS SONT LES INDICATEURS DE QAI EXISTANTS À UTILISER ET À AFFINER AFIN DE LES COMPLÉTER PAR DES INDICATEURS DE PERFORMANCE ÉNERGÉTIQUE ?



COMMENT DÉFINIR, MODÉLISER ET CARACTÉRISER LES ÉCONOMIES D'ÉNERGIE RÉALISÉES PAR LES SYSTÈMES DE VENTILATION AFIN DE CONSTRUIRE ET DE VALIDER UN NOUVEL ENSEMBLE D'INDICATEURS DE PERFORMANCE COUPLANT ÉNERGIE ET QAI ?

LES SOURCES D'ÉMISSIONS DE POLLUANTS ET LES SCÉNARIOS

Pour effectuer les calculs de performance globale d'un système de ventilation, il est nécessaire de sélectionner des conditions limites (données d'entrée), telles que des scénarios d'occupation et d'émissions associées, des données météorologiques, etc. Même si l'élaboration de scénarios d'occupation ou de conditions météorologiques est un domaine de recherche actif, il est encore difficile d'établir les scénarios de taux d'émission de polluants de l'air intérieur à l'échelle du logement. Les émissions de polluants utilisées dans les modèles actuels sont sous-estimées ou surestimées par rapport aux résultats des campagnes de mesure (Boulangier et al., 2012). La proposition de sources de polluants et de scénarios pour calculer la performance globale des ventilations dans une MOPA peut être développée au travers des questions de recherche suivantes :



COMMENT ESTIMER ET CARACTÉRISER CORRECTEMENT LES ÉMISSIONS D'UNE SOURCE POLLUANTE À PARTIR DE DIVERS MATÉRIAUX, PRODUITS ET ACTIVITÉS EXISTANTS DANS UN BÂTIMENT, AFIN D'ÉLABORER UN SCÉNARIO D'ÉMISSIONS PERTINENT À L'ÉCHELLE DU LOGEMENT ?



QUELS SONT LES IMPACTS DES HYPOTHÈSES ET PARAMÈTRES UTILISÉS DANS LA MODÉLISATION DE CES SOURCES DE POLLUANTS AU REGARD DU MANQUE DE DONNÉES DISPONIBLES ET DES DIFFICULTÉS À LES EXTRAPOLER À L'ÉCHELLE DU BÂTIMENT ?

INCERTITUDE DE LA MÉTHODE ET ROBUSTESSE

Le retour d'expérience sur l'amélioration des performances énergétique du bâtiment, montre qu'il y a toujours un écart entre la performance théorique au stade de la conception et les performances réelles mesurées dans les bâtiments occupés. Néanmoins, pour être pertinente, une MOPA doit fournir un résultat de performance de la conception de référence qui doit être aussi proche que possible de la performance réelle future et avec une faible incertitude. Dans ce contexte, la notion d'incertitude décrit la quantification de l'erreur entre les résultats de performance de référence et les résultats calculés à partir de plusieurs scénarios. En effet, au cours du processus de modélisation au stade de la conception, plusieurs paramètres d'entrée et scénarios peuvent être utilisés. Ces variations d'entrée génèrent de multiples résultats de performance qui peuvent être répartis sur une large gamme ou concentrés autour d'une valeur unique. Cette dispersion des résultats de performance doit être quantifiée par une mesure de l'incertitude et il est crucial de comprendre quelles entrées ont le plus d'impact sur l'OPA. La nouveauté des stratégies de contrôle intelligentes introduit une incertitude supplémentaire qui doit être quantifiée.

De plus, le terme "robustesse" décrit la capacité de la MOPA à classer plusieurs systèmes testés en fonction de leurs performances et éventuellement être utilisé comme un outil d'aide à la décision. Cependant, avec l'utilisation de plusieurs indicateurs de performance, le poids accordé à chaque indicateur pourrait influencer l'ordre final. Cela soulève donc la question de l'importance relative de la QAI par rapport à l'énergie pour garantir une OPA. Le risque est de développer une MOPA qui favorise artificiellement une stratégie de ventilation en particulier. Par conséquent, pour éviter de surestimer (ou de sous-estimer) les résultats des performances et de donner un avantage injustifié à un système de ventilation par rapport aux autres, la quantification de l'incertitude et la robustesse doivent être intégrées dans la MOPA par le biais des questions de recherche suivantes :



QUELLE EST L'INCERTITUDE ET QUELS SONT LES PRINCIPAUX PARAMÈTRES D'ENTRÉE AYANT UN IMPACT SUR LA PERFORMANCE ÉVALUÉE ?



COMMENT ÉQUILIBRER L'IAQ ET L'ÉVALUATION DE LA PERFORMANCE ÉNERGÉTIQUE POUR OBTENIR UN CLASSEMENT SOLIDE DES SYSTÈMES DE VENTILATION ?

METHODOLOGIE

Les questions de recherche concernant l'évaluation de la performance globale des systèmes de ventilation pourraient être abordées tout au long du cycle de vie d'un bâtiment. Par exemple, au stade de la conception, l'OPA peut être utilisée pour sélectionner le système de ventilation le plus adapté ; au stade de la livraison pour comparer la conception et la performance réelle ; dans un projet de rénovation de bâtiment pour évaluer l'amélioration de la QAI et les économies d'énergie dues à l'installation d'un système de ventilation intelligent. Cependant, ce travail se concentre uniquement sur la phase de conception des bâtiments résidentiels et est orienté vers les bâtiments à faible consommation d'énergie. Avec une attention particulière accordée à l'applicabilité de la MOPA aux systèmes de ventilation intelligents.

Pour poursuivre le développement de la MOPA au stade de la conception, nous avons orienté nos recherches et construit une méthodologie basée sur la modélisation, des simulations de bâtiments et des outils numériques. De plus, les recherches menées pour le développement de la méthode ont été principalement axées sur le contexte européen et adaptées autant que possible à la France. Cependant, la littérature internationale a également été incluse et adaptée lorsqu'aucune information spécifique n'a été trouvée dans le contexte européen / français.

CAS D'ÉTUDE

Pour les études de cas, nous avons limité le cadre à l'échelle d'un logement et appliqué l'OPA à la ventilation d'une maison individuelle et d'un appartement dans un immeuble collectif. Comme la méthode se concentre sur la phase de conception, nous avons sélectionné des bâtiments récents à haute efficacité énergétique, tels que la maison individuelle, qui est un logement à faible consommation d'énergie, et l'appartement, qui est un bâtiment récemment rénové.

UNE MAISON INDIVIDUELLE FRANÇAISE BASSE CONSOMMATION D'ÉNERGIE

Cette étude de cas est le principal bâtiment modélisé et étudié dans le cadre de la thèse. Il a été choisi car c'est une maison basse consommation d'énergie (Figure 3). De plus les paramètres pour décrire le bâtiment tels que : la répartition des défauts de perméabilité, les débits d'air de ventilation par pièce, les horaires d'occupation étaient disponibles ; ainsi que des données de mesures in situ sur deux périodes de deux semaines qui ont été exploitées dans le §2.1.1a)

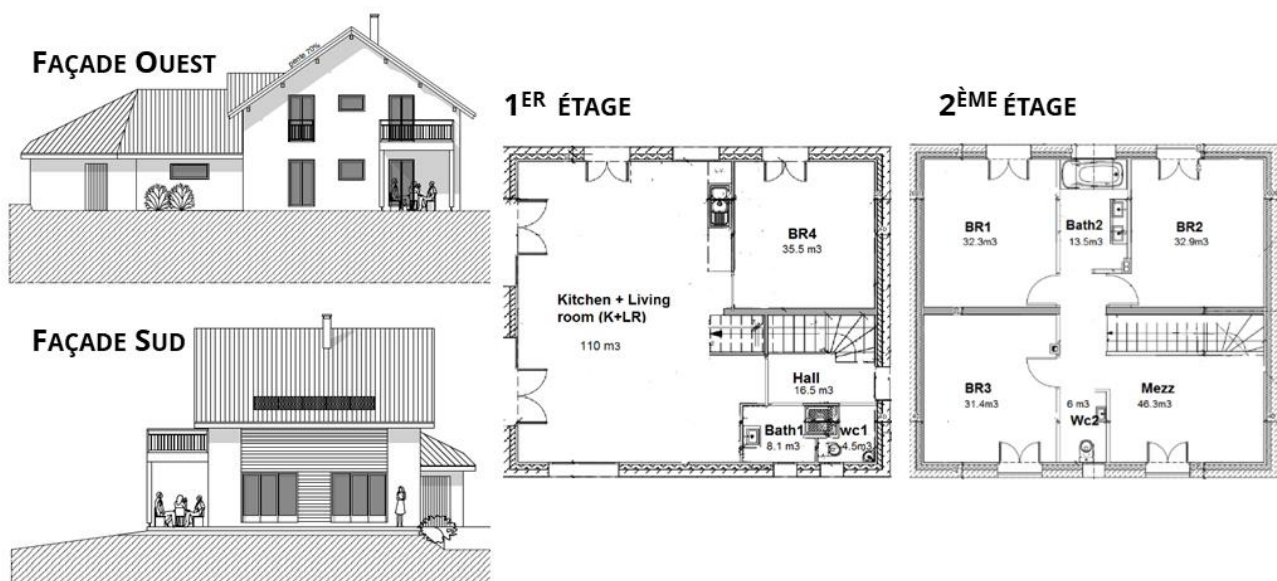


FIGURE 3 : SYNTHÈSE DE LA MÉTHODE D'ÉVALUATION DE LA PERFORMANCE GLOBALE PROPOSÉE POUR LA VENTILATION

UN APPARTEMENT DANOIS DANS UN IMMEUBLE COLLECTIF

Cette étude de cas a été élaborée dans le cadre d'une mobilité internationale à DTU, au Danemark. Il s'agit d'un appartement danois rénové dans un immeuble collectif (Figure 4). Il a été choisi parce qu'un système de ventilation innovant avec une stratégie de contrôle intelligent a été développé et intégré dans cet appartement après la rénovation. C'était également une bonne occasion de mettre en œuvre cette stratégie de ventilation intelligente (MVHR-rb) dans CONTAM et de l'ajouter aux modèles développés. De plus, ce fut l'occasion de tester l'intégration et les performances des systèmes de ventilation français (MEV-cav ; MEV-rh ; MVHR-cav) dans le contexte danois. Plus de détails sont donnés dans l'article conférence au §3.2.2 c).



FIGURE 4 : PLAN ET PHOTO DE LA FAÇADE DE L'APPARTEMENT DANOIS DANS UN IMMEUBLE COLLECTIF

SYSTÈMES ET STRATÉGIES DE VENTILATION

Dans ce travail, à travers les quatre chapitres, 6 systèmes de ventilation ont été modélisés pour étendre l'approche basée sur la performance des systèmes de ventilation à débit d'air constant aux systèmes de ventilation intelligents avec des débits d'air variables. Pour décrire la ventilation, les termes "stratégie" et "système" de ventilation ont été utilisés. Le terme "stratégie" de ventilation a été utilisé principalement pour décrire les stratégies de contrôle du débit d'air. Avec par exemple : *cav* pour un contrôle constant ; *rh* pour un contrôle basé sur l'humidité. Le terme "système" de ventilation décrit quant à lui l'ensemble de la ventilation, y compris : le type de ventilation (MEV pour l'extraction uniquement et MVHR pour les systèmes équilibrés avec récupération de chaleur) et la stratégie de ventilation.

SYSTÈMES DE RÉFÉRENCE

Deux types de ventilation avec des stratégies de débits d'air constants ont été regroupés ici en tant que "systèmes de référence" pour être comparés aux systèmes intelligents.

MEV-CAV, pour ventilation mécanique par extraction à volume d'air constant,

MVHR-CAV, pour ventilation mécanique équilibrée avec récupération de chaleur et volume d'air constant.

SYSTÈMES INTELLIGENTS

Ces systèmes dits intelligents sont des systèmes avec des stratégies de débits d'air variables

MEV-RH, pour ventilation mécanique par extraction et contrôle de l'humidité,

Il convient de noter que deux variantes d'alimentation en air dans les chambres et le salon ont été modélisées. La première, appelée Hygro A, est dotée d'entrées d'air autoréglable (comme le MEV-cav). La seconde, plus récente, est appelée Hygro B et comporte des entrées d'air hygroréglables. Le système Hygro B est aujourd'hui le plus répandu dans les logements construits après 2013 en France et a été le système modélisé dans les §1.1.6.b), §3.1.3.c) et §3.2.2. L'Hygro A a été modélisé au §4.1.2 afin de réduire la complexité de la modélisation et d'élargir les possibilités de variation des données d'entrée pour l'analyse de sensibilité.

MVHR-RH, pour ventilation mécanique équilibrée avec récupération de chaleur et contrôle de l'humidité au niveau de l'appartement.

MVHR-RB, pour ventilation mécanique équilibrée avec récupération de chaleur et contrôle du CO₂ et de l'humidité au niveau de la pièce.

Il s'agit de la stratégie de ventilation intelligente la plus avancée que nous avons modélisée.

MEV-RB, pour ventilation mécanique par extraction et contrôle du CO₂ et de l'humidité au niveau de la pièce, en tant qu'adaptation fictive du MVHR-rb, afin de tester cette stratégie de ventilation intelligente avec l'extraction uniquement.

ORGANISATION DE LA THÈSE

Comme l'illustre la Figure 5, ce manuscrit de thèse est basé sur des articles publiés ou soumis. Il est organisé en 4 parties reliées entre elles par des sections intermédiaires nommées "Highlights & Learnings" pour "Contributions et enseignements" résumant la contribution de chaque partie par rapport aux questions de recherche et aux objectifs de la thèse. La suite de ce résumé de thèse long en Français est principalement la traduction des Highlight & Learnings.

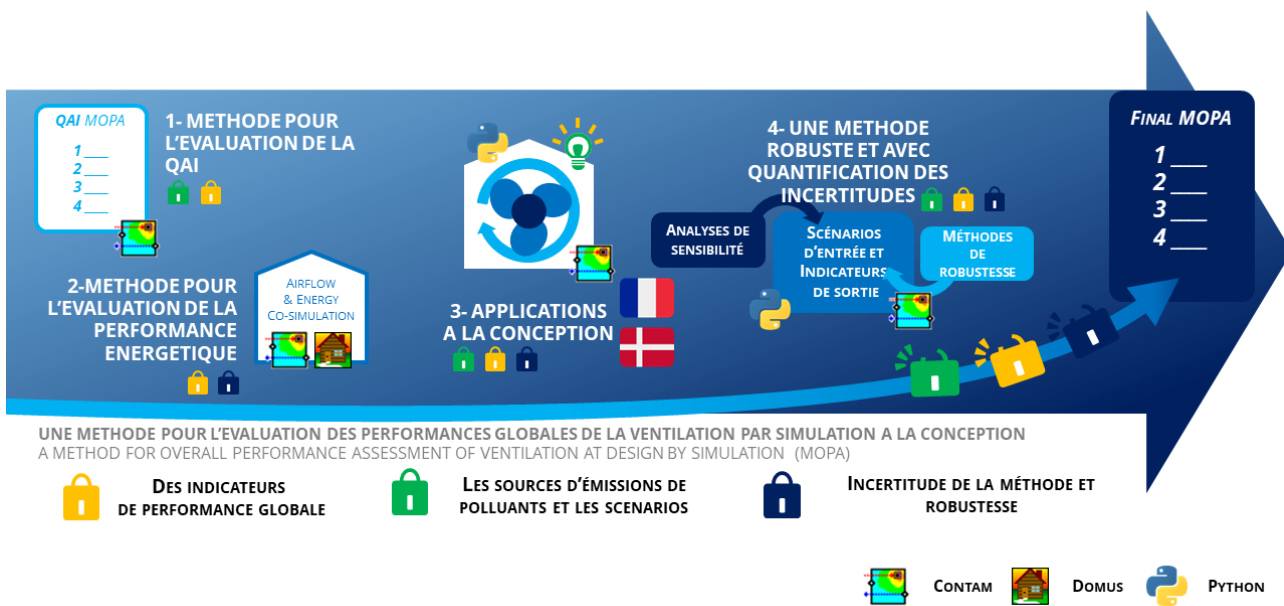


FIGURE 5 : PRINCIPALES ÉTAPES DE LA MÉTHODOLOGIE PROPOSÉE POUR LE DÉVELOPPEMENT DES MOPA ET RÉPONSE AUX QUESTIONS DE RECHERCHE

PARTIE 1 : MÉTHODE DE PERFORMANCE POUR LA QAI

Cette première partie est consacrée à la présentation et au développement de l'approche basée sur la performance de la QAI, afin d'évaluer la performance globale de la ventilation des bâtiments. L'approche de la méthode est basée sur des simulations aérauliques, réalisées ici avec CONTAM un modèle multizone. Nous avons défini dans deux articles de revue de littérature un ensemble pertinent d'indicateurs de performance de la QAI qui peuvent être utilisés comme résultat de sortie (de la méthode), avec leurs scénarios d'émission de polluants associés et leurs horaires d'occupation en tant qu'entrée (de la méthode).

L'humidité relative, le CO₂, le formaldéhyde et les PM_{2.5} ont été sélectionnés comme les paramètres clés de l'air intérieur à étudier. En effet, le CO₂ et l'humidité sont deux paramètres historiquement utilisés et adaptés à l'évaluation de la QAI, car leur présence due à l'émission de bio-effluents est un bon marqueur de l'occupation et du mauvais renouvellement de l'air dans une pièce. De plus, le formaldéhyde et les PM_{2.5} ont été identifiés comme deux polluants intérieurs prioritaires à prendre en compte pour leur fort impact sur la santé.

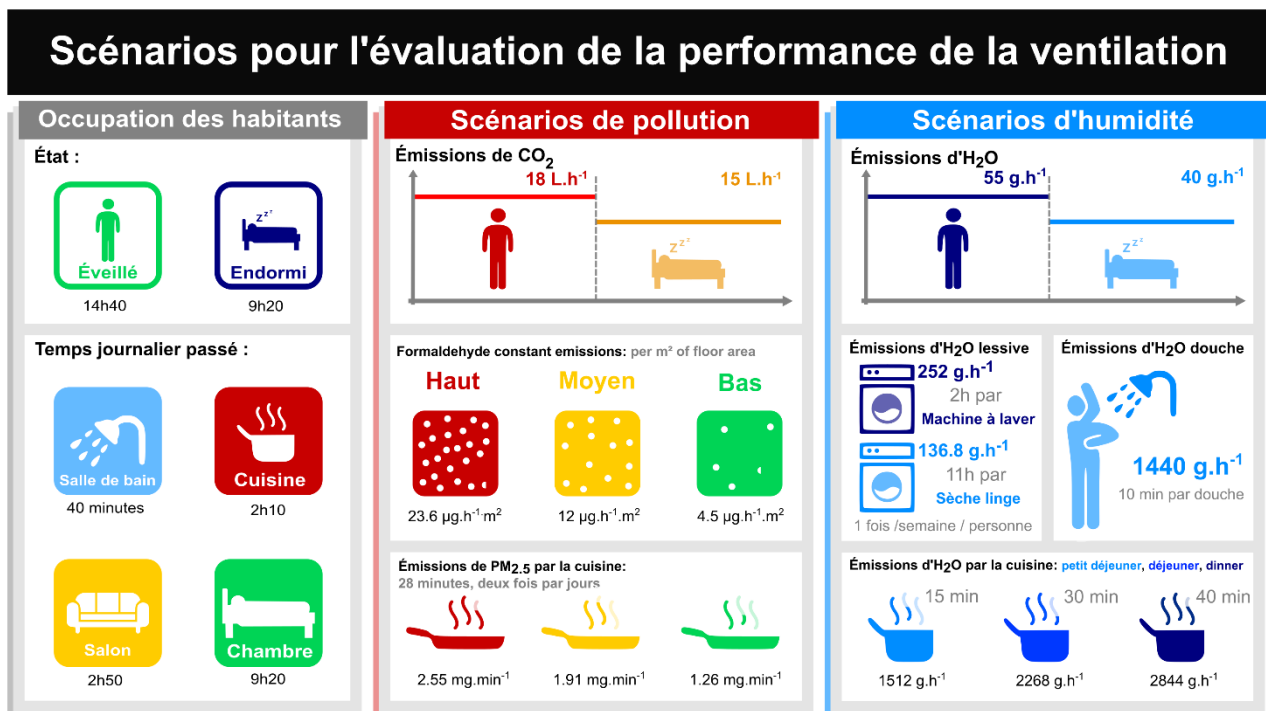


FIGURE 6 : SCÉNARIOS D'ÉMISSIONS DE POLLUANTS ET D'OCCUPATION UTILISÉS (D'APRÈS (POIRIER ET AL., 2021)

Les sources de polluants peuvent être décrites à l'aide des trois niveaux de taux d'émission (faible, moyen, élevé) reflétant les occupants et les activités (par exemple, douche, cuisine), ainsi que les matériaux de construction (Figure 6). Ces scénarios pourraient éventuellement être adaptés en fonction des besoins. Ils donnent au moins une fourchette de variation basse et haute qui équivaut à la configuration idéale et à la configuration la plus défavorable. De plus, à ce stade, le scénario moyen peut être considéré comme un scénario de référence. Et, le temps quotidien passé par les occupants dans les pièces peut être utilisé comme calendrier d'occupation détaillé afin de calculer l'exposition des occupants et les émissions de polluants provenant des activités des occupants.

RÉSUMÉ LONG EN FRANÇAIS

PARTIE 1 : MÉTHODE DE PERFORMANCE POUR LA QAI

Ensuite, les cinq indicateurs de performance de la QAI proposés (I_{CO_2} , I_{HCHO} , $I_{PM_{2.5}}$, I_{RH70} , I_{RH30_70}) peuvent être calculés sur la base des concentrations de polluants dans les pièces et de l'exposition des occupants. Ces cinq indicateurs ont été associés à un seuil qui caractérise une performance limite au-delà de laquelle la performance atteinte n'est pas acceptable. Afin de comparer les performances de plusieurs systèmes de ventilation, ces 5 indicateurs peuvent être normalisés, ce qui rend la visualisation et la comparaison des performances plus directes (Figure 7). Ainsi, pour un système de ventilation donné, lorsque la valeur d'un indicateur normalisé est supérieure à 1, la performance n'est pas atteinte.

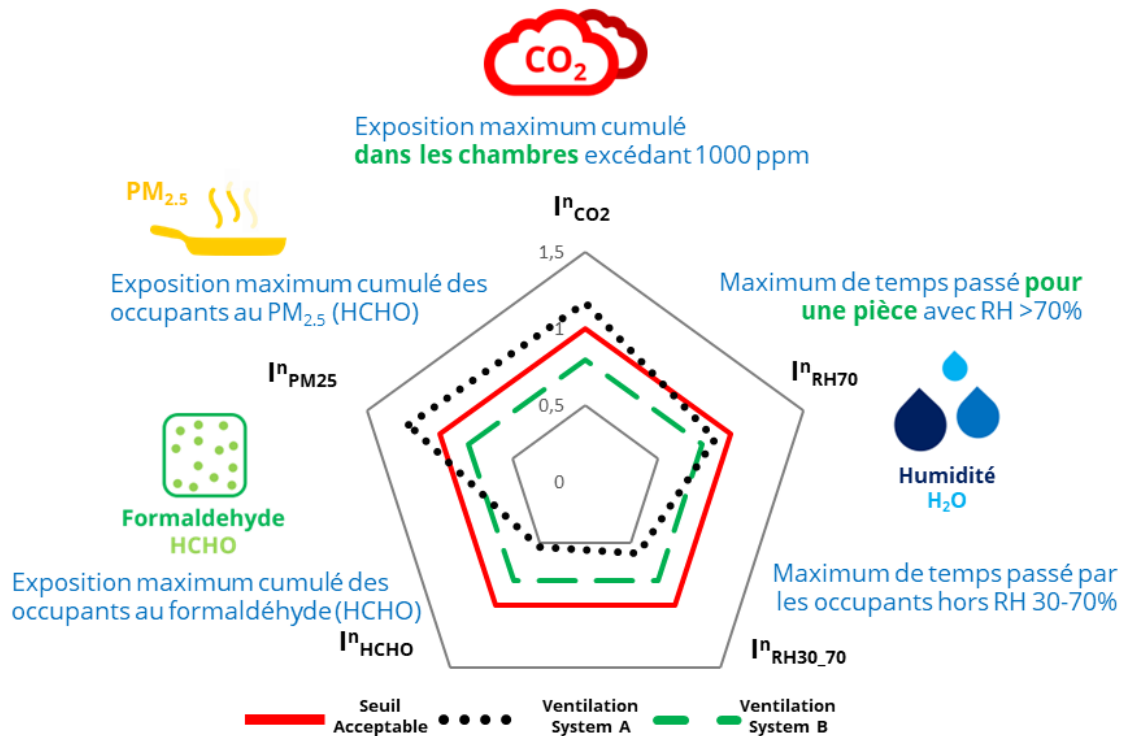


FIGURE 7 : ILLUSTRATION DES CINQ INDICATEURS DE QAI NORMALISÉ ET REPRÉSENTÉ DANS UN DIAGRAMME RADAR

Cependant, ces indicateurs normalisés peuvent conduire à des résultats de performance discutables lorsque les indicateurs sont proches de 1. En effet, en fonction des scénarios d'entrée utilisés, on peut facilement osciller entre une performance acceptable et une performance inacceptable. Les trois scénarios testés peuvent ne pas être suffisants pour valider la performance évaluée. Pour tenir compte de l'impact des scénarios d'entrée sur les indicateurs de performance de sortie, nous avons procédé dans le chapitre 4 à une quantification de l'incertitude à l'aide de d'une méthode d'analyse de sensibilité.

Enfin, ces premiers résultats de performance issus d'une application sur l'étude de cas Français ont mis en évidence l'importance de prendre en compte des paramètres de QAI autres que les traditionnels CO_2 et l'humidité, pour une meilleure prise en compte de la QAI dans les bâtiments. La prochaine étape consiste à compléter le MOPA avec des indicateurs énergétiques afin d'évaluer l'impact des systèmes de ventilation sur la QAI et sur la performance énergétique.

PARTIE 2 : MÉTHODE POUR LA PERFORMANCE ÉNERGÉTIQUE

En complément des indicateurs de QAI développés dans la partie 1, nous proposons dans la partie 2 d'explorer la possibilité de couplage entre le modèle aéralique de CONTAM avec une simulation thermique pour le calcul d'indicateurs énergétiques. Cette partie présente les travaux de recherche et les résultats obtenus en matière de simulation thermique. Les résultats obtenus n'ont pas fait l'objet de publications par rapport aux autres parties du manuscrit.

Les deux principales sources de consommation d'énergie pour les systèmes de ventilation sont la consommation électrique des ventilateurs, et les déperditions thermiques dues au renouvellement de l'air. Dans la réglementation française sur la construction, RE2020, les pertes de chaleur dues au renouvellement de l'air sont indirectement incluses dans un coefficient appelé "Bbio". Les valeurs de référence sont obtenues pour un bâtiment avec d'une ventilation mécanique idéale avec récupération de chaleur (double flux / MVHR-cav). De plus la consommation électrique des ventilateurs est incluse dans le calcul du Cep. Le Bbio est un indicateur qui mesure l'impact de l'efficacité énergétique du bâtiment sur les besoins de chauffage, de refroidissement et d'éclairage artificiel. Le coefficient Cep exprimé en kWh/(m² de surface de référence de référence) d'énergie primaire (ou kWh_{ep}/(m².an)) représente la consommation d'énergie pour le chauffage, le refroidissement, l'eau chaude sanitaire, les auxiliaires et l'éclairage des bâtiments.(RE-2020 ANNEXE III).

Les limites de l'utilisation de ces calculs réglementaires à l'échelle du bâtiment pour évaluer la performance de la ventilation sont qu'ils ne se concentrent pas directement sur les systèmes de ventilation. Dans ce travail de recherche, nous avons besoin d'un calcul plus détaillé centré sur les systèmes de ventilation afin de mieux comprendre et quantifier leurs impacts sur la consommation d'énergie du bâtiment. Nous proposons dans un premier temps de nous concentrer uniquement sur les pertes de chaleur dues au renouvellement de l'air.

Ces déperditions thermiques peuvent être calculées en suivant l'équation 1, inspirée de la méthode déjà mentionnée pour le calcul du Bbio (RE-2020 ANNEXE III) et d'autres études (Abadie et al., 2017 ; Molina et al., 2021). En effet, la quantité de déperditions thermiques due au renouvellement de l'air peut être facilement calculée à l'aide d'un modèle aéralique, car ce calcul utilise les flux d'air vicié et la différence de température entre l'intérieur et l'extérieur :

$$H_{thl} = \frac{C_{pm}}{3600} \cdot (1 - \varepsilon_{heat_{ex}}) \int q_m(t) \cdot [T_{in}(t) - T_{ex}(t)] \cdot dt$$

EQUATION 1

Avec H_{thl} les pertes de chaleur thermique dues au renouvellement de l'air [kWh], q_m les débits massiques totaux d'air extrait en [kg.s⁻¹], C_{pm} la capacité thermique massique de l'air (nous avons utilisé 1 kJ.kg⁻¹.°C⁻¹), $\varepsilon_{heat_{ex}}$ l'efficacité de l'échangeur de chaleur supposée idéale et constante. On peut utiliser par exemple un rendement théorique constant de 0,8 pour une ventilation avec récupération de chaleur et de 0 pour une ventilation sans récupération de chaleur. T_{in} la température de la zone où l'air est évacué, et T_{ex} la température extérieure [°C].

A ce stade, l'utilisation du logiciel CONTAM, basé sur un modèle sans simulation énergétique et une hypothèse de température constante dans les zones, nous interroge sur :

- QUEL EST L'IMPACT D'UNE HYPOTHÈSE DE TEMPÉRATURE CONSTANTE DANS CHAQUE ZONE POUR LE CALCUL DE H_{thl} ?
- COMMENT PRENDRE EN COMPTE LES VARIATIONS DE TEMPÉRATURES INTERNES ET LE BESOIN DE COUPLAGE DE CONTAM AVEC UN MODÈLE THERMIQUE ?

RÉSUMÉ LONG EN FRANÇAIS

PARTIE 2 : MÉTHODE POUR LA PERFORMANCE ÉNERGÉTIQUE

A partir de ces deux questions, dans cette partie 2, nous proposons tout d'abord une évaluation de l'impact des températures variables sur le H_{th} basée sur des mesures in-situ. Enfin, nous avons mené une étude exploratoire de co-simulation entre CONTAM et DOMUS afin d'évaluer le potentiel de la co-simulation et améliorer la méthode d'évaluation de la performance de la ventilation.

Dans la partie 2.1 nous avons conclu que l'utilisation de températures constantes au lieu de températures variables issues de la simulation thermique ne modifie pas de manière significative le calcul de H_{th} . Ainsi, l'utilisation d'une hypothèse de température moyenne constante à l'échelle du bâtiment, sans détail à l'échelle des pièces est acceptable pour l'évaluation des déperditions thermiques par ventilation et est encore plus pertinente pour les mois froids. Par conséquent, pour la MOPA, l'hypothèse de température constante peut être utilisée pour simplifier le processus de modélisation sans perdre trop de précision. Toutefois, la simulation énergétique étendue à l'ensemble de la période de chauffage a montré que l'utilisation de cette hypothèse de température constante présente certaines limites pour les mois d'intersaison d'octobre, mars et avril (mois du printemps et de l'automne en Europe) (Figure 8).

Ensuite, un travail exploratoire de co-simulation en collaboration avec le laboratoire LST de l'Université PUCPR (Curitiba, Brésil) a permis d'initier le couplage entre DOMUS et CONTAM. Cependant à ce stade, la complexité du couplage avec CONTAM limite la valeur ajoutée d'une co-simulation par rapport à un simple calcul des déperditions thermiques avec une simulation aéraulique uniquement (CONTAM).

Enfin, à ce stade, le H_{th} est un indicateur énergétique provisoire car il n'a pas été testé sur un cas d'étude complet. Néanmoins, ce test sera effectué dans la partie 3 sur l'étude de cas Danoise, avec l'intégration de la consommation du ventilateur dans le calcul. De plus, la déclinaison de la normalisation de l'indicateur énergétique sera développée dans la partie 4 pour être intégrée dans le MOPA afin de construire un ensemble complet d'indicateurs de performance globale.

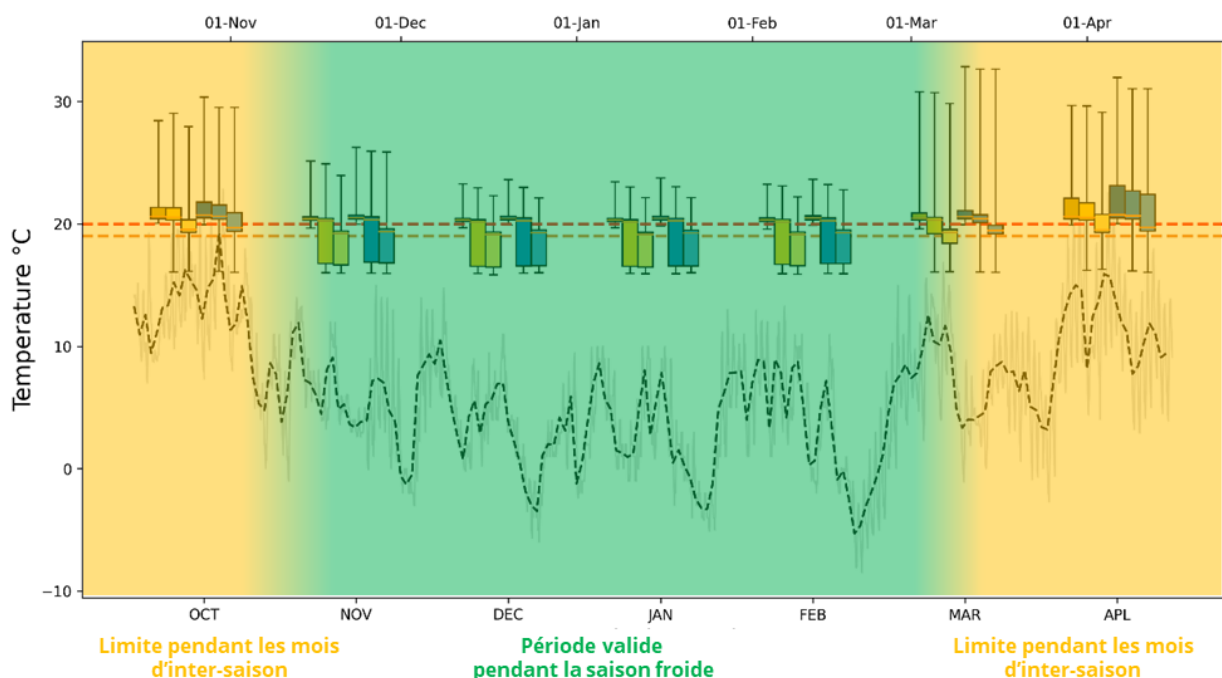


FIGURE 8 : ILLUSTRATION DES LIMITES INTER-SAISON ET SAISON FROIDE ; TEMPÉRATURES MOYENNES DANS LE BÂTIMENT, POUR 2 SYSTÈMES DE VENTILATION (MEV-cav EN JAUNE ; MEV-rh EN BLEU) ET 3 STRATÉGIES DE CONTRÔLE DE LA TEMPÉRATURE (T_{20} $T_{20/16}$ $T_{19/16}$ DE GAUCHE À DROITE PAR SYSTÈME DE VENTILATION)

PARTIE 3 : CAS D'APPLICATION

Après la description de la méthode générale basée sur les performances de la QAI dans la partie 1, et de la méthode basée sur les performances étendues aux indicateurs énergétiques dans la partie 2, différentes applications des méthodes développées seront présentées dans cette partie 3.

Dans CONTAM, il est relativement facile de mettre en œuvre des systèmes de ventilation avec des stratégies de débits d'air constants, mais les stratégies de débits d'air variables (comme dans les stratégies de ventilation intelligente) nécessitent des développements supplémentaires. Dans ce chapitre, les résultats d'un développement progressif de l'approche performancielle et de la mise en œuvre dans CONTAM, des systèmes de ventilation intelligents, sont présentés dans deux articles de conférence.

Le premier article présente une ventilation mécanique hygroréglable (MEV-rh) et deux systèmes de ventilation à débit constant (MEV-cav et MVRH-cav) dans un contexte français. Dans cette étude, trois scénarios d'entrée de polluants ont été testés sur ces trois systèmes de ventilation, dans une approche performancielle uniquement sur la QAI.

Dans le deuxième article de conférence, deux autres systèmes de ventilation avec des débits d'air variables basés sur l'humidité et le CO₂ ont été développés (MVHR-rh et MVHR-rb). Ici, l'approche performancielle a été utilisée pour évaluer le potentiel de réduction des débits d'air minimaux et le potentiel d'économies d'énergie sans réduire le niveau de QAI. De plus, un indicateur énergétique intégrant la consommation du ventilateur en plus des déperditions thermiques a été testé.

Dans cette troisième partie, nous avons démontré l'applicabilité de la MOPA dans différents contextes et pour une diversité de stratégies de ventilation. Nous avons modélisé deux types d'habitations, une maison individuelle à faible consommation d'énergie et un appartement dans un immeuble collectif. Ces deux études de cas ont fourni un cadre pour le développement progressif et la mise en œuvre des stratégies de ventilation intelligente dans CONTAM. Par exemple, une stratégie de ventilation intelligente plus avancée basée sur le CO₂ et l'humidité.

De plus, des routines ont été développées avec Python, pour la variation des paramètres d'entrée et l'extraction des résultats de sortie, afin de préparer la mise en place des outils d'analyse de sensibilité dans la partie 4. Cela a mis en évidence les avantages de la flexibilité offerte par les outils de simulation des flux d'air de CONTAM pour ce type de travaux de recherche.

Dans les deux études, les performances de QAI concernant les PM_{2.5} étaient largement au-dessus de la limite acceptable. Dans l'appartement, nous avons observé des indicateurs de performance PM_{2.5} plus dégradés (entre 3,5 et 5 selon le système de ventilation pour un seuil fixé à 1) que dans la maison individuelle (entre 1,5 et 2), pour le même scénario d'émission de cuisine moyen de PM_{2.5}. Cet écart peut s'expliquer par la configuration du bâtiment et les volumes modélisés. En effet, dans l'appartement, la cuisine est fermée et plus petite que dans la maison où la cuisine est ouverte sur le salon. Par conséquent, pour l'étude de cas danoise, une modélisation plus précise de la hotte de cuisine serait nécessaire pour obtenir des concentrations de PM_{2.5} plus réalistes dans la cuisine. Cela pourrait se faire en intégrant par exemple un modèle source/puit dans CONTAM pour représenter la capture et le filtrage des polluants par la hotte. Ceci est moins pertinent dans le contexte français, où les hottes de cuisine ne sont pas obligatoires et ne sont pas encouragées par les réglementations thermiques pour les nouveaux bâtiments. Cet exemple montre que la nécessité de s'adapter aux spécificités d'un pays peut influencer les hypothèses de modélisation par rapport aux spécificités d'un autre pays.

RÉSUMÉ LONG EN FRANÇAIS

PARTIE 3 : CAS D'APPLICATION

Dans l'étude de cas danoise, nous avons développé et testé l'évaluation des risques d'exposition à court terme aux PM_{2.5} et au formaldéhyde, avec deux indicateurs à court terme $I_{PM2.5_short}$, I_{HCHO_short} . Toutefois, les résultats n'ont pas été concluants. En effet, l'exposition à court terme aux PM_{2.5} ne donne pas plus d'informations que son équivalent à long terme ($I_{PM2.5}$). Pour le formaldéhyde, avec les sources utilisées dans l'étude, nous n'avons pas observé de risque d'exposition à court terme. Des études plus spécifiques sur les indicateurs de risque d'exposition à court terme pour l'OPA devraient être réalisées sur ces polluants (ou d'autres). C'est pourquoi nous avons décidé d'inclure ces deux indicateurs d'exposition à court terme dans la quantification de l'incertitude de la partie 4.

Le contexte Danois soulève également un problème d'air sec avec les systèmes MVHR, où les valeurs observées par l'indicateur I_{RH30_70} sont trop élevées (temps passé en dehors de la plage 30-70% d'humidité relative), ce qui n'a pas été observé dans le contexte français. En effet, les deux types de conditions climatiques extérieures, ont un impact différent sur le temps passé par l'occupant avec une humidité relative inférieure à 30 % (annexe III). Il en résulte une augmentation de l'indicateur I_{RH30_70} . Cela montre le rôle de la différenciation entre les conditions d'humidité élevée, grâce à l'indicateur I_{RH70} (orienté vers l'identification du risque de développement de moisissures dans les pièces) et l'identification des conditions défavorables à la santé et au confort des occupants grâce à l'indicateur I_{RH30_70} y compris les conditions de faible humidité). Cela souligne la complémentarité de ces deux indicateurs de QAI basés sur l'humidité relative.

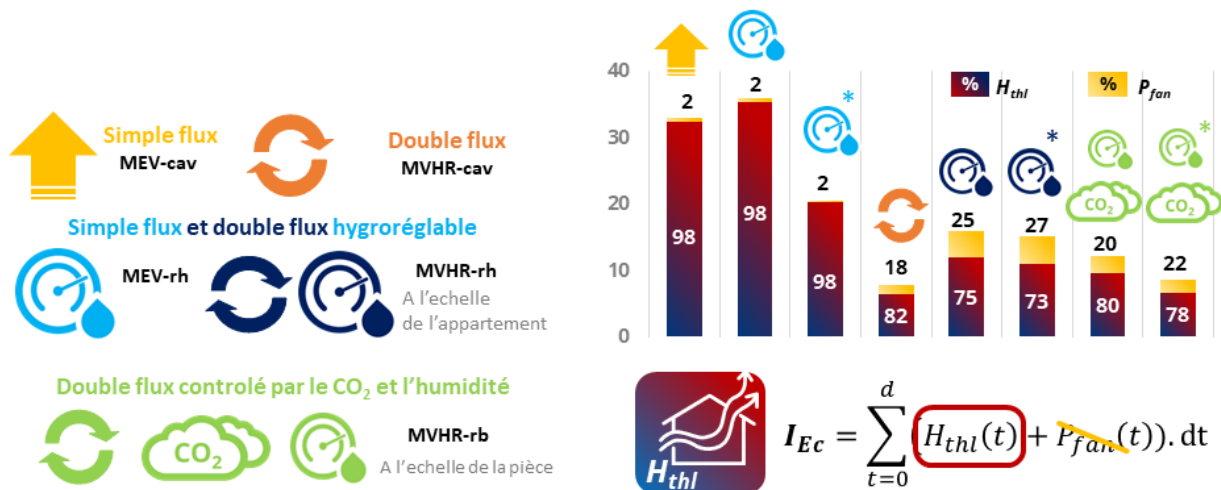


FIGURE 9 : SYSTÈMES DE VENTILATION MODÉLISÉS ET APPRENTISSAGE SUR L'INDICATEUR I_{Ec} AU TRAVERS DU CAS D'ÉTUDE DANOIS ; * DÉBIT MINIMAUX TESTÉS

Enfin, dans le cadre des travaux sur la réduction des débits minimaux d'extraction, l'indicateur énergétique (I_{Ec}) a été étendu à la consommation électrique des ventilateurs (I_{epan}). Nous avons proposé dans l'annexe III (ici Figure 9) de détailler la répartition entre les pertes de chaleur et la consommation des ventilateurs. Dans cette analyse complémentaire, la consommation du ventilateur représente 2% de l'énergie totale calculée dans I_{Ec} pour les types de ventilation MEV, alors qu'elle représente entre 18% et 27% de I_{Ec} total pour la ventilation MVHR. Pour la MOPA, nous proposons de ne conserver que la partie perte de chaleur de l'indicateur I_{Ec} . En effet, nous considérons qu'il est plus pertinent de se concentrer sur le potentiel de réduction des déperditions thermique par une stratégie de ventilation variable (intelligente) plutôt que sur la consommation d'énergie du (des) ventilateur(s). En fait, nous pouvons supposer que le fonctionnement des ventilateurs est indirectement inclus dans l'indicateur I_{ewh} par le biais des débits d'air extrait. En effet, la puissance instantanée des ventilateurs est proportionnelle aux débits d'air extrait.

Toutes les questions soulevées et les améliorations apportées à l'application de ces deux études de cas seront poursuivies dans la partie 4 avec l'analyse d'incertitude et la méthode de robustesse pour classer les performances des systèmes de ventilation.

PARTIE 4 : UNE MÉTHODE ROBUSTE ET QUANTIFICATION DES INCERTITUDES

Cette dernière partie du manuscrit mobilise tous les enseignements des parties précédentes pour l'application d'une analyse de sensibilité et la quantification de l'incertitude la MOPA sur le cas d'étude de la maison individuelle en appliquant la méthode d'analyse de sensibilité RBD-FAST.

Cette méthode consiste à faire varier les entrées sur un grand nombre de simulations pour calculer les indices de Sobol, qui permettent de quantifier la sensibilité des données de sortie par rapport aux variations des paramètres d'entrée. L'objectif est de quantifier les impacts des scénarios d'occupation et d'émission de polluants proposés comme paramètre d'entrée sur les résultats de performance obtenus avec les indicateurs de performances en sorties. De plus, certaines hypothèses de modélisation des bâtiments ont également été incluses dans l'analyse de sensibilité, telles que : les coefficients de re suspension et de dépôt des $PM_{2.5}$; les paramètres du modèle du tampon et le niveau de perméabilité du bâtiment. La méthode a été testée sur cinq systèmes de ventilation (MEV-cav, MEV-rh, MEV-rb, MVHR-cav, MVHR-rb). Dans cette analyse de sensibilité nous avons fait varier 12 entrées du modèle sur 2500 simulations (500 par systèmes) et étudié les impacts sur 9 paramètres de sortie.

Dans cette analyse de sensibilité, un total de 540 indices de sensibilité (de Sobol noté S_i ; 108 par stratégie de ventilation) ont été calculés pour les 12 variables d'entrée et les 9 indicateurs de sortie. Face au défi pour représenter un si grand nombre de S_i , nous avons créé ce que nous appelons un "diagramme fleur" qui regroupe ces 540 indices par stratégie de ventilation dans la Figure 10.

Sur ce graphique, chaque ligne représente l'indicateur de sortie et chaque colonne la variable d'entrée. Chacune des 108 "fleurs" comporte 5 cercles, un pour chaque stratégie de ventilation. Le cercle gris représente le S_i maximum possible, avec un cercle de couleur dont la taille est proportionnelle à sa valeur réelle. Chaque couleur représente un système. De plus, la valeur en pourcentage ($S_i\%$) est affiché uniquement si les indices sont significatifs ($S_i > 0,1$) et les indices ne sont pas représentés si $S_i < 0,05$. En d'autres termes, une fleur vide signifie que pour tous les systèmes de ventilation, l'impact de la variabilité d'entrée correspondante sur la variabilité de sortie est insignifiant, tandis que les pétales colorés indiquent un impact important.

Les principaux paramètres d'entrée influents identifiés sont les bio-effluents, les émissions de $PM_{2.5}$ et d'activités émettant de la vapeur d'eau, les émissions de formaldéhyde provenant des meubles, la vitesse de déposition des $PM_{2.5}$ et les valeurs de débit d'air. Cela a confirmé la nécessité de poursuivre les recherches sur les paramètres des scénarios d'émissions de polluants. Pour simplifier l'hypothèse de la MOPA, l'effet tampon de l'humidité et le taux de remise en suspension des $PM_{2.5}$ pourraient être fixés à des valeurs par défaut, car leur variabilité n'a pas d'impact sur les indicateurs de performance. En ce qui concerne le niveau de perméabilité de l'enveloppe, la valeur de référence peut être utilisée si la valeur réelle du bâtiment est inconnue, car elle ne semble pas être un paramètre influent. Toutefois, il pourrait être utile, dans le cadre d'un travail ultérieur, d'effectuer une analyse de sensibilité détaillée en testant des niveaux de défauts de perméabilité plus élevés, en se concentrant sur la distribution des fuites d'air autour de l'enveloppe (voir l'idée détaillée à l'annexe IV). En effet, la plage qui a été testée pour le q4Pa [0,05 ; 0,9] correspond aux valeurs mesurées sur des bâtiments récents à haute performance énergétique avec une enveloppe étanche à l'air. Si la méthode est appliquée à la rénovation, les bâtiments anciens pourraient présenter des défauts de perméabilité quatre à dix fois plus élevés, combinés à une répartition non uniforme des fuites d'air, ce qui pourrait avoir un impact sur l'indicateur de performance.

Les indicateurs supplémentaires de QAI pour les expositions à court terme, I^1_{HCHO-s} et $I^1_{PM_{2.5-s}}$, fournissent pratiquement les mêmes informations que leurs équivalents à long terme.

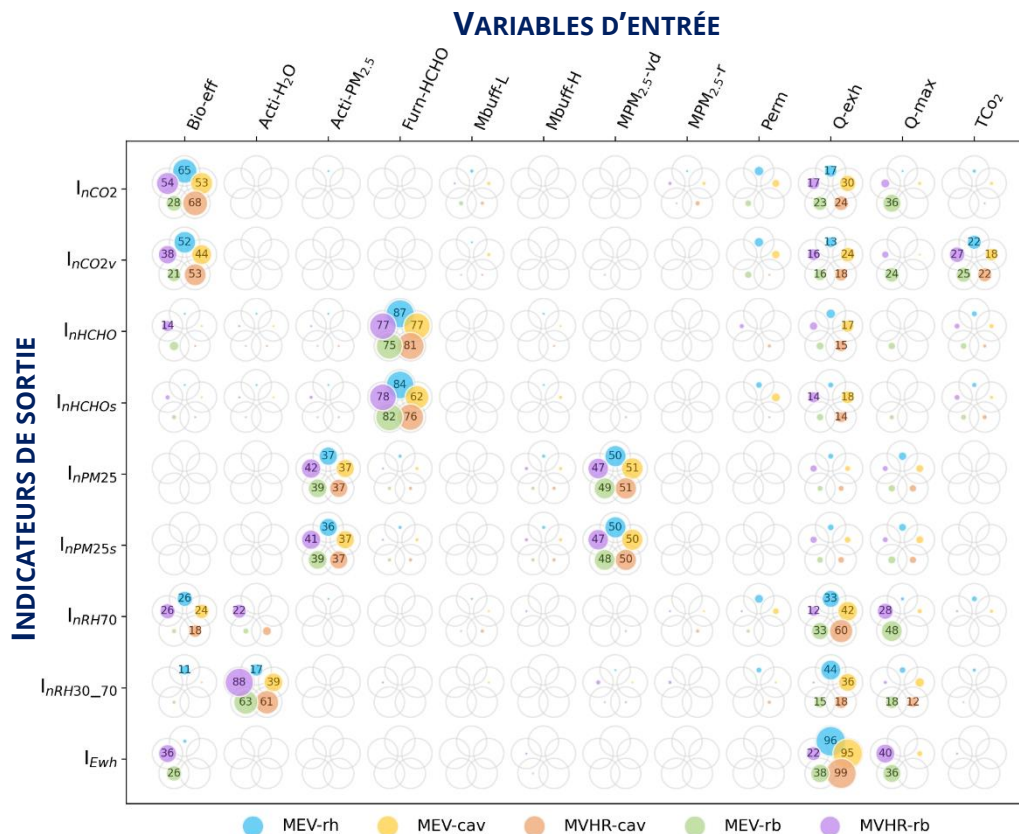


FIGURE 10 : REPRÉSENTATION DES 540 INDICES DE SENSIBILITÉ CALCULÉS POUR LES 5 STRATÉGIES DE VENTILATION

Nous avons donc décidé de ne pas les retenir dans la MOPA et de conserver un ensemble réduit de cinq indicateurs de QAI. Nous proposons également de conserver l'utilisation du MVHR-cav comme stratégie de référence pour normaliser les indicateurs I_{Ewh} qui permettent une comparaison plus facile des autres stratégies dans l'évaluation de la performance énergétique.

En complément un travail sur la robustesse de la méthode a été mené. Ce travail est basé sur les résultats de performance des cinq systèmes de ventilation simulés pour l'analyse de sensibilité. Les indicateurs de performance sélectionnés ont été agrégés en une seule valeur d'indicateur calculée à l'aide d'une méthode d'agrégation multicritères. Cette valeur agrégée est ensuite utilisée pour classer les performances des stratégies de ventilation testées et fournir un critère robuste d'aide à la décision en phase de conception.

Nous avons appliqué une méthode en trois étapes pour calculer un "design score" robuste qui permet de classer les performances des systèmes. La première étape consistait à calculer la performance des systèmes de ventilation testés. Pour cette étape, nous avons basé notre application sur les résultats de performance calculés pour l'analyse de sensibilité. Ensuite, nous avons utilisé la méthode SAW (Simple Additive Weighting) pour l'étape d'agrégation multicritère. C'est une méthode de pondération simple qui regroupe les 5 indicateurs de QAI et l'indicateur énergétique sous une seule valeur que nous avons appelée I_{MC} pour "multi-criteria indicator" (indicateur multicritère). Au-delà de 3 systèmes de ventilation testés avec plusieurs indicateurs de performance calculés et de nombreux scénarios d'entrée, il devient complexe d'identifier les systèmes les plus performants les uns par rapport aux autres. Pour cela une troisième étape utilisant la minimax regret méthode a permis de calculer un design score robuste afin de classer les systèmes de ventilation. Cette méthode de calcul intègre l'incertitude de toutes les simulations effectuées (ici 500 par système) dans le classement.

Tous ces enseignements tirés de l'analyse de sensibilité et du calcul de design score robuste ont permis d'affiner les hypothèses de modélisation en entrée, les indicateurs de performance en sortie et ainsi de faciliter le classement entre les systèmes de ventilation.

SYNTHÈSE ET CONCLUSION

Pour démontrer que nous avons atteint dans la mesure du possible les objectifs de ce travail de doctorat, nous avons présenté dans la Figure 11 une synthèse de la méthode MOPA développée pour l'évaluation des performances globales qui est illustrée par un résultat d'application final dans la Figure 2.

Ces résultats montrent l'amélioration de la méthode d'évaluation de la performance globale des systèmes de ventilation au stade de la conception. En effet, le travail a commencé dans la partie 1 avec cinq indicateurs de QAI qui ont maintenant été complétés par des indicateurs énergétiques et un score de conception pour le classement.

Ensuite, dans cette MOPA, nous proposons trois niveaux de scénarios d'entrée qui pourraient être utilisés en fonction du niveau de quantification de l'incertitude nécessaire. Si aucune incertitude n'est nécessaire, un seul scénario peut être utilisé. Pour une quantification partielle de l'incertitude, les trois scénarios de référence peuvent être utilisés. Enfin, pour une quantification complète de l'incertitude, une large gamme de scénarios doit être simulée pour réaliser une analyse de sensibilité (dans cette application, nous avons simulé 500 scénarios d'entrée). L'utilisation de CONTAM comme outil de simulation aéraulique est proposée pour modéliser les options de conception des systèmes de ventilation, mais d'autres outils de simulation aéraulique ou d'autres modèles de bâtiment pourraient être utilisés. Nous retenons une distribution de pondération pour l'agrégation des indicateurs de performance multicritères, mais une autre distribution pourrait être utilisée en fonction des besoins. Enfin, le design score peut-être calculé avec la méthode de robustesse minimax regret et normalisé pour le classement des performance des systèmes.

Entrées	Description	Bas	Reference	Haut
Bio-eff	émissions de CO ₂ et d'H ₂ O des occupants	0	0.333	1
Acti-H₂O	émissions des activités émettant de la vapeur d'eau	0.7	1	1.3
Acti-PM_{2.5}	émissions de PM _{2.5} de cuisine	1.26	1.91	2.55
Furn-	HCHO émissions de formaldéhyde du mobilier	4.5	12	23.6
Q-exh	multiplicateur du débit total d'air extrait	0.7	1	1.3
Q-max	multiplicateur du débit d'air maximum/Qboost	0.7	1	1.3

TABLEAU 1 : RÉSUMÉ DES VARIABLES ENTRÉES POUR L'APPLICATION FINALE

Sorties	Description	AT
IⁿCO₂	Exposition cumulative de CO ₂ au dessus de 1000 ppm	1000 .d (ppm.h)
IⁿHCHO	Exposition cumulative maximale au HCHO parmi tous les occupants	9.d (µg.m ⁻³ .h)
IⁿPM₂₅	Exposition cumulative maximale de PM _{2.5} parmi tous les occupants	10.d (µg.m ⁻³ .h)
IⁿRH70	Pourcentage maximal de temps où l'humidité relative est > 70 % parmi toutes les pièces	18%; 10.8%;1.8%
IⁿRH30_70	Pourcentage maximal du temps passé par l'occupant avec une humidité relative en dehors de la plage [30-70%].	14.4%
I_{Ewh}	Déperditions thermiques liées au débit total d'air	-

TABLEAU 2 : RÉSUMÉ DES VARIABLES DE SORTIES POUR L'APPLICATION FINALE

RÉSUMÉ LONG EN FRANÇAIS

SYNTHÈSE ET CONCLUSION

Afin d'explorer le potentiel de l'approche basée sur la performance en tant qu'outil de prise de décision pour les systèmes de ventilation dans la conception des bâtiments, nous avons appliqué cette OPA finale aux cinq systèmes de ventilation étudiés dans la partie 4, avec en plus le système MEV-RhB des parties 1 & 3. Le niveau d'incertitude complet a été sélectionné avec 500 nouveaux scénarios échantillonnés. Seuls les paramètres d'entrée influents identifiés dans la partie 4 (résumés dans le Tableau 1-2) ont été modifiés. Le niveau de perméabilité du bâtiment a été considéré comme inconnu et fixé avec un q4a à 0,4 m³.h.m⁻² conformément à la valeur de référence recommandée dans la réglementation nationale française en matière de construction. Le taux de remise en suspension des PM_{2.5} a également été fixé à la valeur de référence, dans l'attente d'un travail plus approfondi sur ce paramètre.

Pour illustrer l'impact des choix de décision dans la distribution des pondérations, nous avons calculé l'indicateur multicritère I_{MC} avec les distributions proposées dans la partie 4 pour l'IAQ-E et l'IAQ-E*. Nous obtenons ainsi deux designs score et deux classements robustes.

La Figure 2 présente les performances de chaque système, telles qu'elles pourraient être présentées dans un tableau de bord d'un outil d'aide à la conception ou à la décision. La représentation développée pour les performances en matière de QAI combine un graphique radar et un diagramme boîte à moustache, avec la valeur médiane en trait plein et l'enveloppe q1-q3 sur un fond de couleur claire. Le radar de la QAI est complété par le diagramme boîte à moustache I_{Ewh}. En dessous, sont regroupés l'I_{MC} et le design pour les deux distributions de pondération testées.

Dans une brève analyse des résultats de l'application finale de la MOPA, selon le design score, les deux systèmes de ventilation MVHR ont des meilleures performances en termes de QAI et d'énergie. Ils sont suivis par les systèmes MEV-rhB ou MEV-rb, selon la pondération choisie, qui affichent également des performances intéressantes en matière de QAI et d'énergie parmi les systèmes MEV. Avec sa troisième position, le MEV-rhB semble avoir un léger avantage sur le MEV-rb qui est pénalisé par de moins bons résultats de performance énergétique. En cinquième position, le système MEV-cav maintient un design score stable qui confirme son rôle de référence pour les systèmes MEV.

Avec sa première position dans cette application finale, le MVHR-rb a confirmé le potentiel de la ventilation intelligente pour fournir des performances acceptables en matière de QAI, associées à des économies d'énergie.

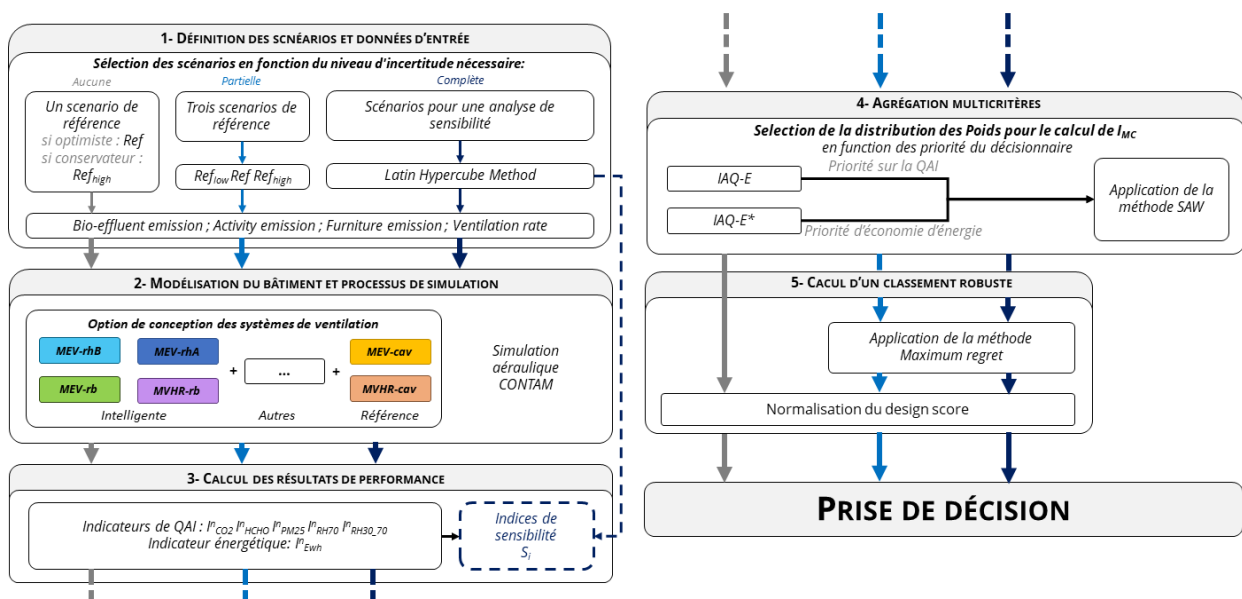


FIGURE 11 : SYNTHÈSE DE LA MÉTHODE D'ÉVALUATION DE LA PERFORMANCE GLOBALE PROPOSÉE POUR LA VENTILATION

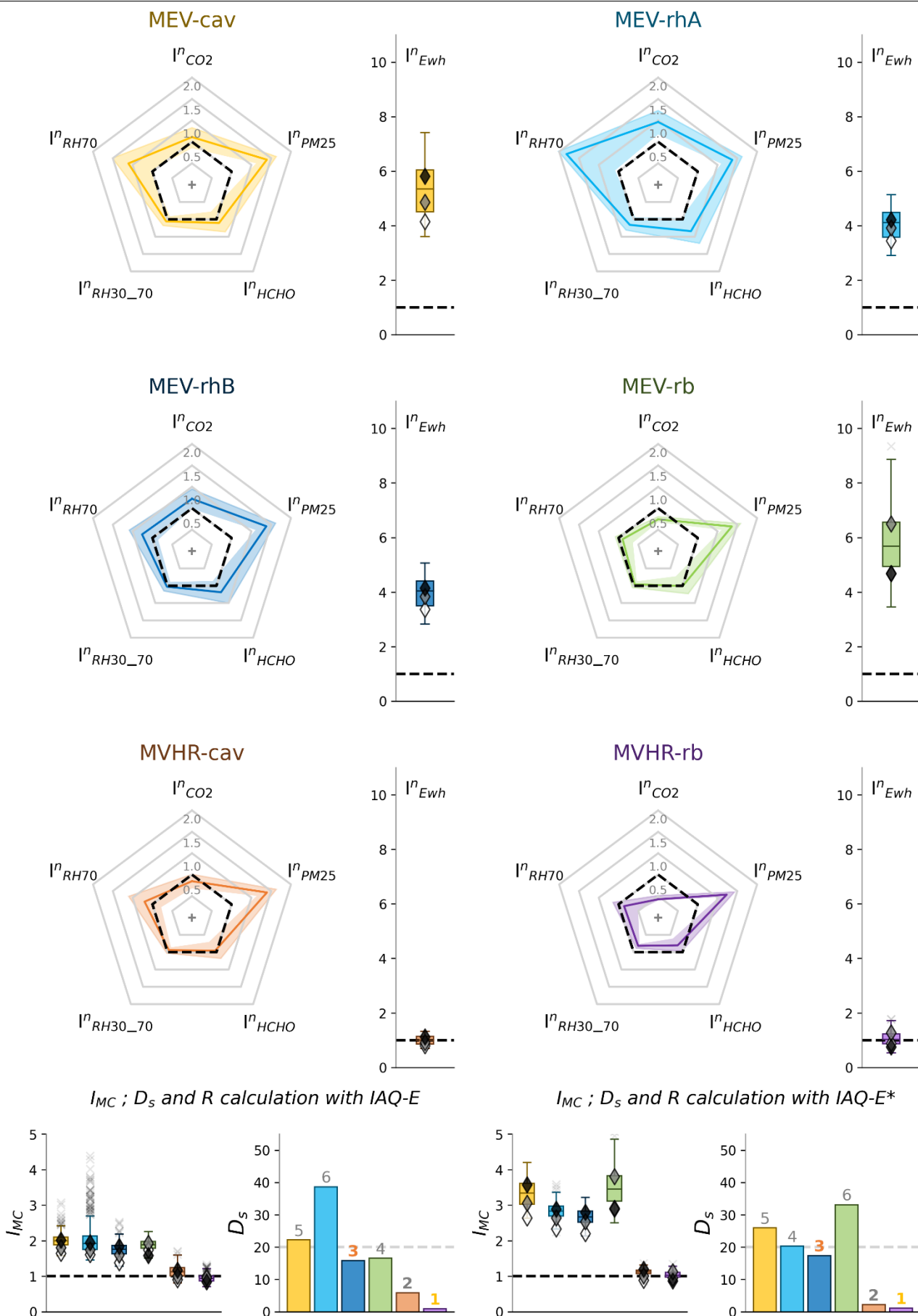


FIGURE 12 : RÉSULTATS DE PERFORMANCE GLOBALE, DESIGN SCORE ET CLASSEMENT DES 6 SYSTÈMES DE VENTILATION TESTÉS

RÉPONSES AUX QUESTIONS DE RECHERCHE

QUELS SONT LES INDICATEURS DE QAI PERTINENTS ?

COMMENT LES COMPLÉTER PAR DES INDICATEURS DE PERFORMANCE ÉNERGÉTIQUE ?

Les indicateurs pertinents de QAI identifiés sont un ensemble de 5 indicateurs qui ont été proposés dans la partie 1 : IⁿCO₂, IⁿHCHO, IⁿPM₂₅, IⁿRH₇₀, IⁿRH_{30_70}. Ces indicateurs sont normalisés par les seuils acceptables qui leur sont associés. Les indicateurs inférieurs à 1 signifient que la performance est atteinte et ceux qui sont supérieurs à 1 signifient que la performance doit être améliorée. De plus, l'utilisation d'indicateurs normalisés facilite la visualisation et l'analyse des résultats, comme le démontrent les différentes représentations des résultats de performance dans ce travail, telles que les graphiques en radar ou les diagrammes boîte à moustache.

Nous avons décidé d'exclure à ce stade les indicateurs d'exposition à court terme car ils fournissent des informations équivalentes à celles fournies par les indicateurs à long terme. Ceci afin de maintenir un nombre réduit d'indicateurs de QAI.

Enfin, ces premiers résultats de performance ont mis en évidence l'importance de prendre en compte des paramètres de QAI autres que les traditionnels CO₂ et humidité, pour une meilleure prise en compte de la QAI dans les bâtiments.

COMMENT DÉFINIR, MODÉLISER ET CARACTÉRISER LES ÉCONOMIES D'ÉNERGIE RÉALISÉES PAR LES SYSTÈMES DE VENTILATION AFIN DE CONSTRUIRE ET DE VALIDER UN NOUVEL ENSEMBLE D'INDICATEURS DE PERFORMANCE COUPLANT ÉNERGIE ET IAQ ?

Pour définir et caractériser les économies d'énergie réalisées par les systèmes de ventilation, la combinaison des déperditions thermiques liés à l'extraction et la consommation d'énergie des ventilateurs sous un seul indicateur de performance énergétique pourrait être l'indicateur le plus précis. Mais avoir une telle précision n'est pas forcément nécessaire pour obtenir quand même un bon ordre de grandeur du potentiel d'économie d'énergie. Concernant l'hypothèse de température constante dans les simulations CONTAM, discutée dans la partie 2, nous avons confirmé qu'une simulation énergétique supplémentaire n'est pas nécessaire si cette méthode est appliquée pendant la période de chauffage.

Par conséquent, nous proposons de conserver uniquement la partie relative déperdition de l'indicateur énergétique I_{EC}. En effet, nous considérons qu'il est plus pertinent de se concentrer sur le potentiel d'économie d'énergie dû aux déperditions thermiques des stratégies de ventilation à débit variable plutôt que sur la consommation d'énergie des ventilateurs. Cela permet également de maintenir un nombre réduit d'indicateurs utilisés pour la MOPA.

COMMENT ESTIMER ET CARACTÉRISER CORRECTEMENT LES ÉMISSIONS D'UNE SOURCE POLLUANTE À PARTIR DE DIVERS MATÉRIAUX, PRODUITS ET ACTIVITÉS EXISTANTS DANS UN BÂTIMENT, AFIN D'ÉLABORER UN SCÉNARIO D'ÉMISSIONS PERTINENT À L'ÉCHELLE DU LOGEMENT ?

Comme nous l'avons souligné dans la première partie, il est difficile d'élaborer des scénarios à partir de l'échelle du matériau, du produit et de l'activité jusqu'à l'échelle du bâtiment.

Pour les scénarios d'occupation et les émissions d'humidité liés aux activités des occupants (douche, cuisine, séchage du linge), nous avons utilisé les données détaillées de l'observatoire national français de la QAI en supposant deux occupants dans une chambre et un dans les autres.

Pour le formaldéhyde, nous suggérons d'utiliser les données in-situ mesurées sur des logements basse consommations en France pour calculer des taux d'émissions moyen à l'échelle du logement.

RÉSUMÉ LONG EN FRANÇAIS

RÉPONSES AUX QUESTIONS DE RECHERCHE

Pour les scénarios d'émission de $PM_{2.5}$, d'après la revue de littérature réalisée dans la partie 1, nous avons retenu dans un premier temps uniquement les émissions provenant des activités de cuisine pour construire des scénarios d'émission faible, moyen et élevé.

Nous avons proposé une infographie (Figure 6) regroupant tous les scénarios d'émissions proposés qui peut être utilisée comme une boîte à outils et peut être ajustée par le modélisateur en fonction du cas d'étude et de son contexte local.

QUELS SONT LES IMPACTS DES HYPOTHÈSES ET PARAMÈTRES UTILISÉS DANS LA MODÉLISATION DE CES SOURCES DE POLLUANTS AU REGARD DU MANQUE DE DONNÉES DISPONIBLES ET DES DIFFICULTÉS À LES EXTRAPOLER À L'ÉCHELLE DU BÂTIMENT ?

Le travail d'analyse de sensibilité de la partie 4 a confirmé la nécessité de poursuivre la recherche sur les paramètres des scénarios d'émission de polluants. Pour simplifier les hypothèses de la MOPA, nous avons montré que les paramètres du tampon hygroscopique et le taux de remise en suspension de $PM_{2.5}$ pouvaient être fixés à leurs valeurs par défaut, car leur variabilité n'a pas eu d'impact sur les indicateurs de performance. Cependant, il est nécessaire de se concentrer sur le paramètre de vitesse de dépôt des $PM_{2.5}$ mis en œuvre dans CONTAM, car il est responsable d'environ 50 % de l'impact de la sensibilité sur l'indicateur $PM_{2.5}$.

QUELLE EST L'INCERTITUDE ET QUELS SONT LES PRINCIPAUX PARAMÈTRES D'ENTRÉE AYANT UN IMPACT SUR LA PERFORMANCE ÉVALUÉE ?

Sur la base des résultats de la partie 4 sur la quantification de l'incertitude, les principaux paramètres d'entrée influents identifiés sont les émissions de bio-effluents, les émissions de $PM_{2.5}$ des activités de cuisine, l'humidité émis par les activités des occupants, le taux d'émission de formaldéhyde et la vitesse de dépôt des $PM_{2.5}$. Cela a confirmé la nécessité de poursuivre les recherches sur tous ces paramètres.

De plus, les débits d'air extrait et les grands débits d'air dans la cuisine sont les principaux facteurs d'incertitude pour l'indicateur énergétique ; ils ont également un impact plus modéré en ce qui concerne l'incertitude relative à la performance de QAI.

COMMENT ÉQUILIBRER L'IAQ ET L'ÉVALUATION DE LA PERFORMANCE ÉNERGÉTIQUE POUR OBTENIR UN CLASSEMENT SOLIDE DES SYSTÈMES DE VENTILATION ?

Pour équilibrer l'évaluation des performances entre la QAI et l'énergie, nous avons proposé dans la partie 4 de regrouper les indicateurs de QAI et d'énergie en un seul indicateur agrégé I_{MC} qui reflète la performance globale des systèmes de ventilation.

La méthode proposée est la méthode de pondération par agrégation simple, et la distribution de la pondération peut être ajustée en fonction des priorités de décision. Ensuite, sur la base de I_{MC} , la méthode de robustesse minimax regret peut être utilisée pour le calcul d'un design score qui est normalisé pour classer les performances des systèmes de ventilation.

PERSPECTIVES

Nous avons résumé les améliorations possibles et les travaux futurs identifiés dans les points suivants :

- **Améliorer les scénarios et les modèles pour les émissions de polluants** : comme l'a montré l'analyse de sensibilité, les principaux paramètres influents sont Bio-eff, Acti-PM_{2,5}, Acti-H₂O, Furn-HCHO, MPM_{2,5}-vd . Le nombre d'occupants et leurs profils d'émissions de bio-effluents pourraient être mélangés pour évaluer si des modèles d'occupants plus détaillés ont un impact sur les performances évaluées ou si les hypothèses de référence sont suffisantes. La même approche pourrait également être utilisée avec les scénarios d'émissions de cuisine en mélangeant les types de cuisson faible, moyen et élevé au cours de la semaine. L'impact d'autres sources supplémentaires de PM_{2,5} doit également être quantifié afin d'évaluer si notre hypothèse d'utiliser uniquement l'activité de cuisson est suffisamment représentative ou si elle sous-estime l'exposition aux PM_{2,5}. Un travail spécifique sur le paramètre de vitesse de déposition des PM_{2,5} dans le modèle CONTAM doit également être réalisé. De plus, l'évaluation de l'impact des concentrations de polluants extérieurs et des taux d'infiltration pourrait également être utile pour explorer d'autres stratégies de ventilation intelligente basées sur le niveau de pollution extérieure.

- **Une déclinaison de la méthode appliquée avec des mesures in-situ** : Les cinq indicateurs de QAI et l'indicateur énergétique pourraient être calculés sur la base de mesures in situ plutôt que des résultats de simulation. Cependant, cela questionne la faisabilité de mesurer dans chaque pièce tous les paramètres de QAI et les débits d'air extrait sur toute la période de chauffage. Pour cela, certaines simplifications peuvent être envisagées, comme par exemple :

- **Une période plus courte**, mais l'incertitude liée à la réduction de cette période devrait être quantifiée. Cela pourrait se faire par des simulations de flux d'air et des comparaisons de mesures sur une période d'une semaine, similaires à la comparaison effectuée sur les campagnes C1 et C2 dans la partie 2. Mais avec un plus grand nombre de périodes testées et une analyse comparative plus poussée.

- **Réduction des paramètres étudiés pour une mesure in situ** : A ce stade, 4 paramètres de l'environnement intérieur sont utilisés pour calculer les indicateurs de QAI et d'énergie (CO₂, humidité relative, formaldéhyde et PM_{2,5}). Cependant, ces paramètres pourraient être corrélés. Si cette corrélation peut être caractérisée, le nombre de paramètres étudiés pourrait alors être réduit. De plus, ces corrélations peuvent être calculées et approfondies avec des simulations et une analyse de sensibilité.

Cette déclinaison de la méthode avec des mesures in situ pourrait aider à évaluer la performance des systèmes de ventilation lors de la mise en service afin de quantifier l'écart entre la performance à la conception et la performance réelle. Elle pourrait également être utilisée pour mesurer la garantie de performance dans le temps.

- **Tester d'autres indicateurs d'exposition à court terme** : Les indicateurs d'exposition à court terme testés dans les parties 3 et 4, mais non retenus, ont été élaborés sur la base des indicateurs d'exposition à court terme disponibles dans la littérature. Cependant, peu de propositions étaient disponibles dans la littérature, et nous avons montré qu'elles n'étaient pas adaptées à l'évaluation de la performance globale pour la ventilation. En effet, la moyenne sur 24 heures pour les PM_{2,5} ne semble pas adaptée pour une évaluation en environnement intérieur et aux pics d'exposition liés à une activité fortement émettrice (telle que la cuisine dans le cadre de ce travail, mais d'autres en général). En ce qui concerne le formaldéhyde, la période d'une heure n'est peut-être pas non plus la plus pertinente, car nous avons modélisé le formaldéhyde avec une émission de fond constante. Un travail de sensibilité sur la période idéale, le seuil et les variations des sources d'émissions pourrait être utile pour élaborer un indicateur à court terme spécifique à intégrer dans la MOPA.

- **Des simulations énergétiques pour des indicateurs de performance énergétique étendus** : L'indicateur énergétique était limité aux seules déperditions thermiques dues à la ventilation, car nous nous concentrons uniquement sur la période de chauffage. Mais un indicateur de performance énergétique amélioré pourrait inclure d'autres aspects tels que le potentiel de refroidissement nocturne, l'impact sur le confort d'été. Cela est encore plus pertinent avec les systèmes de ventilation intelligents qui pourraient être spécifiquement conçus pour fournir un rafraîchissement passif en été. Dans ce cas, l'utilisation d'un modèle thermique est nécessaire pour surmonter les limites inter-saisonniers et estivales des hypothèses de température constante mises en évidence avec CONTAM dans la partie 2.

- **La co-simulation DOMUS-CONTAM** : le travail initié pour le couplage entre DOMUS et CONTAM avec le LST de PUCPR Curitiba sera poursuivi pour finaliser la mise en œuvre du processus de co-simulation. L'objectif est de valoriser ce développement par une application qui fonctionne sur un bâtiment complet.

- **La sensibilité de la méthode d'agrégation multicritères** : la méthode utilisée pour l'agrégation multicritères était la méthode SAW avec une pondération simple. L'impact de la distribution des poids de pondération doit être clairement explorée afin de proposer une distribution adaptée aux indicateurs de QAI et d'énergie utilisés, mais aussi pour pouvoir proposer plus de déclinaisons adaptées à plusieurs profils de décision. De plus, d'autres agrégations multicritères pourraient être testées et pourraient être plus pertinentes pour l'évaluation de la performance globale de la performance de la ventilation.

- **La sensibilité de la méthode de robustesse de calcul du design score** : la méthode utilisée pour le calcul du design score et le classement a été basée sur la méthode du regret minimax, car elle semblait la plus pertinente. Cependant, il existe d'autres méthodes et le nombre de simulations utilisées pour le calcul du design score ou le nombre de stratégies de ventilation testées peut avoir un impact sur le classement final. Ceci doit être quantifié sur d'autres études de cas pour être généralisé.

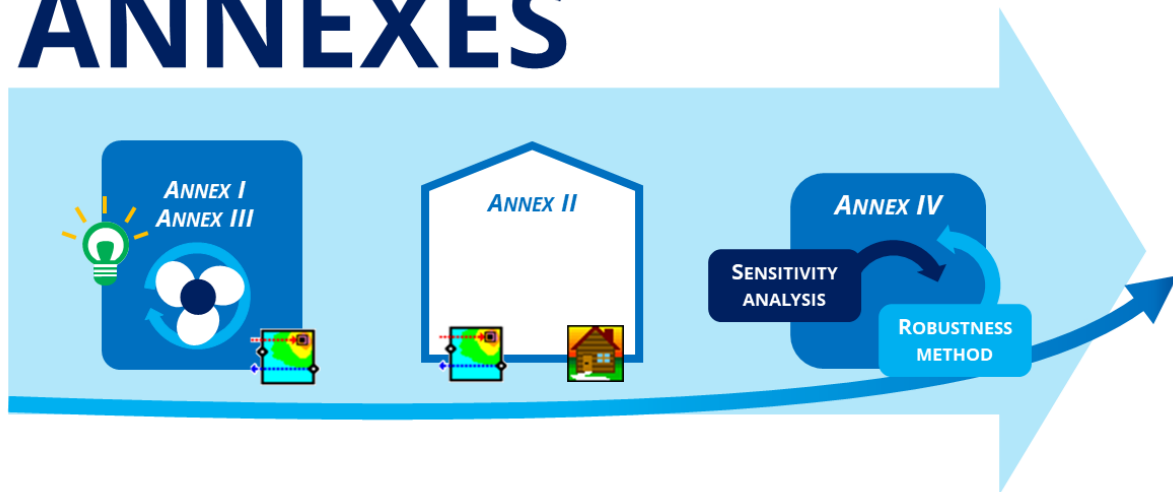
Enfin, cette MOPA est une proposition de méthode d'évaluation de la performance globale qui a mis en évidence le potentiel de l'approche performanciel pour l'évaluation des performance globales des systèmes de ventilation. Elle fournit des éléments de réponse aux questions de recherche posées dans ce travail de doctorat, mais elle ouvre également la discussion sur la manière de généraliser une telle méthode au stade de la conception et sur l'ensemble du cycle de vie du système de ventilation dans un bâtiment. En effet, nous devons garder à l'esprit que cette méthode n'a été testée que sur quelques études de cas basées sur des simulations et que plusieurs autres applications sur différentes géométries de maisons et de systèmes de ventilation doivent être étudiées avant d'être généralisées.

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ANNEXES



ANNEX I

A-I.1 CONTAM SUPER ELEMENTS FOR MEV-RH IMPLEMENTATION

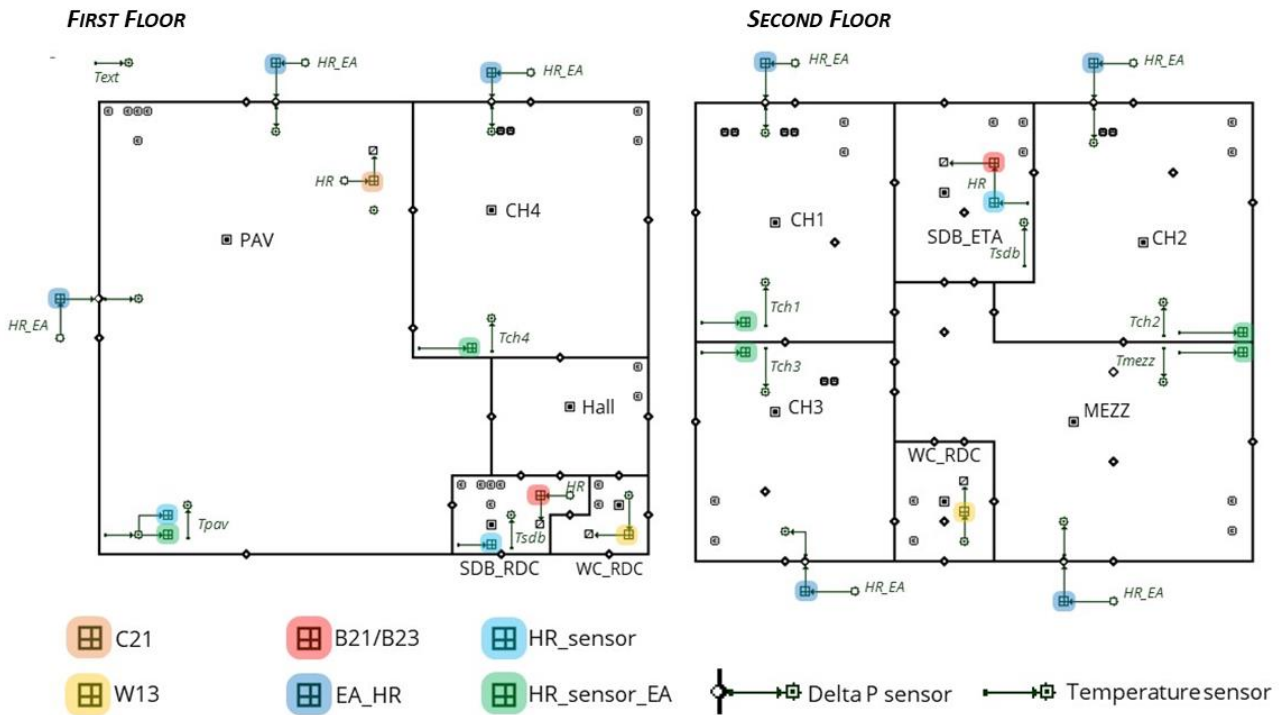
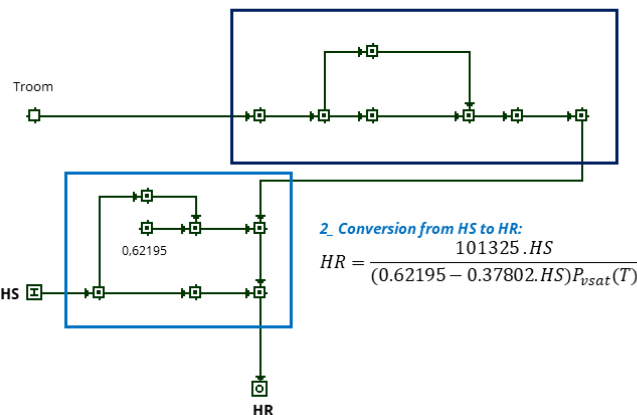


FIGURE 13 : IMPLANTATION OF THE SUPER ELEMENT IN THE FRENCH CASE STUDY FOR MEV-RH

HR SENSOR :

1. Calculation of P_{vsat} with Dilley's method:

$$P_{vsat}(T_{capt}) = 610.78e^{237.34/T_{capt}}$$



HR SENSOR EA :

Temperature adjustment:

$$T_{capt} = T_{room} - 0.3 (T_{room} - T_{ext})$$

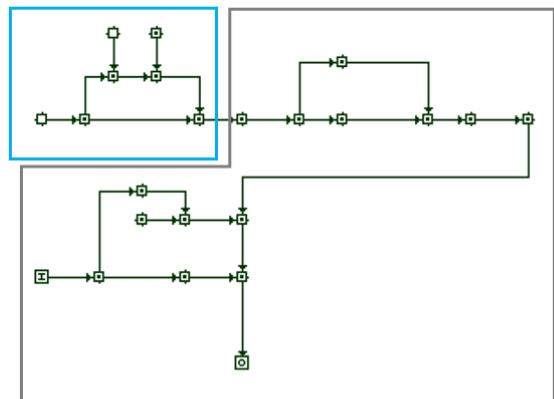


FIGURE 14 : HR SENSOR AND HR SENSOR EA SUPER ELEMENTS

AIR-INLET HYGRO (EA_HR):

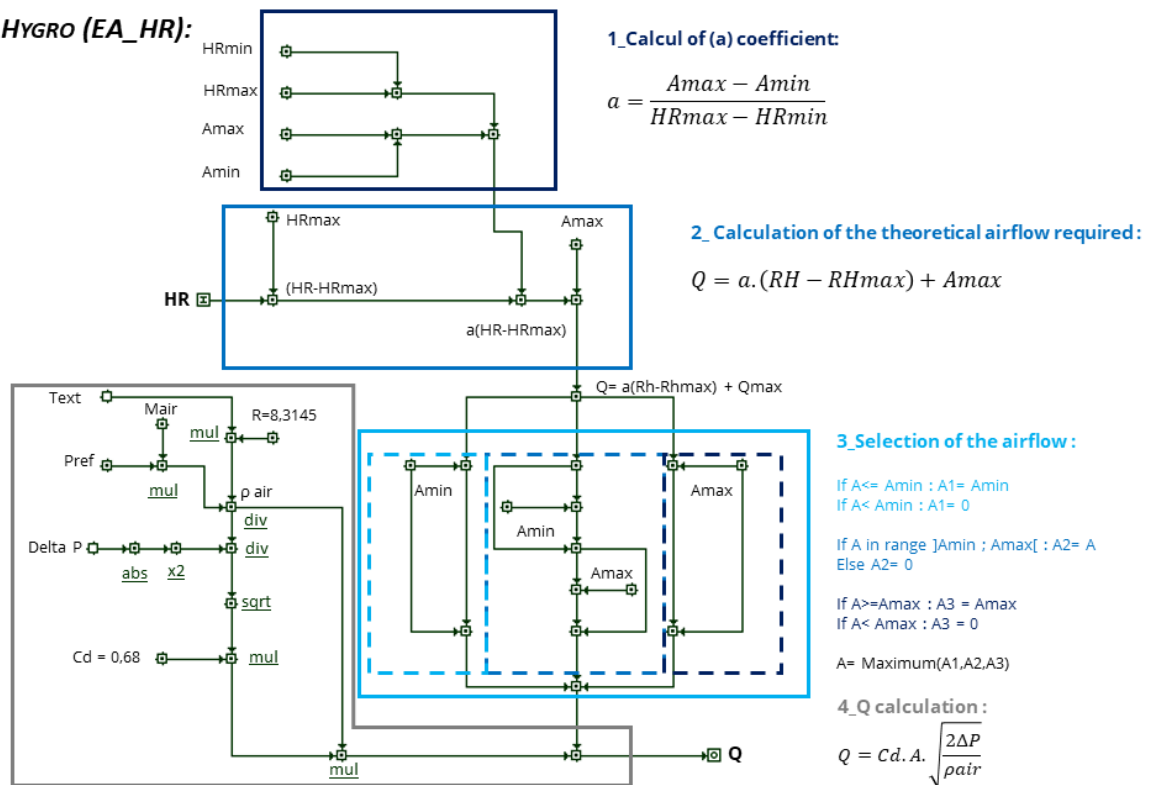


FIGURE 16 : EA_RH SUPER ELEMENT

B21-B23 – EXHAUST HYGRO :

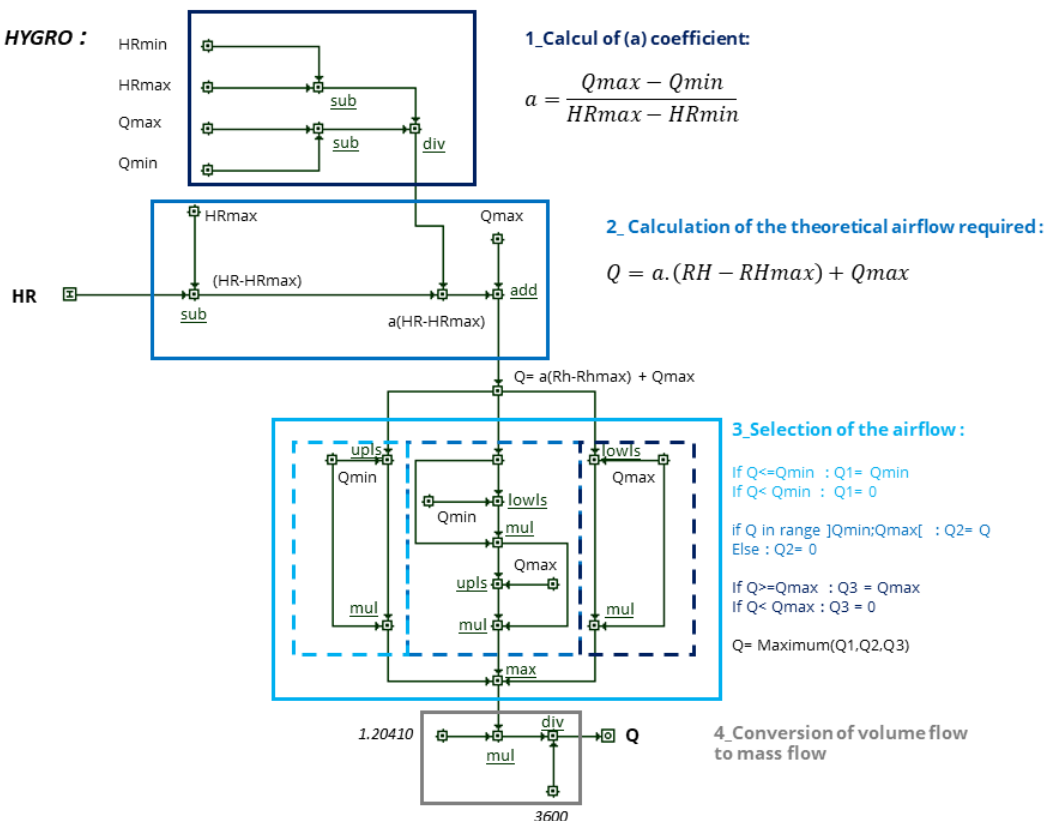


FIGURE 15 : B21/B23 SUPER ELEMENT

C21 – EXHAUST HYGRO :

1_Same operation as B21 and B23 with :

2. Q_{boost} in kitchen integration:
 Si commande = 1, alors Q_{pointe} = 135
 Si commande = 0, alors Q_{pointe} = 0

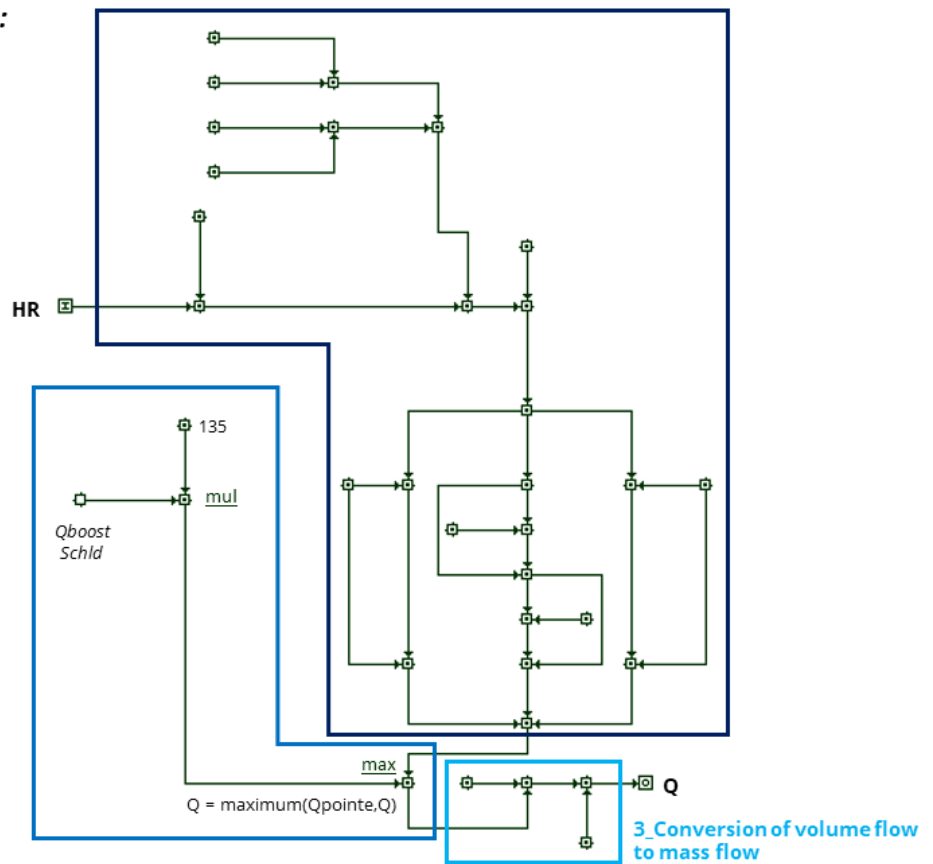


FIGURE 17 : C1 SUPER ELEMENT

A-I.2 CONTAM SUPER ELEMENTS FOR MEV-RB IMPLEMENTATION

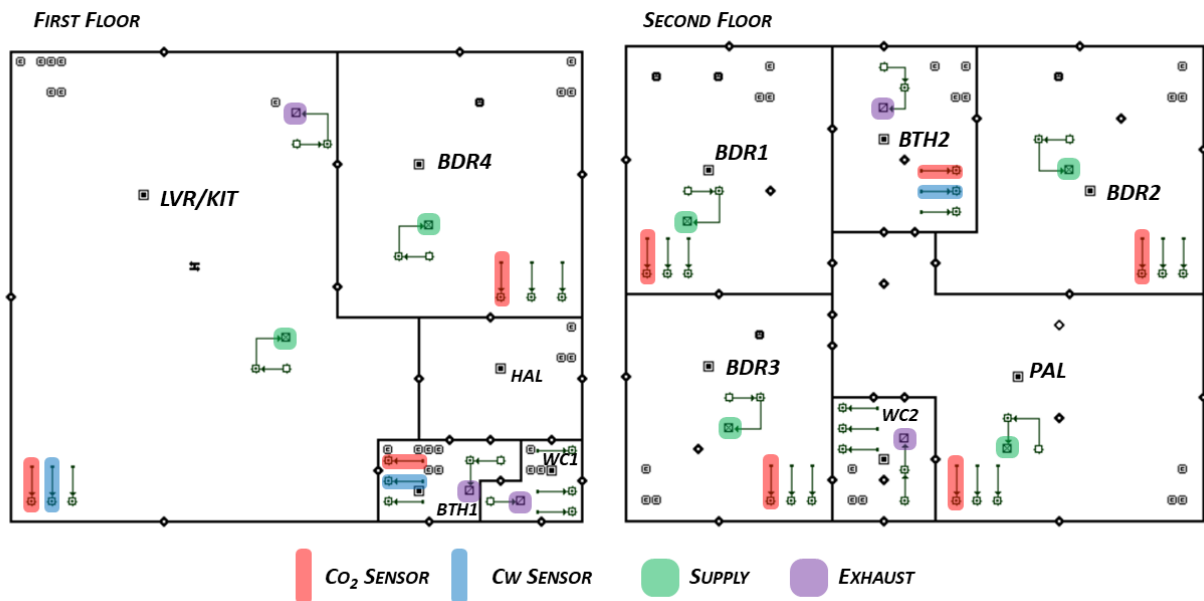


FIGURE 18 : IMPLANTATION OF THE SUPER ELEMENTS IN THE FRENCH CASE STUDY FOR MEV-RB

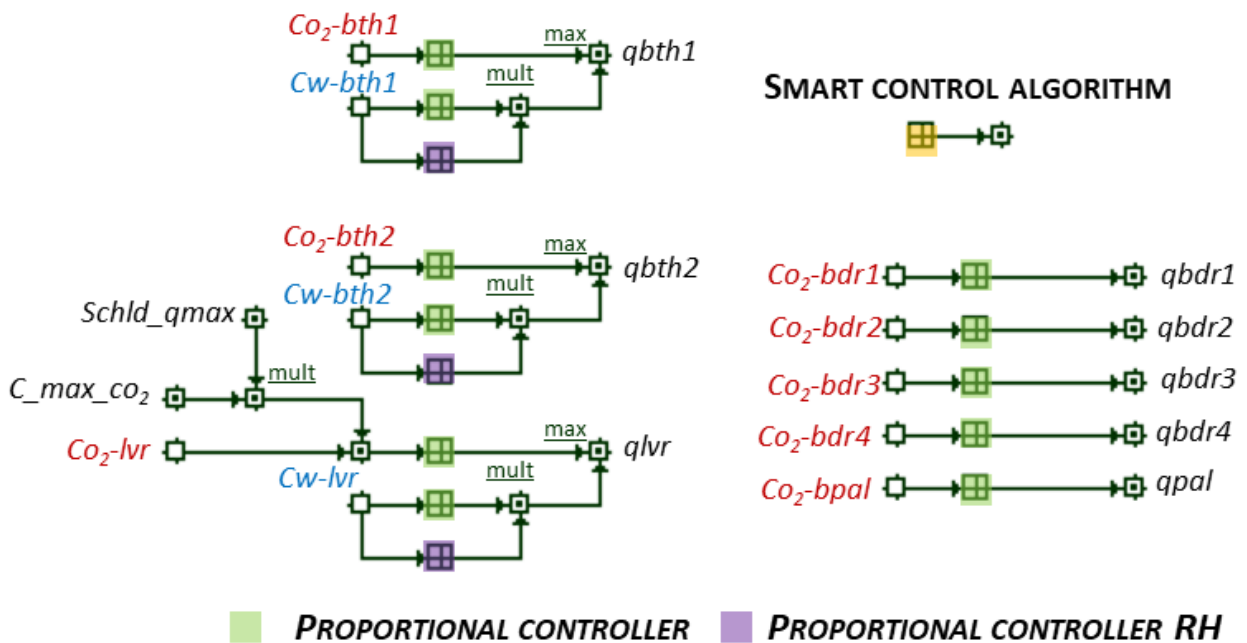


FIGURE 19 : ADDITIONAL SUPER ELEMENTS IMPLEMENTED IN THE FRENCH CASE STUDY FOR MEV-RB

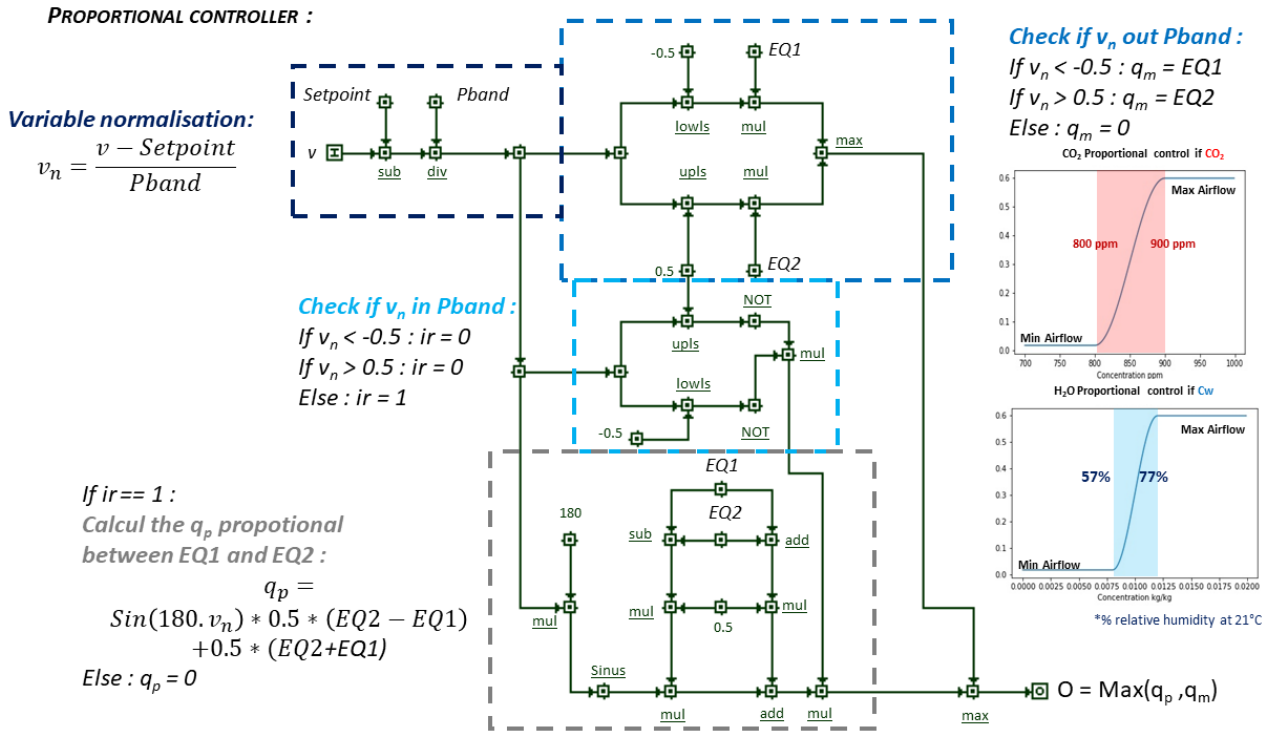
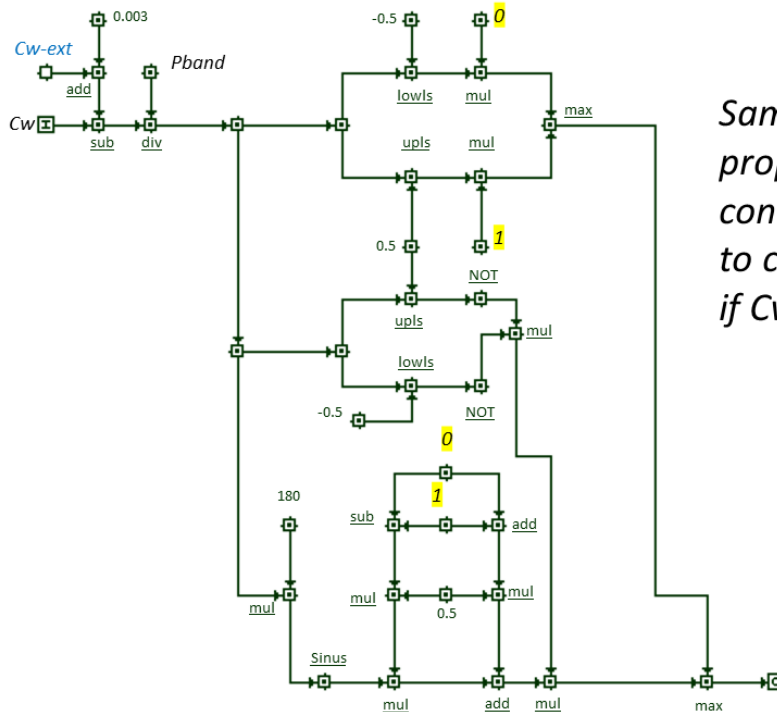


FIGURE 20 : PROPORTIONAL CONTROLLER SUPER ELEMENT

PROPORTIONAL CONTROLLER HR :



Same structure as the proportional controller, but edited to check :
 if $Cw > Cw\text{-ext} + 0.003$

FIGURE 21 : PROPORTIONAL CONTROLLER HR SUPER ELEMENT

SMART CONTROL ALGORITHM :

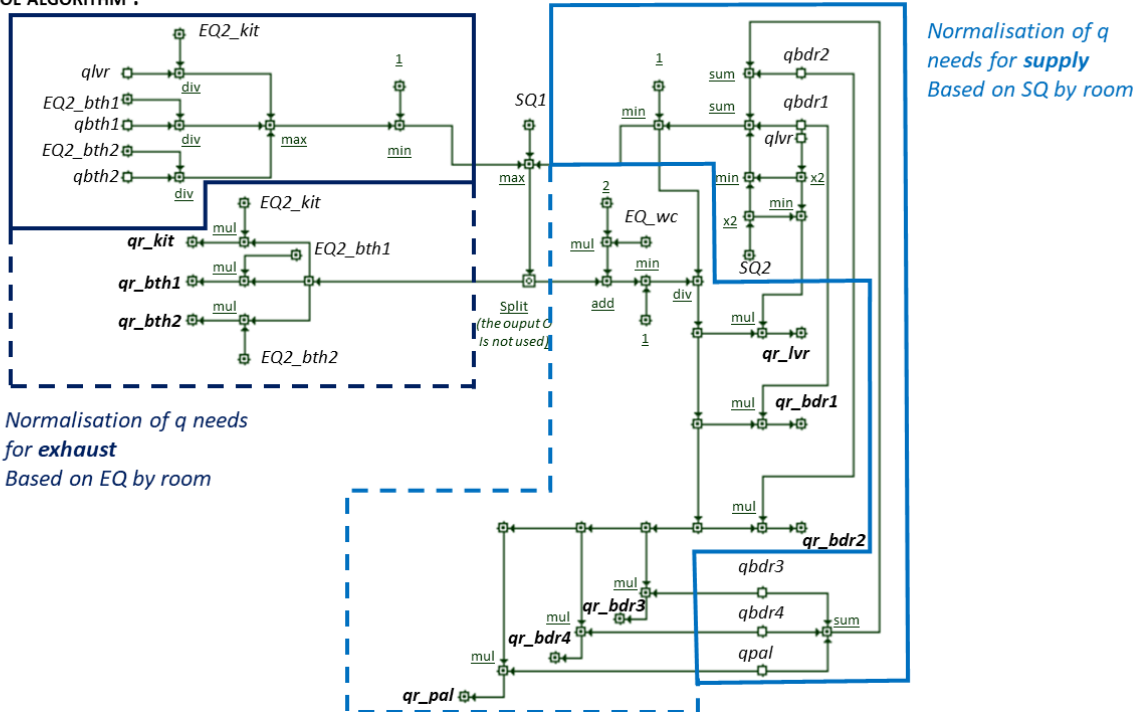


FIGURE 23 : SMART CONTROL ALGORITHM SUPER ELEMENT

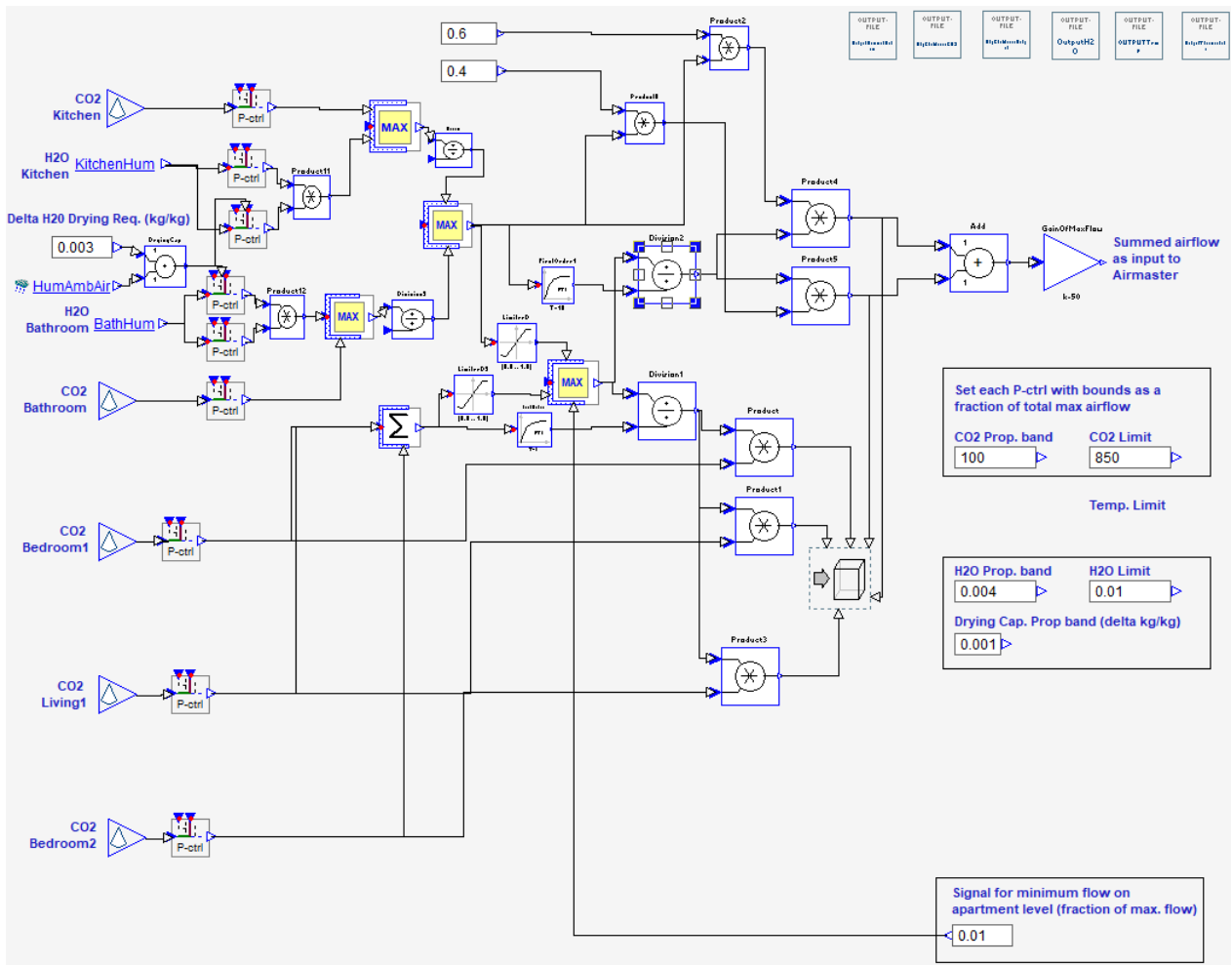


FIGURE 22 : IMPLEMENTATION OF THE MEV-RB CONTROL STRATEGIES IN IDA-ICE

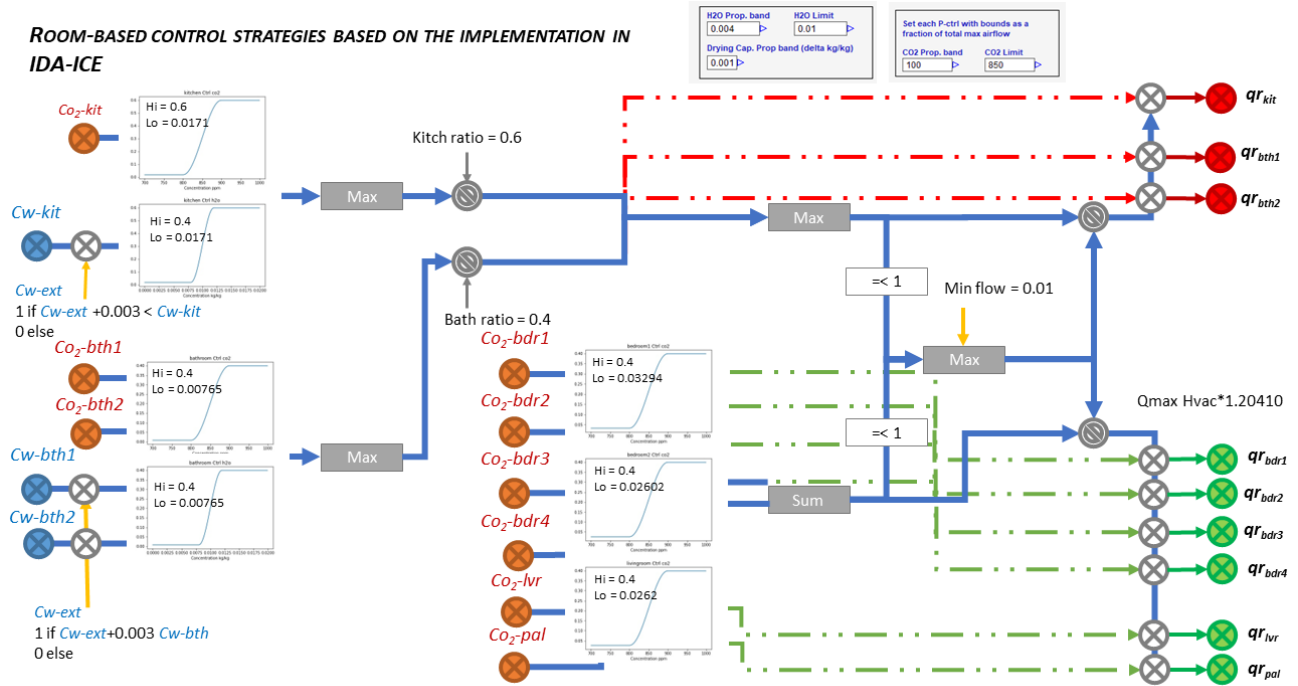


FIGURE 24 : VISUALIZATION OF THE CONTROL STRATEGIES ALGORITHM FOR THE MEV-RB BASED ON THE IMPLEMENTATION IN IDA-ICE

A-I.3 IDA-ICE SIMULATION RESULTS COMPARISON FOR MVHR-RB IMPLEMENTATION VALIDATION IN CONTAM

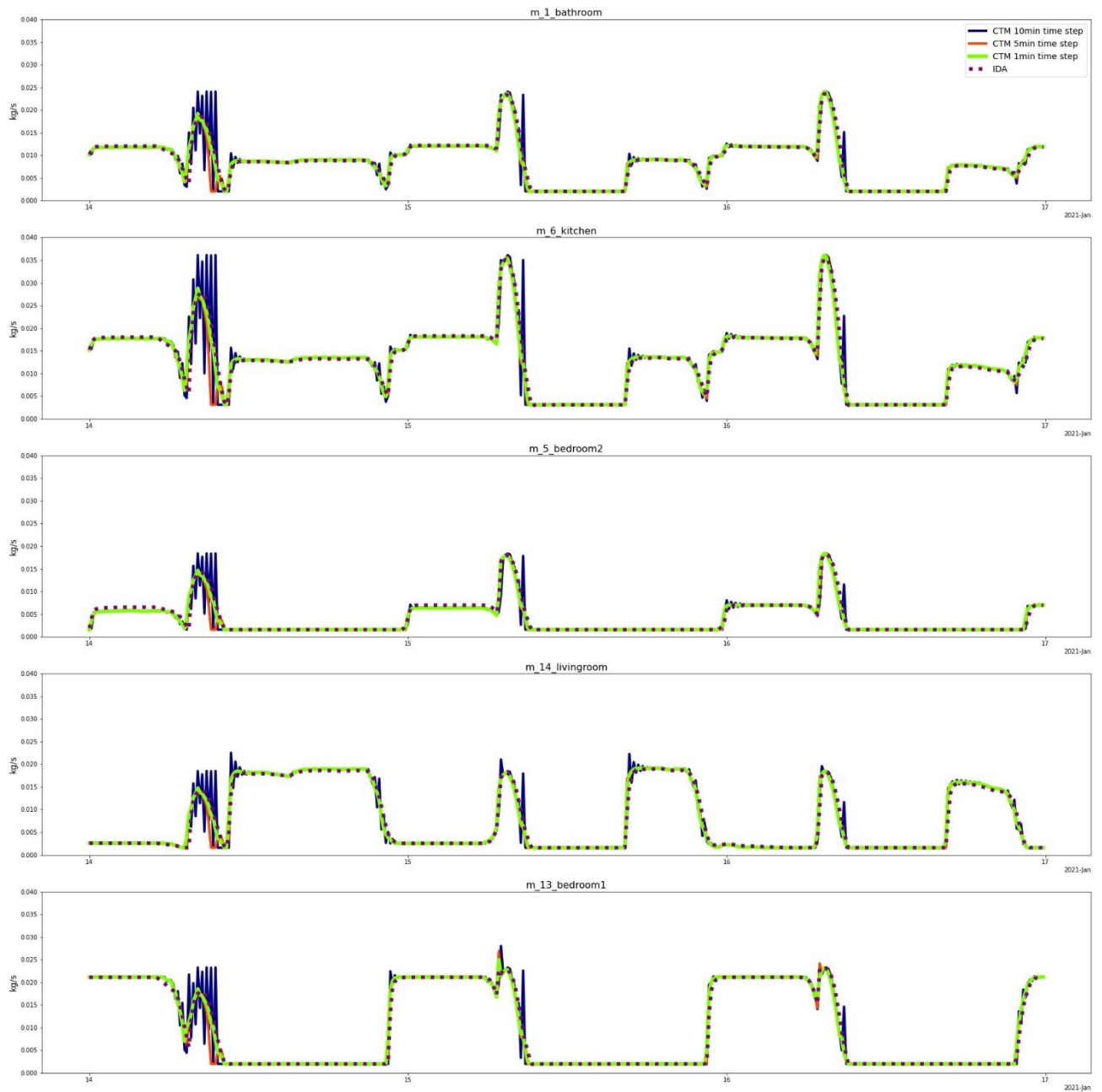


FIGURE 25: MVHR-RB AIRFLOWS (THE DANISH CASE STUDY) ; 10MIN, 5MIN, 1MIN TIME STEP TESTED IN CONTAM SIMULATION

ANNEXES

ANNEX I

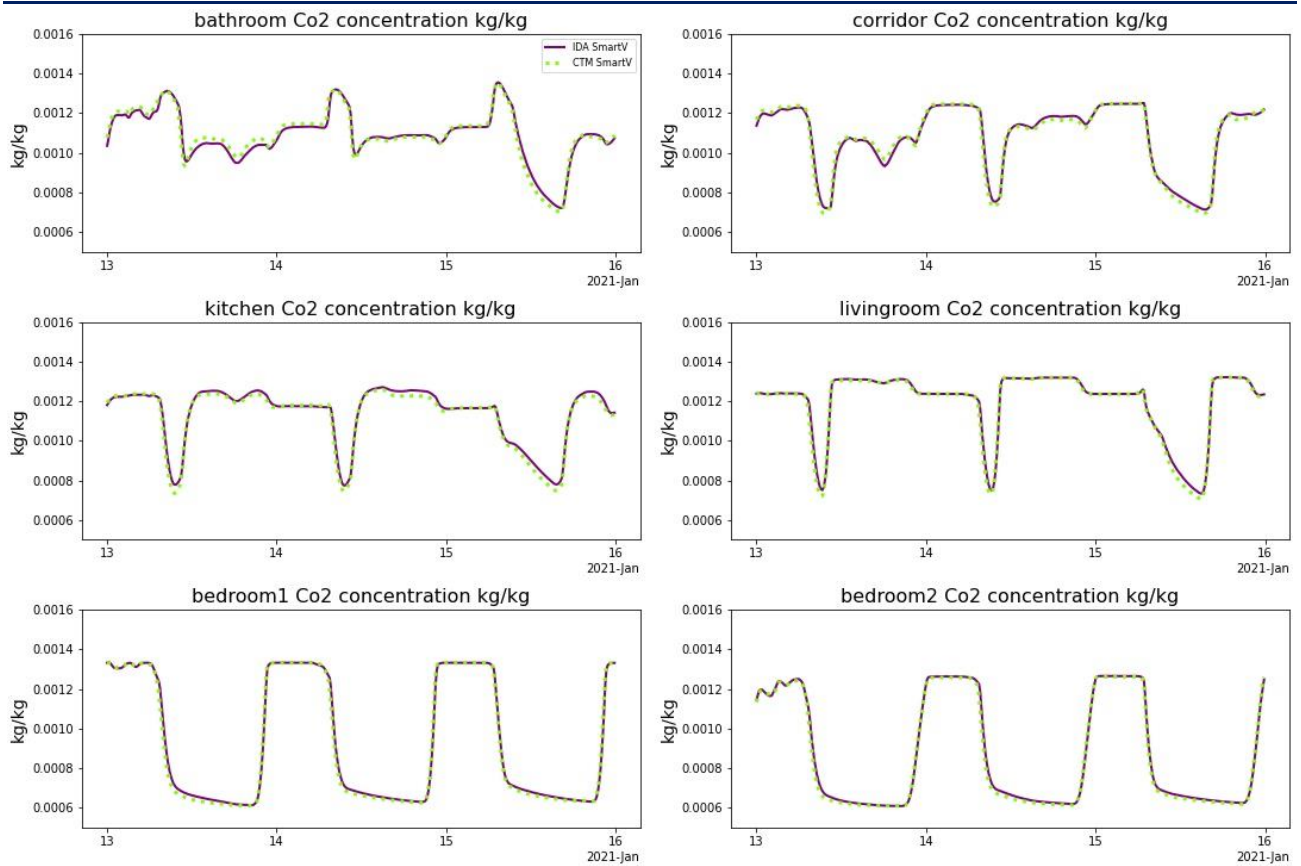


FIGURE 26 : CO₂ CONCENTRATION (DANISH CASE STUDY) WITH THE MEV-RB ; IDA AND CONTAM MODELLING

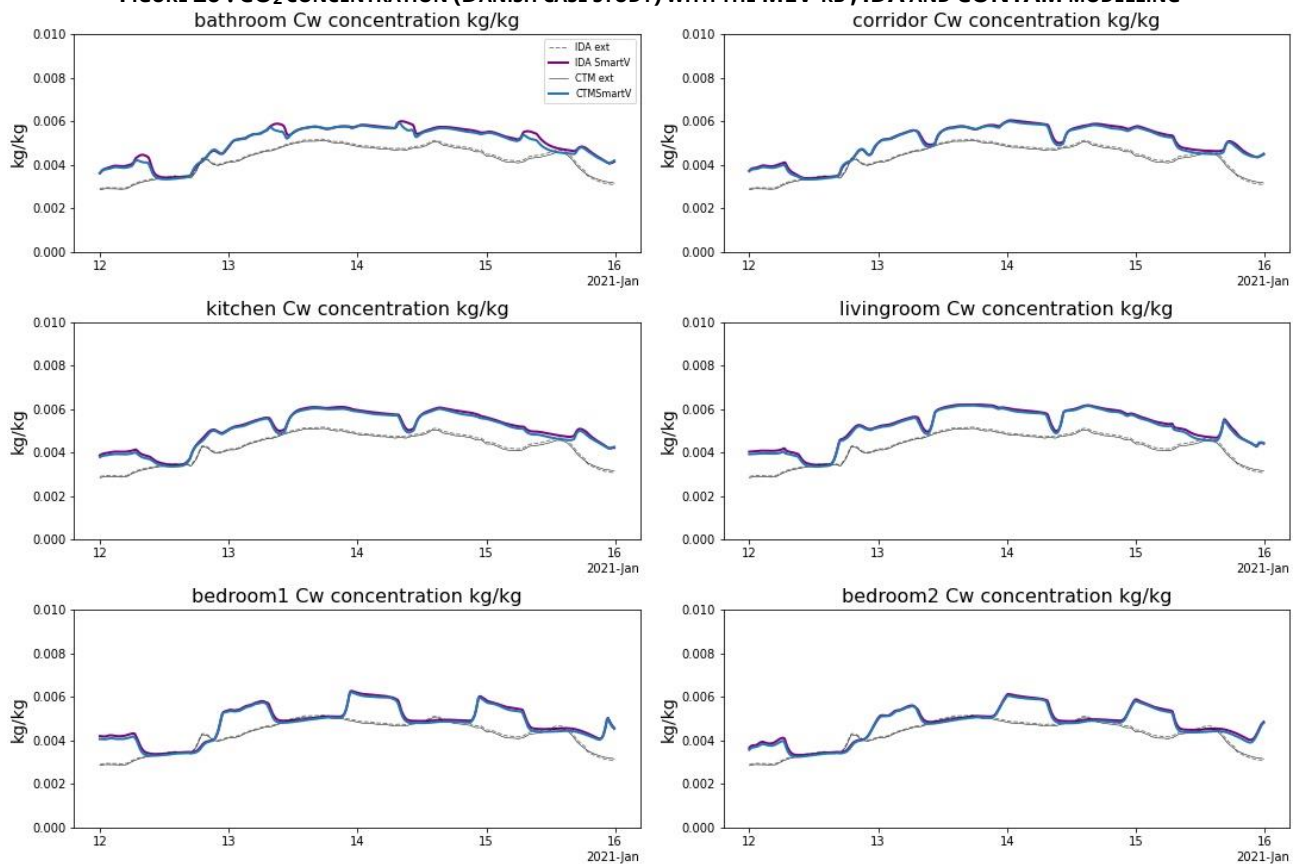


FIGURE 27 : CO₂ CONCENTRATION (DANISH CASE STUDY) WITH THE MEV-RB ; IDA AND CONTAM MODELLING

ANNEX II

A-II.1 IN SITU MEASUREMENT CAMPAIGN DETAILS:

Campaign 1 : Temperatures °C								
	Ext	LVRk	LVRp	BTH2	BR1	BR2	BR3	BR4
mean	3,20	21,95	23,28	18,98	17,39	17,78	16,94	18,63
std	4,48	1,63	1,41	0,97	1,24	1,40	1,20	0,90
min	-3,80	19,00	20,80	17,00	9,60	8,80	10,10	16,80
0,25	0,30	21,00	22,40	18,50	17,00	17,30	16,70	18,00
0,50	2,80	21,40	22,90	18,80	17,60	18,20	17,10	18,40
0,75	4,80	22,30	23,60	19,30	17,90	18,40	17,50	19,30
max	20,70	26,90	28,40	24,60	20,80	20,20	18,70	21,30

TABLEAU 3 : STATISTICS DETAILS BY LOCATION ON THE MEASURED TEMPERATURES DURING THE CAMPAIGN 1

Campaign 2 : Temperatures °C								
	Ext	LVRk	LVRp	BTH2	BR1	BR2	BR3	BR4
mean	8,30	21,94	20,66	19,08	20,42	19,51	18,79	19,45
std	5,70	1,32	1,06	0,98	0,86	0,91	1,41	0,81
min	-1,60	19,70	18,60	16,90	17,02	15,30	9,10	16,80
0,25	3,90	20,90	19,80	18,60	19,98	19,05	18,30	18,80
0,50	7,60	21,80	20,50	18,90	20,46	19,47	18,80	19,40
0,75	11,40	22,70	21,30	19,40	20,80	20,01	19,30	20,10
max	27,30	26,10	24,80	25,10	22,40	22,09	22,00	22,00

TABLEAU 4 : STATISTICS DETAILS BY LOCATION ON THE MEASURED TEMPERATURES DURING THE CAMPAIGN 2

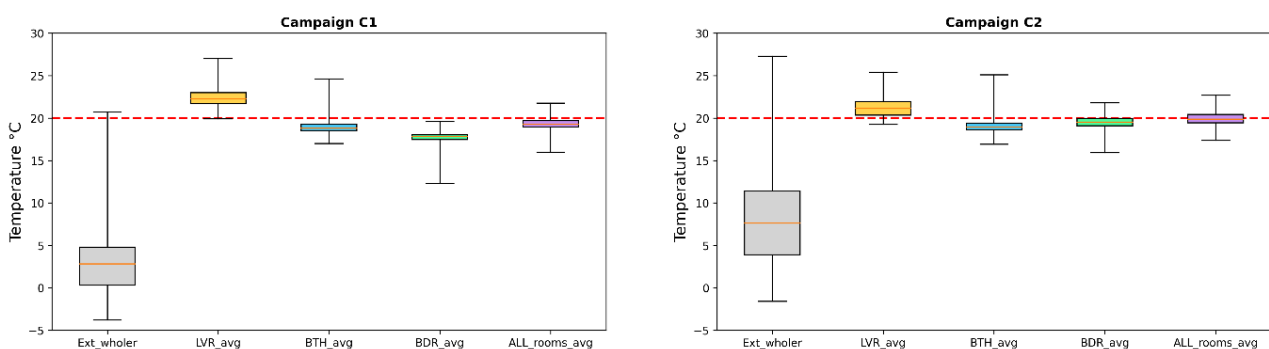


TABLEAU 5 : BOXPLOT OF THE MEASURED TEMPERATURES BY ZONES

A-II.2 DETAILED SIMULATION RESULTS:

SIMULATED EXHAUST AIRFLOWS

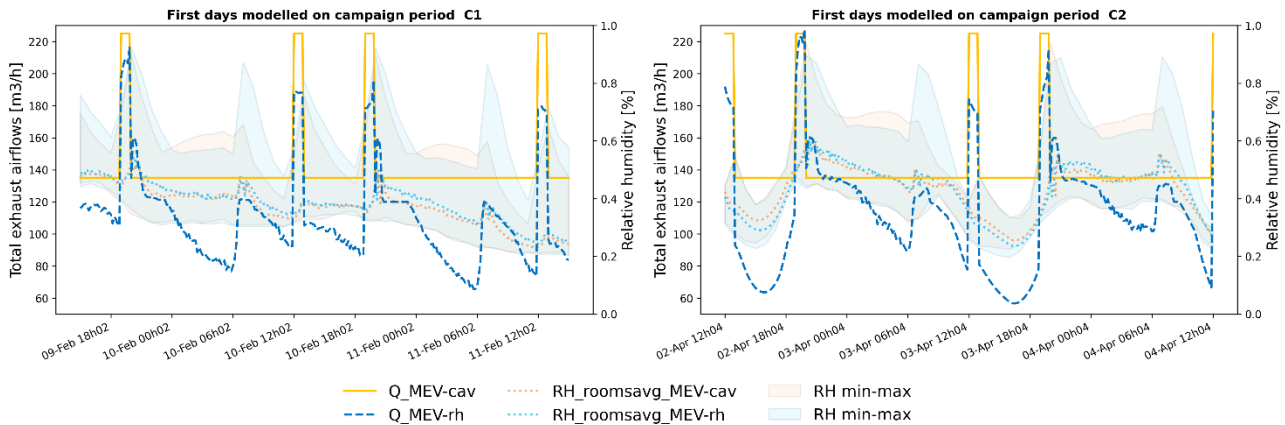


FIGURE 28 : TOTAL EXHAUST AIRFLOWS MODELLED BY SYSTEM ON THE FIRST DAYS OF THE CAMPAIGN PERIODS C1 AND C2

SIMULATED TEMPERATURES ON THE CAMPAIGN 1 PERIOD

MEV-cav T20cst : Températures °C (campaign 1)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	4,13	20,42	20,69	20,24	20,62	20,05	20,22	20,66	20,72	20,1	20,55	20,36	20,37
std	3,28	/	2,49	0,35	1,58	0,28	0,32	1,88	0,55	0,28	0,45	0,37	0,39
min	-1,98	17,76	17,76	19,59	19,29	19,48	19,58	19,51	19,51	19,53	19,56	19,69	19,71
25%	1,7	/	19,95	19,92	19,98	19,81	19,94	20,07	20,35	19,85	20,25	20,06	20,05
50%	4,32	/	20,3	20,26	20,27	20,04	20,21	20,32	20,75	20,13	20,55	20,37	20,38
75%	6,32	/	20,64	20,48	20,46	20,27	20,46	20,77	21,14	20,32	20,87	20,59	20,64
max	11	36,82	36,82	21,23	29,3	21,02	21,04	36,68	22,24	20,89	21,82	21,88	21,82
MEV-rh T20cst : Températures °C (campaign 1)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	4,13	20,58	21,52	20,3	20,69	20,33	20,2	20,42	21,16	20,11	20,96	20,31	20,34
std	3,28	/	3,61	0,36	1,67	0,36	0,32	1,12	0,83	0,28	0,67	0,36	0,37
min	-1,98	17,84	19,71	19,66	19,53	19,65	19,53	17,84	19,63	19,5	19,66	19,66	19,62
25%	1,7	/	20,25	19,97	19,98	20,02	19,94	19,93	20,49	19,85	20,39	19,99	20,04
50%	4,32	/	20,72	20,33	20,28	20,33	20,2	20,28	21,26	20,12	21,02	20,34	20,36
75%	6,32	/	21,42	20,55	20,52	20,61	20,43	20,65	21,85	20,34	21,5	20,56	20,57
max	11	42,94	42,94	21,68	29,75	21,48	21,03	31,92	23,98	21,03	22,4	21,68	21,73

SIMULATED TEMPERATURES ON THE CAMPAIGN 2 PERIOD

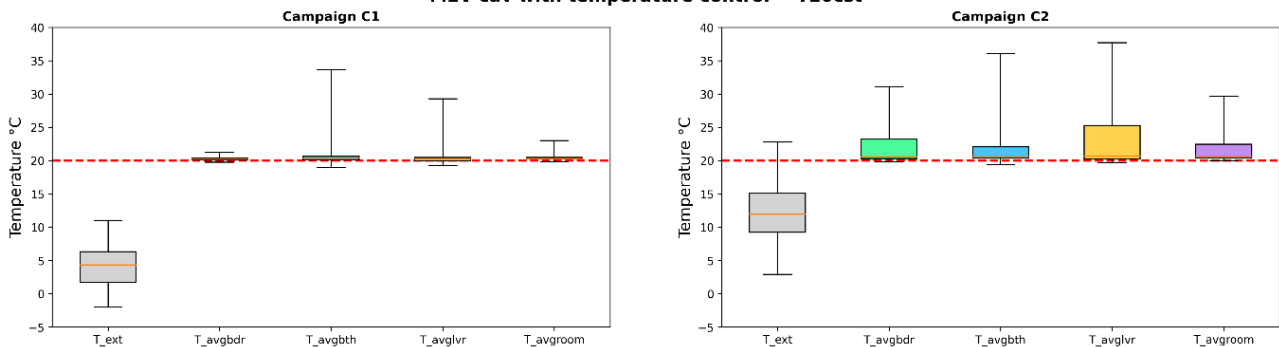
MEV-cav T20cst : Températures °C (campaign 2)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	12,11	22,02	22,11	21,81	23,14	21,33	21,16	21,59	21,57	21,65	21,89	22,96	22,98
std	4,69	/	3,33	2,71	4,02	2,25	1,71	2,74	1,57	2,61	2,33	3,81	3,86
min	2,9	18,34	18,34	19,63	19,69	19,57	19,65	19,67	19,58	19,58	19,63	19,73	19,69
25%	9,21	/	20,26	20,18	20,26	20,02	20,19	20,23	20,59	20,08	20,48	20,35	20,38
50%	11,9	/	20,79	20,59	20,71	20,39	20,57	20,6	21,25	20,45	21,02	20,89	20,9
75%	15,12	/	22,05	22,08	25,29	21,01	21,16	21,39	21,95	22,05	21,87	24,82	24,83
max	22,78	40,68	39,43	30,15	37,69	28,79	27,34	40,68	27,16	29,51	29,22	32,44	32,93
MEV-rh T20cst : Températures °C (campaign 2)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	12,11	22,65	23,92	22,78	23,67	22,7	21,3	21,31	22,08	22,06	22,83	23,14	23,34
std	4,69	/	5	3,79	4,58	3,65	2	2,18	2,08	3,11	3,24	4,12	4,38
min	2,9	19,54	19,74	19,73	19,71	19,71	19,66	19,54	19,65	19,63	19,72	19,7	19,71
25%	9,21	/	20,52	20,3	20,3	20,32	20,16	20,14	20,63	20,11	20,61	20,34	20,35
50%	11,9	/	21,55	20,78	20,81	20,78	20,55	20,48	21,57	20,46	21,61	20,81	20,89
75%	15,12	/	26,3	24,34	26,23	24,39	21,19	21,18	22,53	23	23,8	25,25	25,75
max	22,78	46,05	46,05	33,77	38,9	33,15	28,42	35,31	28,86	31,14	31,82	33,55	35,02

SIMULATED TEMPERATURE ON THE HEATING PERIOD

T20 CONSTANT CONTROL STRATEGY

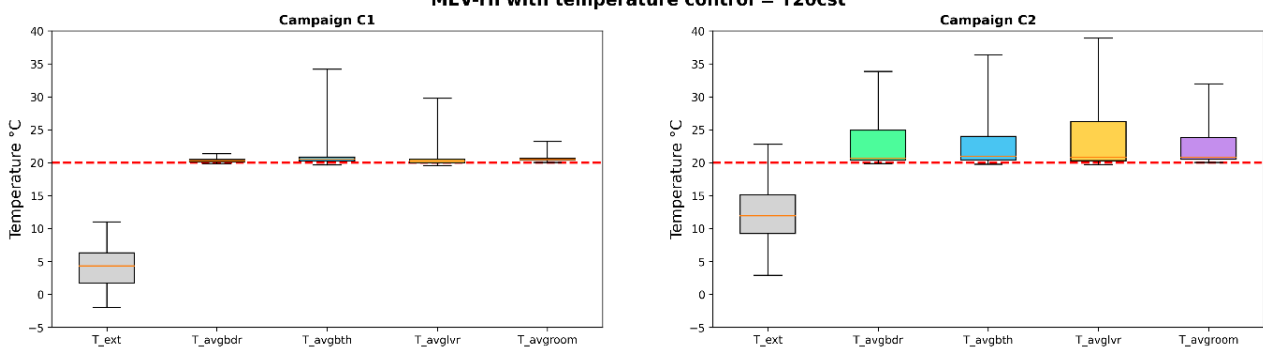
MEV-cav T20cst : Temperatures °C (heating period)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	6,43	20,71	20,95	20,5	21,11	20,27	20,4	20,8	20,89	20,36	20,78	20,86	20,87
std	5,5	/	2,59	1,17	2,34	0,96	0,76	2,07	0,85	1,13	1,06	1,77	1,78
min	-8,49	16,47	16,47	19,53	19,01	18,81	19,41	19,44	19,42	19,26	19,5	19,63	19,59
25%	2,48	/	20,03	19,98	20,01	19,84	19,99	20,09	20,37	19,87	20,28	20,1	20,1
50%	6,1	/	20,43	20,31	20,34	20,13	20,3	20,4	20,84	20,18	20,64	20,45	20,46
75%	10,02	/	20,81	20,57	20,64	20,36	20,58	20,8	21,29	20,4	21	20,77	20,79
max	22,88	40,68	39,43	31,35	40,02	29,46	27,67	40,68	27,61	30,93	30,38	34,77	34,73

MEV-cav with temperature control = T20cst



MEV-rh T20cst : Températures °C (heating period)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	6,43	20,96	21,92	20,78	21,29	20,78	20,4	20,57	21,29	20,45	21,24	20,87	20,95
std	5,5	/	3,87	1,72	2,62	1,66	0,87	1,36	1,12	1,37	1,51	1,91	2,05
min	-8,49	17,84	19,65	19,59	19,32	19,62	19,35	17,84	19,53	19,25	19,62	19,59	19,58
25%	2,48	/	20,27	20,06	20,03	20,07	19,97	19,99	20,49	19,89	20,41	20,07	20,09
50%	6,1	/	20,82	20,4	20,37	20,41	20,29	20,33	21,25	20,2	21,07	20,42	20,44
75%	10,02	/	21,6	20,71	20,71	20,72	20,56	20,69	21,89	20,42	21,6	20,73	20,77
max	22,88	46,05	46,05	34,46	41,28	33,86	28,57	35,31	29,71	32,37	33,44	35,48	35,9

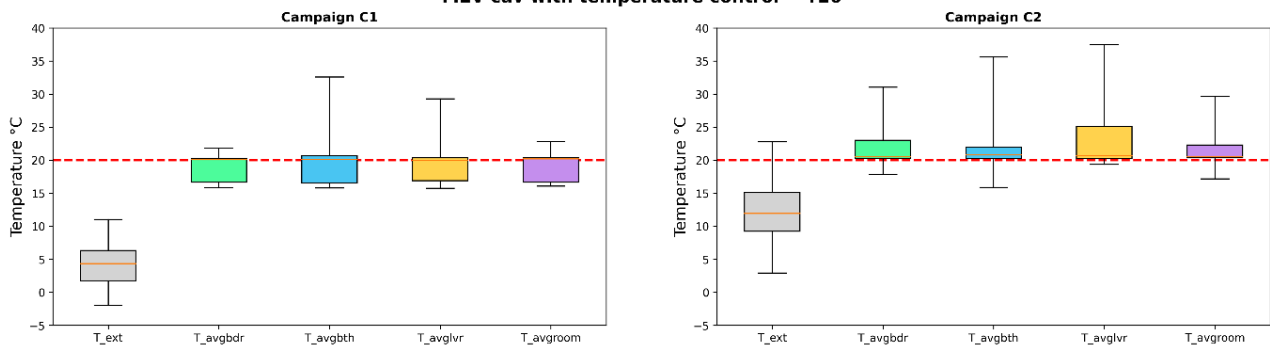
MEV-rh with temperature control = T20cst



T20/16 VARIABLE CONTROL STRATEGY

MEV-cav T20/16: Températures °C (heat period)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	6,43	19,58	19,82	19,4	20,1	19,13	19,17	19,63	19,55	19,25	19,59	19,85	19,87
std	5,5	/	3,23	2,19	2,95	2,07	1,98	2,93	2,01	2,14	2,12	2,53	2,57
min	-8,49	15,33	15,61	15,58	15,63	15,33	15,61	15,52	15,5	15,36	15,62	15,69	15,62
25%	2,48	/	17,15	17,07	19,27	16,74	16,9	16,83	17,49	16,9	17,43	18,85	18,78
50%	6,1	/	19,99	20,03	20,11	19,85	19,99	20,03	20,31	19,89	20,28	20,19	20,2
75%	10,02	/	20,86	20,43	20,5	20,25	20,41	20,9	20,96	20,28	20,78	20,61	20,64
max	22,88	39,73	38,56	31,29	39,73	29,42	27,64	39,33	27,57	30,86	30,31	34,68	34,64

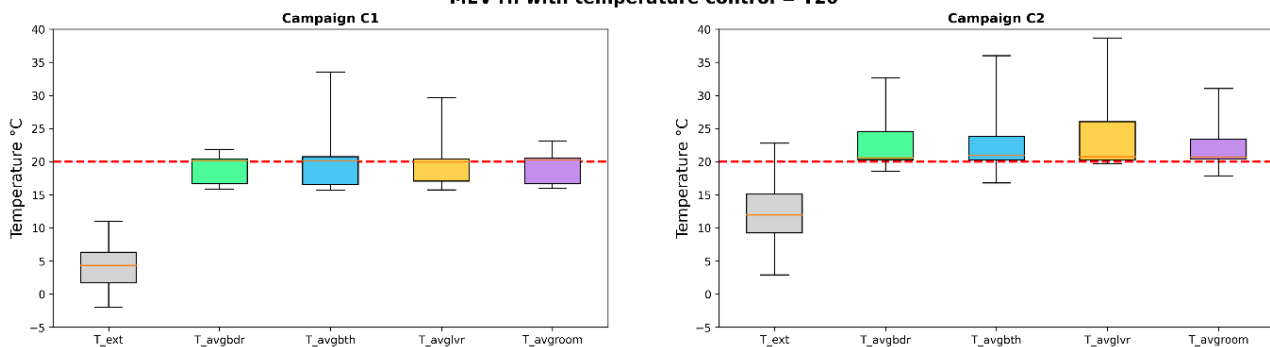
MEV-cav with temperature control = T20



MEV-rh T20/16 : Températures °C (heat period)

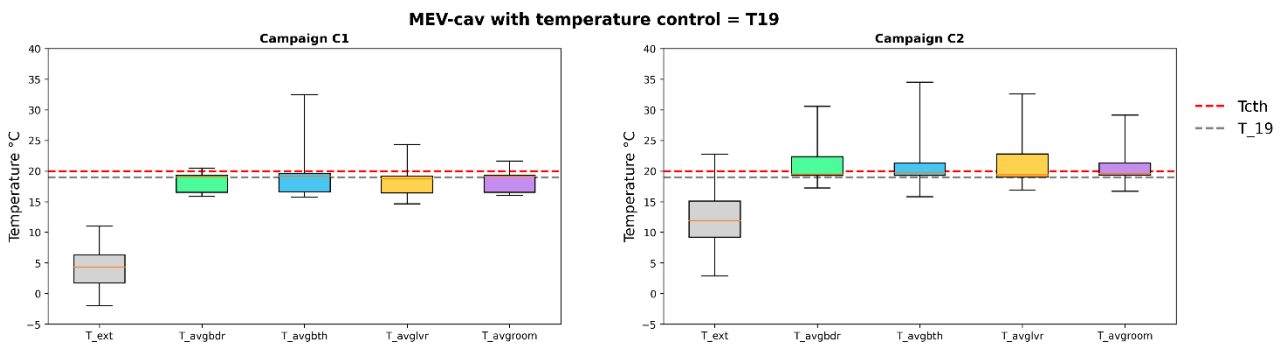
MEV-rh T20/16 : Températures °C (heat period)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	6,43	19,81	20,7	19,69	20,27	19,7	19,18	19,29	19,92	19,35	20,05	19,86	19,9
std	5,5	/	4,33	2,44	3,14	2,4	2,01	2,4	2,17	2,25	2,4	2,61	2,67
min	-8,49	15,27	15,7	15,7	15,67	15,68	15,58	15,37	15,62	15,27	15,7	15,59	15,63
25%	2,48	/	18,34	18,13	19,66	18,36	16,86	16,7	18,01	17,34	18,12	18,95	18,92
50%	6,1	/	20,39	20,14	20,17	20,15	19,97	19,87	20,49	19,92	20,51	20,18	20,19
75%	10,02	/	21,43	20,55	20,56	20,57	20,39	20,61	21,46	20,3	21,28	20,58	20,61
max	22,88	44,89	44,89	34,13	40,94	33,55	28,44	34,37	29,59	32,22	33,29	35,32	35,57

MEV-rh with temperature control = T20

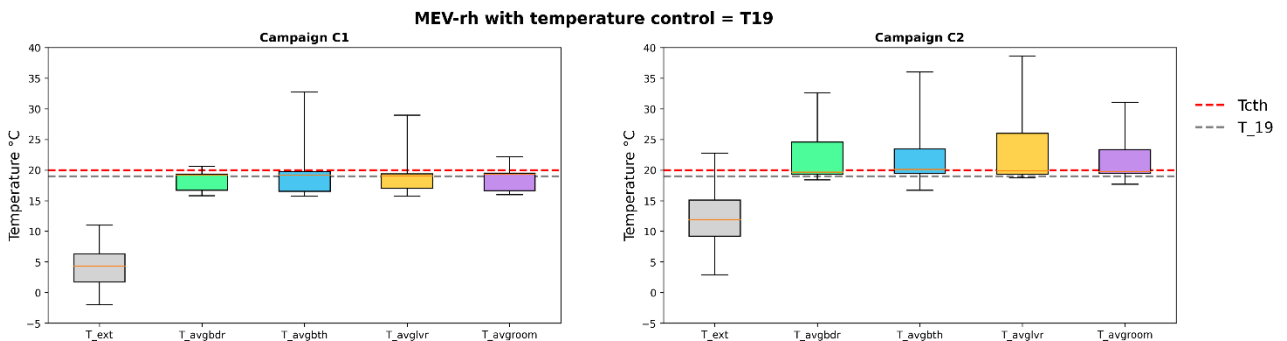


T19/16 VARIABLE CONTROL STRATEGY

MEV-cav T19/16 : Températures °C (heat period)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	6,43	18,82	19,08	18,72	18,76	18,44	18,51	18,97	18,92	18,57	18,91	19,08	19,08
std	5,5	/	2,97	1,92	2,21	1,75	1,63	2,71	1,68	1,86	1,81	2,26	2,28
min	-8,49	13,8	15,55	15,56	13,8	15,27	15,57	15,54	15,51	15,34	15,6	15,69	15,68
25%	2,48	/	17,04	16,99	17,2	16,66	16,82	16,76	17,44	16,78	17,33	18,16	18,07
50%	6,1	/	19,1	19,04	18,88	18,87	19,02	19,07	19,36	18,92	19,32	19,2	19,21
75%	10,02	/	19,63	19,46	19,28	19,26	19,45	19,95	20,01	19,31	19,82	19,63	19,64
max	22,88	38,36	37,67	30,81	34,54	28,79	27,07	38,36	27,17	30,18	29,58	33,47	33,44

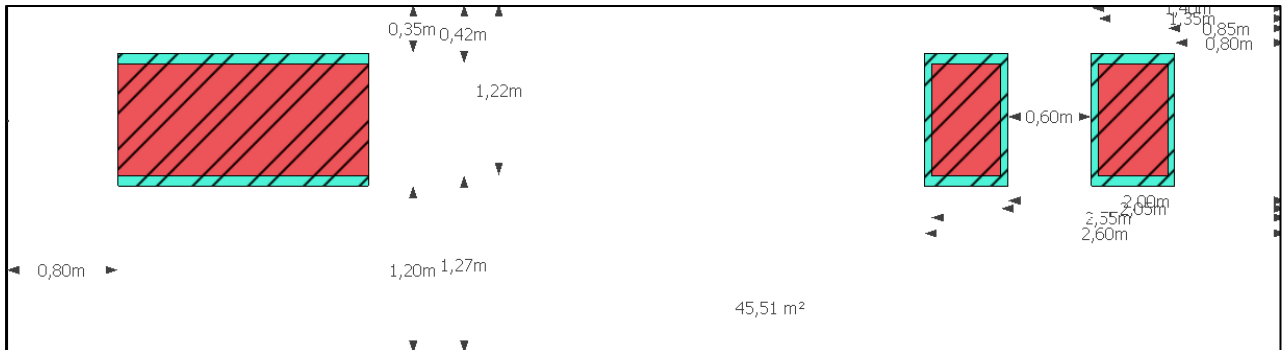


MEV-rh T19/16 : Températures °C (heating period)													
	EXT	ALL_rooms	BTH2	BR2	LVR	BR4	HAL	BTH1	WC1	PAL	WC2	BR3	BR1
mean	6,43	19,19	20,07	19,06	19,66	19,07	18,56	18,69	19,3	18,73	19,41	19,23	19,28
std	5,5	/	4,2	2,33	3,11	2,28	1,74	2,15	1,9	2,1	2,24	2,55	2,61
min	-8,49	15,4	15,7	15,63	15,62	15,63	15,52	15,43	15,65	15,4	15,68	15,67	15,58
25%	2,48	/	18,1	17,94	18,74	18,12	16,82	16,68	17,98	17,2	18,03	18,65	18,63
50%	6,1	/	19,44	19,19	19,22	19,19	19	18,92	19,54	18,97	19,53	19,22	19,24
75%	10,02	/	20,52	19,59	19,63	19,61	19,42	19,66	20,52	19,34	20,33	19,63	19,66
max	22,88	44,89	44,89	34,14	40,91	33,55	28,44	34,38	29,59	32,22	33,29	35,32	35,58

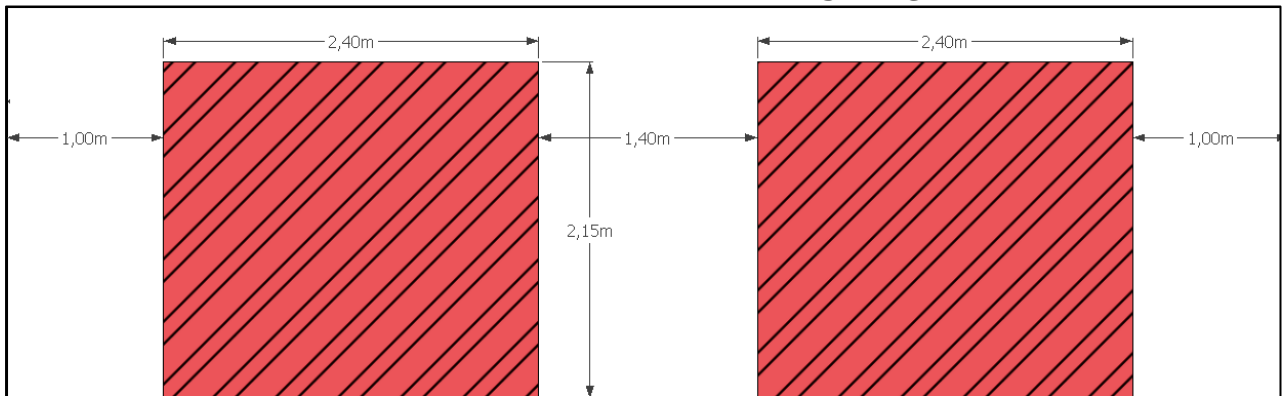


A-II.3 CO-SIMULATION ADDITIONAL DETAILS

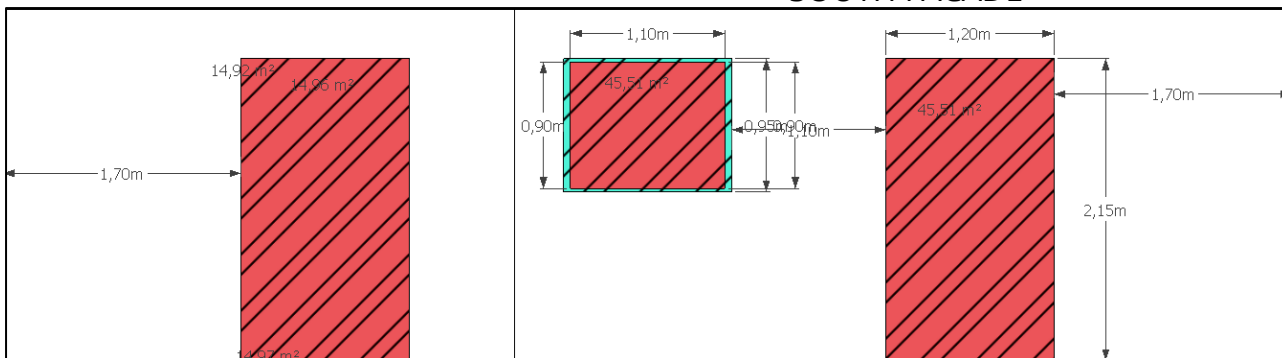
WINDOWS DISTRIBUTION PER FACADES



EAST FACADE



SOUTH FACADE

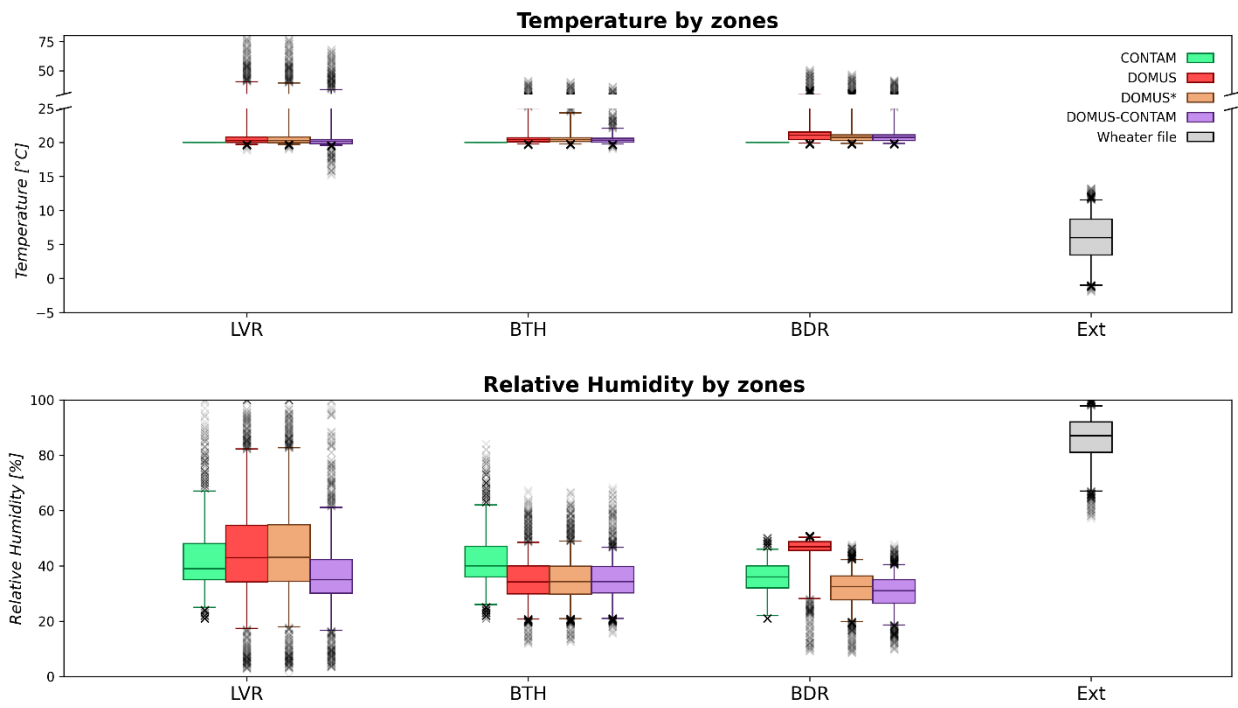


WEST FACADE

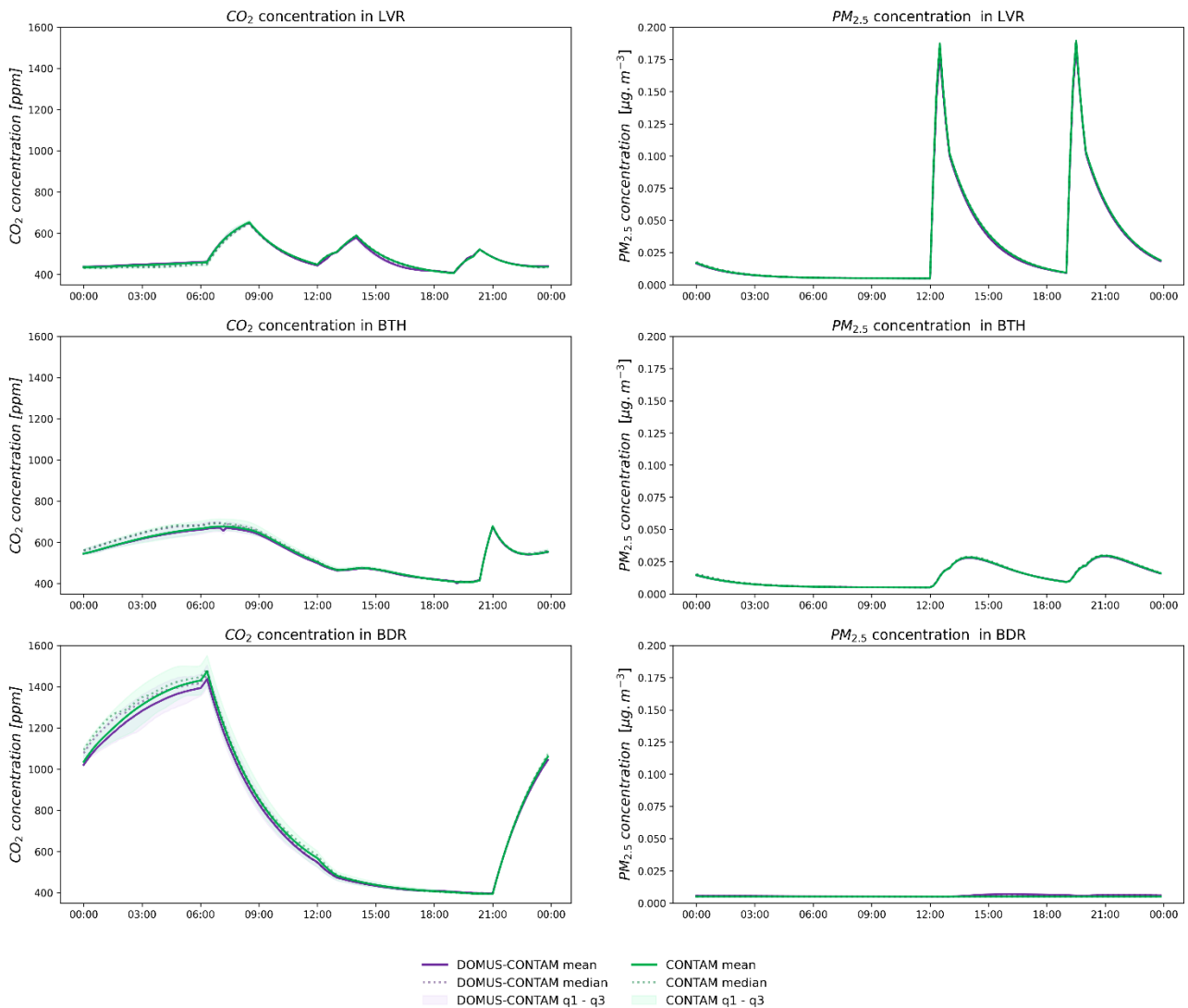


NORTH FACADE

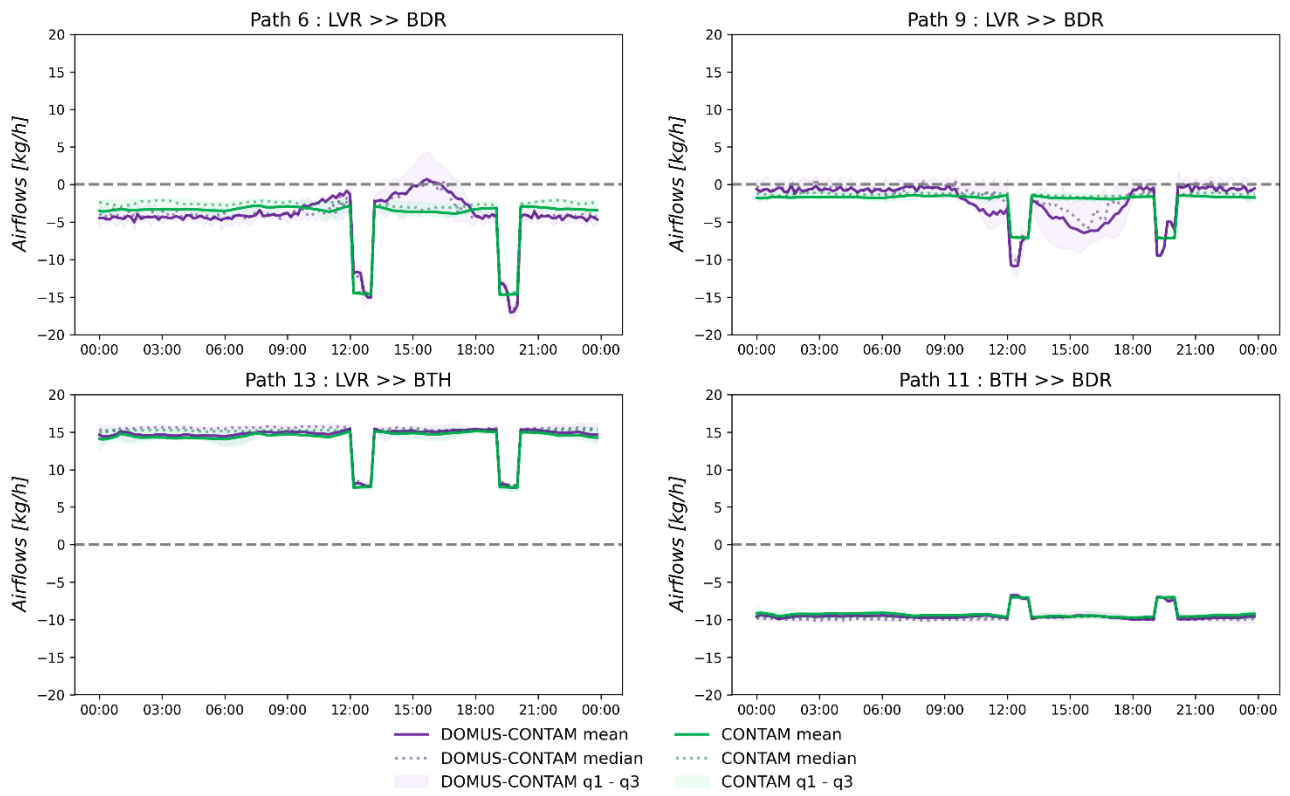
TEMPERATURE & HUMIDITY BOXPLOT



POLLUTANTS EVOLUTION



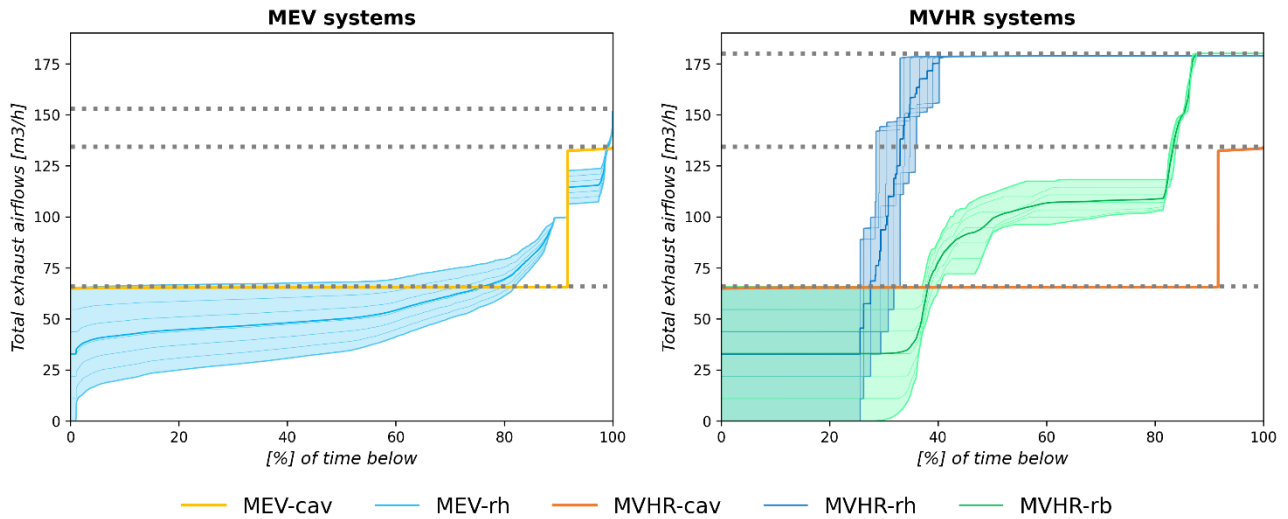
INTER-ZONE AIRFLOWS



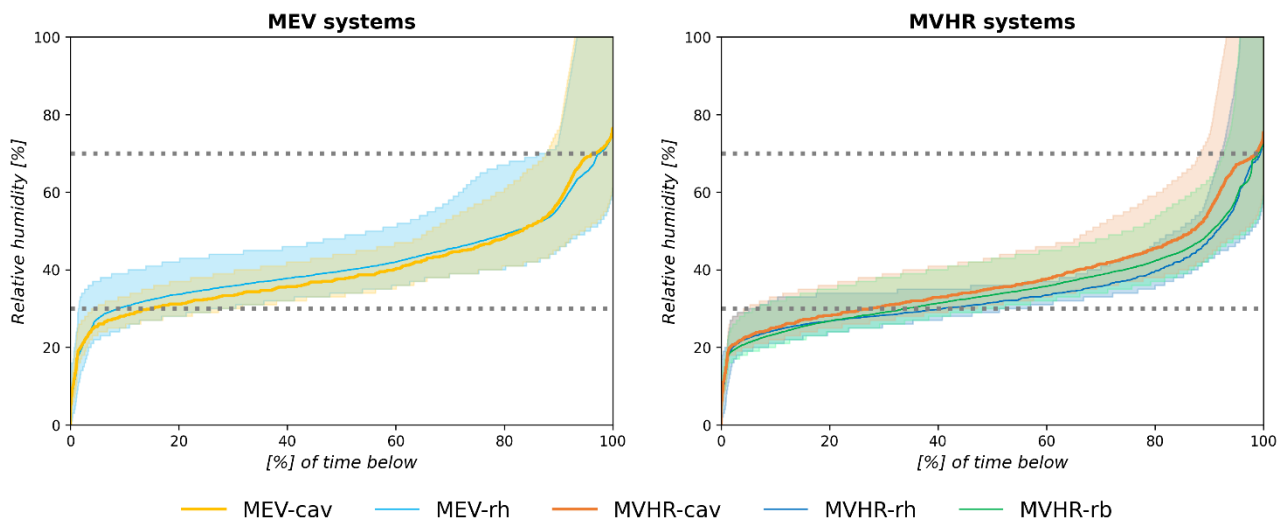
ANNEX III

A-III.1 ADDITIONAL RESULTS OF THE DANISH CASE STUDY

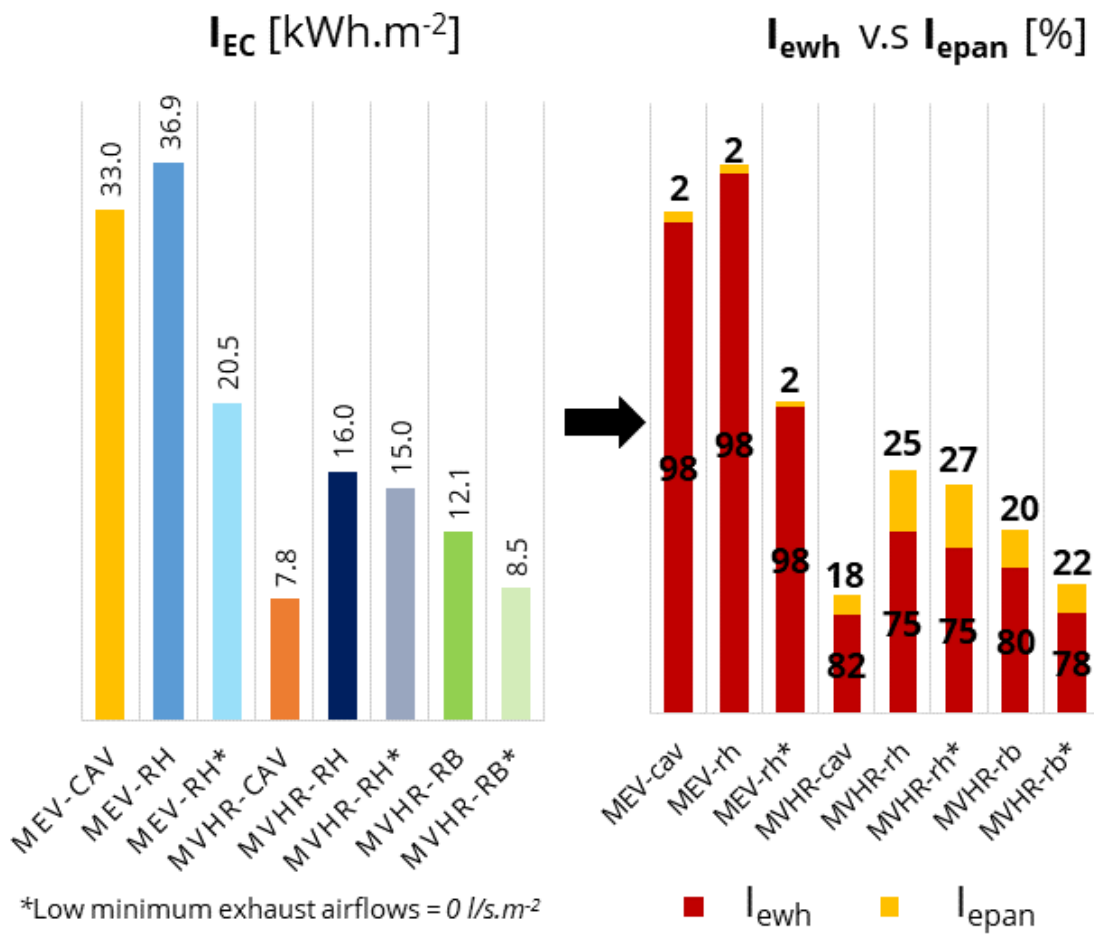
TOTAL EXHAUST AIRFLOWS DISTRIBUTION



RELATIVE HUMIDITY DISTRIBUTION



I_{EC} DISTRIBUTION BETWEEN HEAT LOSSES AND FAN CONSUMPTION



ANNEX IV

A-IV.1 OTHER DESIGN SCORE CALCULATION METHODS

MAX-MIN METHOD

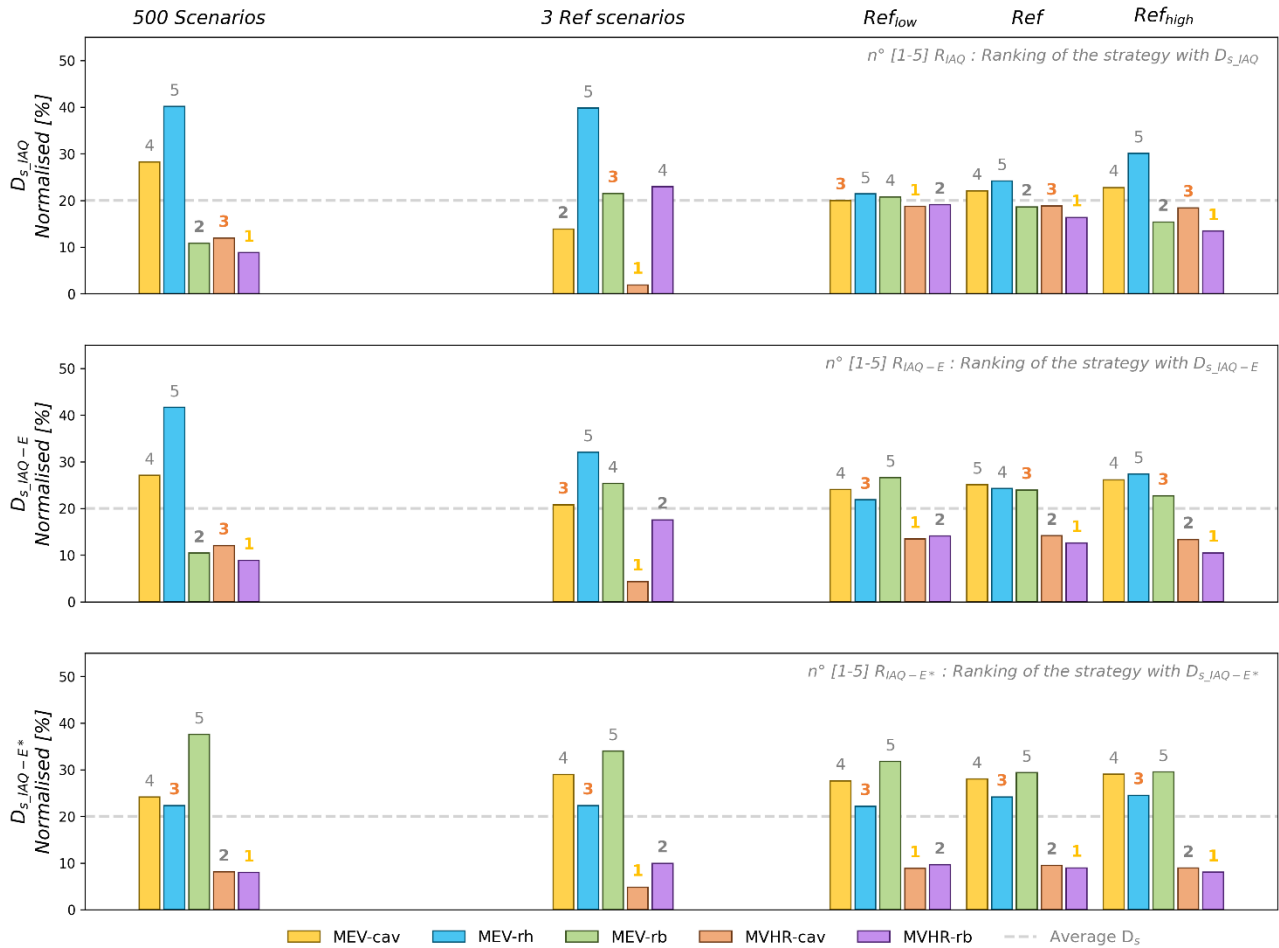


FIGURE 29 : ROBUST DESIGN SCORE AND RANKING, MAX-MIN METHOD.

DIFFERENT WEIGHT DISTRIBUTIONS ARE PRESENTED: EQUAL IAQ (TOP), EQUAL IAQ AND ENERGY, IAQ-E (MIDDLE), AND ENHANCED ENERGY AND HEALTH IAQ-E* (BOTTOM).

DIFFERENT SCENARIOS ARE PRESENTED: 500 PER SYSTEM USING UNCERTAINTY DISTRIBUTION ON INPUT PARAMETERS (LEFT), THREE PER SYSTEM: HIGH/REF/LOW (MIDDLE), AND ONE PER SYSTEM, SEPARATING HIGH/REF/LOW (RIGHT).

BEST-CASE AND WORST-CASE METHOD

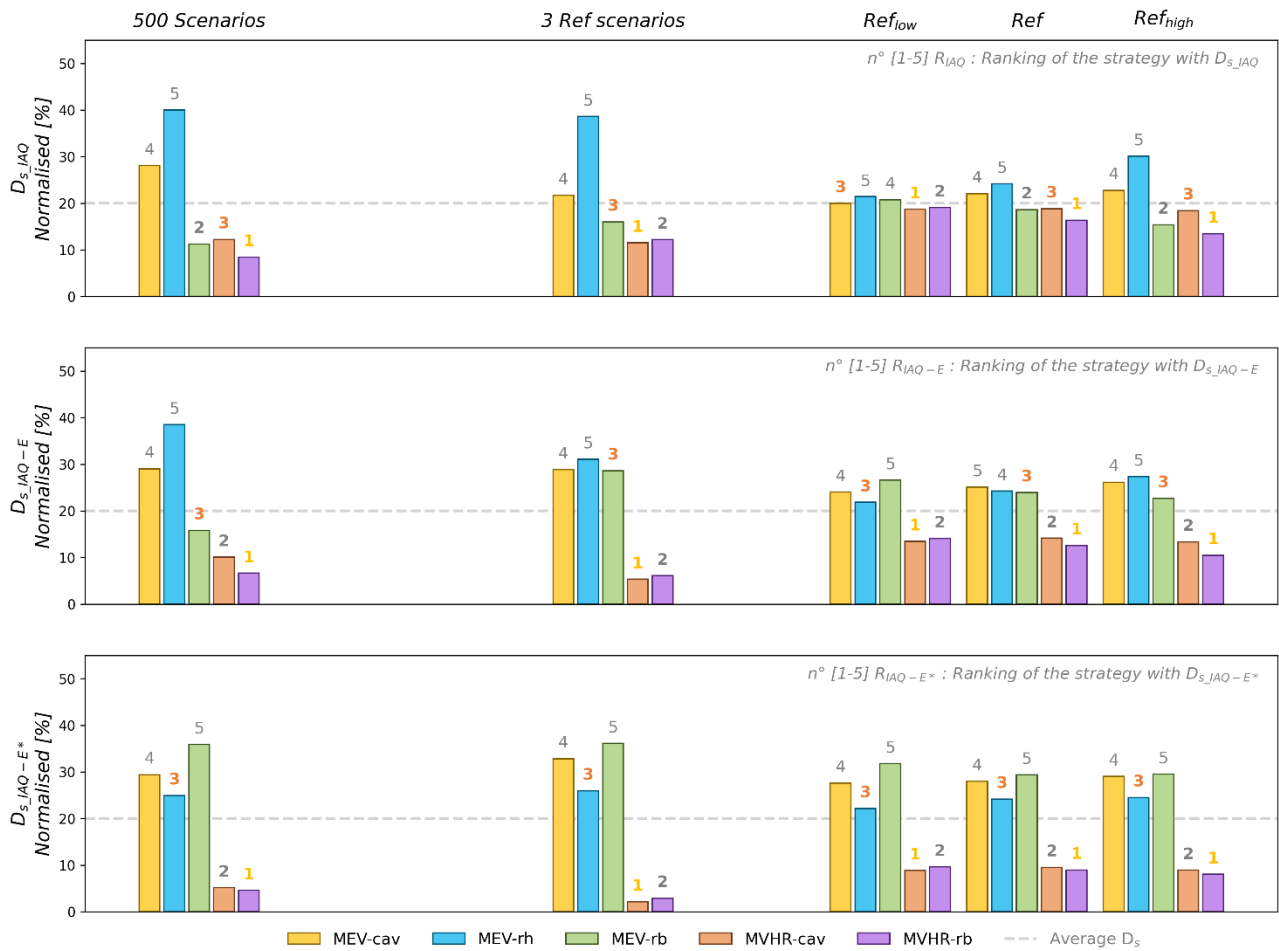


FIGURE 30: ROBUST DESIGN SCORE AND RANKING, MINMAX REGRET METHOD.

DIFFERENT WEIGHT DISTRIBUTIONS ARE PRESENTED: EQUAL IAQ (TOP), EQUAL IAQ AND ENERGY, IAQ-E (MIDDLE), AND ENHANCED ENERGY AND HEALTH IAQ-E* (BOTTOM).

DIFFERENT SCENARIOS ARE PRESENTED: 500 PER SYSTEM USING UNCERTAINTY DISTRIBUTION ON INPUT PARAMETERS (LEFT), THREE PER SYSTEM: HIGH/REF/LOW (MIDDLE), AND ONE PER SYSTEM, SEPARATING HIGH/REF/LOW (RIGHT).

THE TAGUCHI METHOD

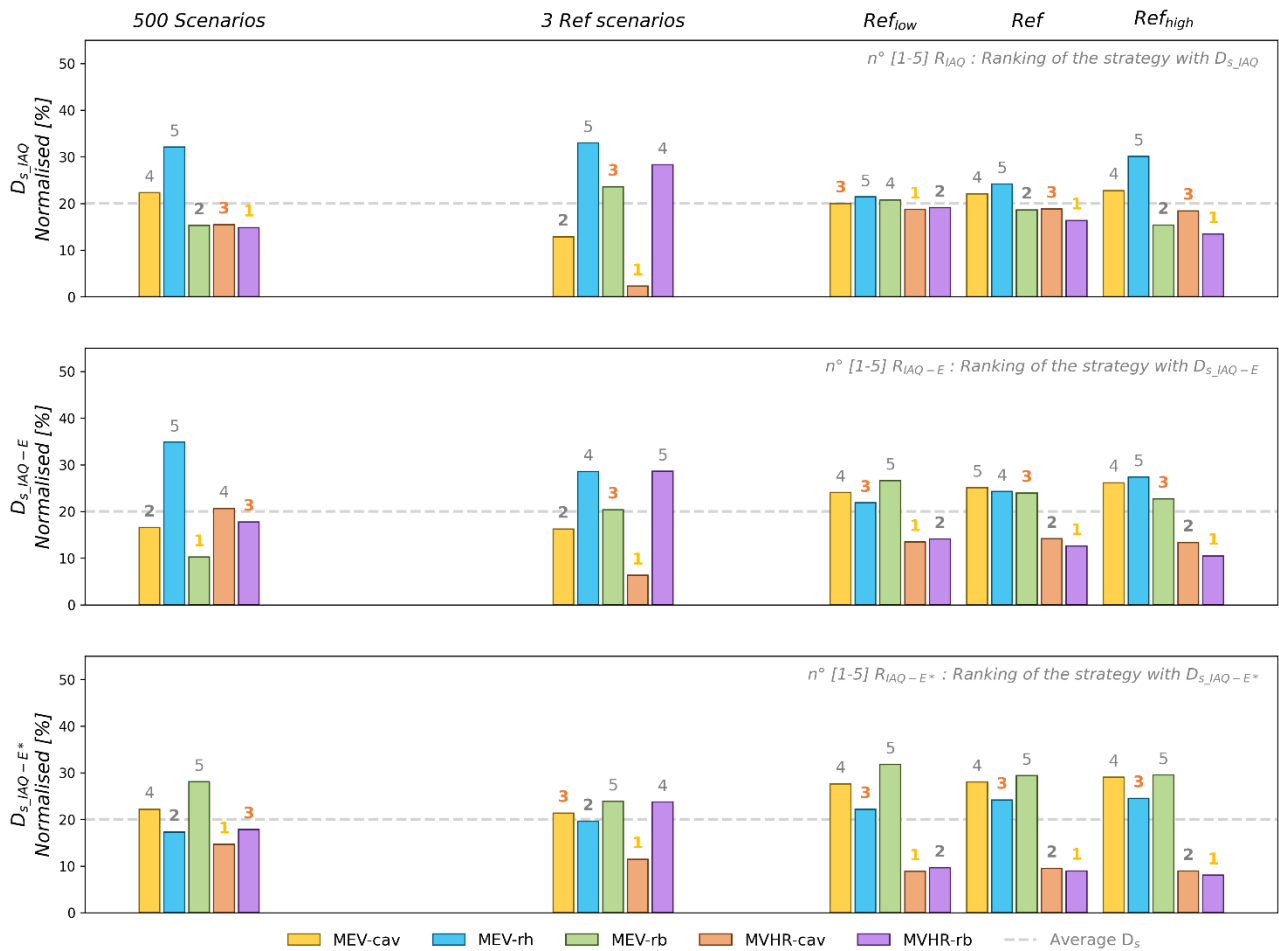
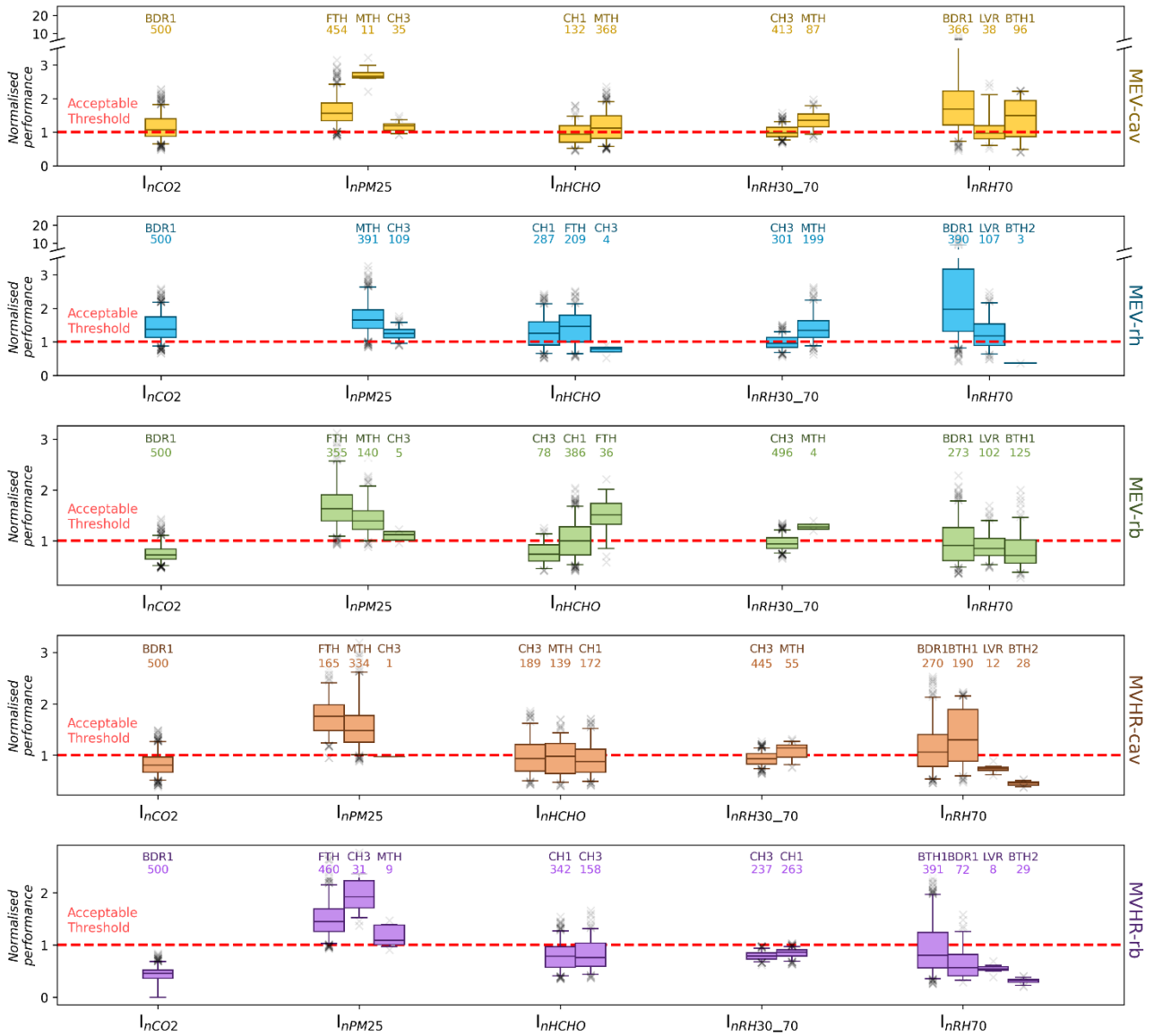


FIGURE 31 : ROBUST DESIGN SCORE AND RANKING, THE TAGUCHI METHOD.

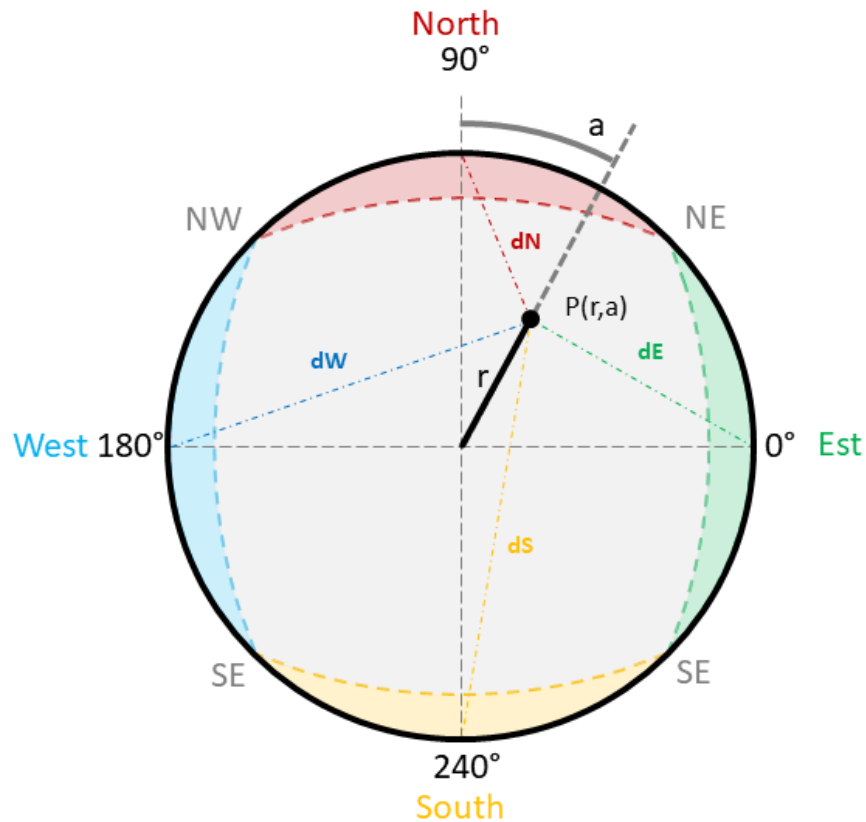
DIFFERENT WEIGHT DISTRIBUTIONS ARE PRESENTED: EQUAL IAQ (TOP), EQUAL IAQ AND ENERGY, IAQ-E (MIDDLE), AND ENHANCED ENERGY AND HEALTH IAQ-E* (BOTTOM).

DIFFERENT SCENARIOS ARE PRESENTED: 500 PER SYSTEM USING UNCERTAINTY DISTRIBUTION ON INPUT PARAMETERS (LEFT), THREE PER SYSTEM: HIGH/REF/LOW (MIDDLE), AND ONE PER SYSTEM, SEPARATING HIGH/REF/LOW (RIGHT).

A-IV.2 DISCUSSION ON MEV-RH WORST STRATEGY?



A-IV.3 AIR LEAKAGE SENSITIVITY ANALYSIS INPUTS PARAMETERS PROPOSITION



Weighting distribution of the air leakage on the four North, South, Est, West face, with a balance sorted function of the distance (dN, dS, dE, dW). Which can be calculated based on $P(r,a)$. With a in range $[0,360]$; r in range $[0,1]$.

