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A Numerical and Experimental Study to Compare Different IAQ-Based Smart Ventilation Techniques

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Abstract: Maintaining indoor environmental quality in residential buildings is essential for occupants' comfort, productivity, and health, with effective mechanical ventilation playing a key role in removing or diluting indoor pollutants. A two-week experimental campaign was conducted in an apartment in Lyon, France, known for its poor urban air quality, assessing temperature, relative humidity, CO₂, and PM_{2.5} concentrations. A model verification study was performed to compare experimental measurements against numerical modeling in the living room and bedroom, leading to errors in the accuracy of the sensors. In addition, this study also investigates the impact of different ventilation strategies on indoor air quality. This research evaluates a baseline mechanical exhaust-only ventilation approach with constant air volume against two innovative smart ventilation approaches: mechanical exhaust-only ventilation with humidity control and mechanical exhaust-only ventilation with room-level CO₂ and humidity control. A key contribution of this research is the novel coupling of multizone simulation models (DOMUS and CONTAM) with a CFD tool to refine pressure coefficients on the building façade, which enhances the accuracy of indoor air quality predictions. The smart ventilation strategies showed improvements, including a 20% reduction in CO₂ concentration and a 5% reduction in the third-quartile PM_{2.5} concentration, highlighting their effectiveness in enhancing ventilation and pollutant dilution. This research provides valuable insights into advanced ventilation strategies and modeling techniques in urban environments.

Keywords: indoor air quality; urban residential building; smart ventilation strategies; experimental campaign; building performance co-simulation



Citation: Lopes, M.B.; Kanama, N.; Poirier, B.; Guyot, G.; Ondarts, M.; Gonze, E.; Mendes, N. A Numerical and Experimental Study to Compare Different IAQ-Based Smart Ventilation Techniques. *Buildings* **2024**, *14*, 3555. <https://doi.org/10.3390/buildings14113555>

Received: 23 September 2024

Revised: 24 October 2024

Accepted: 25 October 2024

Published: 7 November 2024



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1. Introduction

Continuing indoor air quality (IAQ) research remains urgent due to ample evidence linking indoor air pollution to various health problems. Several studies have been conducted to identify the sources of indoor pollution and reveal their impact on the health of occupants, aiming to enhance indoor air quality by reducing pollutant concentrations. Indoor air pollution is also more dangerous to human health than outdoor air pollution [1]. Other studies confirmed the health risks of indoor air pollution due to poor air quality [1–9]. India, in particular, has faced concerns regarding indoor air pollution in recent years [10]. A comprehensive review investigated the causes of indoor pollution and their considerable and diverse impact on the health of residents [11]. The study also addressed the current methods aimed at reducing concentrations of pollutants to ensure improved indoor air

quality. Findings from the review concluded that exposure to contaminants at concentrations exceeding guidelines causes problems with heart problems, vascular issues, ocular and dermal effects, and headaches. Controlling internal sources of pollution significantly reduces health risks [6]. The pollutants present in indoor environments are not limited to the exhaled air but also the activities of the occupants and the geographical location of the building in a polluted external environment [12]. The proximity of industries to urban areas, traffic congestion, and overpopulation increase the exposure of residents to air pollutants [1,7,13]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) considers buildings polluted when 20% of occupants suffer from illnesses [1,7]. High levels of indoor air pollution contribute to approximately 3.5 million deaths annually [1,14] because people spend extended periods indoors [15]. About 90% of individuals typically spend their lives indoors [16]; between 2020 and 2021, due to COVID-19, this percentage touched 100% [17]. Despite the decline of this epidemic, people continued to maintain their lifestyles in indoor places [18], with remote work becoming increasingly prevalent [19].

Many restrictions have been placed to reduce the impact of buildings on energy consumption when constructing or renovating existing buildings, making strengthening energy performance one of the most essential items in energy policy [20]. The building construction sector represents approximately 36% of global energy demand; this is why the International Energy Agency (IEA) is working to enhance energy consumption efficiency [21]. This drive aims to achieve energy efficiency and ensure healthy indoor environments by minimizing energy usage in buildings [22]. Consequently, ensuring the indoor environment represented by indoor air quality has become extremely important in new and even renovated buildings [23]. Enabling the circulation of clean, fresh outdoor air indoors is a key step in creating comfortable and healthy indoor environments for occupants [24]. Once sources of pollution are eliminated, ventilation becomes fundamental for removing or diluting remaining pollutants [25,26]. Efficient ventilation, while minimizing or maintaining energy use, is a key method in providing clean indoor air. Yet, before taking measures, the pollutant sources must be identified to remove or reduce their impact on indoor air quality. In a study involving 117 homes in China, mechanical ventilation with improved filters proved effective in keeping CO₂ and PM_{2.5} concentrations below the recommended guidelines ($C_{CO_2} < 1000$ ppm, $C_{PM_{2.5}} < 25$ µg/m³) [27]. Another study in the city of Xi'an compared natural ventilation in seven homes with mechanical ventilation in three homes, concluding that operating a combination of mechanical and natural ventilation is the most appropriate option to maintain the concentration of CO₂ and PM_{2.5} to ensure indoor air quality [28]. Poor indoor ventilation has been linked to many respiratory diseases, such as influenza and other viruses [29–32]. Studies suggest maintaining a ventilation rate above 0.4 air changes per hour can prevent internal health issues [33]. Increasing ventilation enables the exchange of clean outdoor air with polluted indoor air, reducing concentrations of indoor contaminants. Mechanical ventilation systems are considered one of the pillars of controlling indoor air quality. When properly utilized, these systems increase ventilation, removing polluted indoor air and enhancing overall health [34,35]. A study conducted in Hong Kong on substandard homes revealed that insufficient ventilation led to alarming concentrations of CO₂, VOCs, PM₁₀, and PM_{2.5}, exceeding safety thresholds of 3000 mg/m³, 2000 µg/m³, 1000 µg/m³, and 500 µg/m³, respectively [36]. These pollutants, including formaldehyde, organic matter, PM, and NO₂, affect nearly 50% of the world's population [37–39], potentially increasing the transmission distance of COVID-19 beyond what is typically considered for close contact [40–42]. In addition to ventilation, many factors affect the indoor air quality in residential apartments, such as outdoor environment, floor height, orientation, occupier activities, characteristics, lifestyle choices, etc. [12,43].

One of the strategies to establish a healthier indoor environment involves the real-time or periodic monitoring of IAQ [44]. Long-term monitoring is imperative as it provides data on the exposure of the occupants to pollutants, enabling improvements in thermal comfort and air quality [45,46]. Accurate data collection is important for addressing pollution issues

and safeguarding the productivity and well-being of the residents [11,47]. Several studies focus on IAQ in workplaces, schools, and daytime home environments; bedrooms often receive inadequate ventilation, leading to poor indoor air quality that adversely impacts sleep quality and subsequent daily performance and productivity [48].

Cony (2020) [49] developed a new pollutant index, the ULR-IAQ, and performed a simulation combining energy, airflow, and pollutant transport using Trnsys-CONTAM coupling for a residential building. Poirier (2023) [50] developed a new methodology called MOPA (Method for Overall Performance Assessment) to assess several scenarios of ventilation strategies in the European context. The author applied MOPA in conventional and smart ventilation systems with an extensive sensitive analysis of CONTAM, including contaminant indicators for CO₂, formaldehyde, PM, and moisture. In addition, this study included multi-criteria decision making and a robust design score and ranking to show the better performance of the mechanical balanced ventilation with heat recovery and CO₂ and humidity control at the room level regarding other ventilation strategies for a given application such as in [51]. Tognon et al. (2023) [52] performed simulations applying Trnsys-CONTAM coupling in a residential building to assess different control strategies for hybrid ventilation systems regarding annual energy demand and infection risk mitigation. Lozinsky and Touchie (2024) [53] carried out CONTAM-EnergyPlus coupling in a residential building to assess the energy consumption and concentrations of CO₂ and PM_{2.5} for several airtightness configurations.

The present study assesses three ventilation strategies, including smart ventilation, and their influence on IAQ parameters in a residential apartment in Lyon, France. A two-week experimental campaign encompassing temperature, relative humidity, and contaminant concentrations (CO₂ and PM_{2.5}) was conducted for two zones (living room and bedroom) and the outdoor environment. This study also employs a co-simulation approach, integrating DOMUS v2.6, a hygro-thermal and energy simulation software application, with CONTAM v3.4, a contaminant transport and air transfer software application. DOMUS, known for solving heat and mass transfer equations through building envelope coupling with indoor air balance [54], and CONTAM, recognized for its role in IAQ and ventilation calculations, were combined to provide a comprehensive analysis of both environmental and contaminant parameters [55]. While both DOMUS and CONTAM are established tools in the field of building simulation, this study's novelty lies in their combined application to refine IAQ simulations. The co-simulation allows for a more integrated assessment of thermal and contaminant dynamics within the building. The key findings are illustrated using temporal series and boxplots, with the first part focusing on validating the co-simulation approach against the experimental data and the second part comparing the reference ventilation strategy with two advanced smart ventilation strategies.

Despite numerous studies on IAQ and ventilation strategies, the integration of dynamic simulation tools to analyze both thermal and contaminant dynamics simultaneously remains underexplored, particularly in real-world scenarios with smart ventilation systems. As mentioned above, previous studies focus on either thermal or air quality aspects separately. The relevance of our research lies in bridging this gap by employing a co-simulation approach that combines DOMUS and CONTAM. This novel method allows for a more comprehensive understanding of how advanced ventilation strategies, including smart ventilation systems, can optimize both energy efficiency and indoor air quality in residential settings. By doing so, this study provides critical insights for future building designs aimed at enhancing occupant health and comfort while reducing energy consumption. This approach not only validates the simulation models but also demonstrates the effectiveness of smart ventilation in improving IAQ.

This introduction is followed by Section 2, which describes the methodology in detail, focusing on the co-simulation approach that integrates DOMUS and CONTAM for a comprehensive analysis of IAQ and thermal dynamics. Section 3 presents the results, comparing different ventilation strategies, including smart systems, and highlighting their effectiveness in enhancing IAQ and energy efficiency. Finally, Section 4 offers the conclusions,

emphasizing the novel insights gained from this study and their implications for future building designs aimed at improving indoor environmental quality and occupant health.

2. Methodology

2.1. Experimental Setup

The building is located in Lyon, close to a high-traffic motorway and a tunnel. The apartment was selected due to its surroundings and exposure to a polluted external environment. Positioned just 50 m from a tram train, 100 m from multimodal hubs, 300 m from a motorway, and 400 m from a tunnel, its location highlights the factors impacting its local urban microclimate.

This study evaluated an apartment in a renovated building on the 2nd floor. It comprises three bedrooms, one bathroom, a wash closet (WC), a kitchen, a living room, and a hall, as shown in Figure 1, occupied by one non-smoking adult and two domestic animals. The volume of the apartment is 205.2 m³, with a total floor area of 76 m². The apartment has three facades: east, south, and west. Initially built in 1954, it underwent its first renovation in 1991. A renovation occurred between 2015 and 2017, implementing the MANAG'R methodology developed by the National Energy Management Agency ADEME [56], aligning with national standards.



Figure 1. Plan of study apartment: ventilation components and devices locations in each setting and their symbols: ventilation components (■ trickle vent, ⊗ exhaust); symbols of devices: ● NODE, ● NEMO, ● NEMO outdoor, and ■ IAQ sensors.

The renovation encompassed various aspects, including enhancements to the envelope for thermal, acoustic, and air leakage improvements, along with external thermal insulation. Repair work addressed insulation in the cellar ceilings and the attic, the replacement of external joineries, and modifications to the occultations. The internal renovation focused on thermal and IAQ aspects, such as replacing extractors and the ventilation ductwork.

The apartment is equipped with an MEV-cav ventilation system that complies with the French airing regulation [57]. According to this regulation, the exhausted airflow rates

for this apartment must be $30 \text{ m}^3\text{h}^{-1}$ in the bathroom, $15 \text{ m}^3\text{h}^{-1}$ in the WC, and $45 \text{ m}^3\text{h}^{-1}$ in the kitchen—which can be turned to $120 \text{ m}^3\text{h}^{-1}$ (during cooking activities) if the cord is operated. Additionally, trickle vents are installed on the joinery in the living room and all three bedrooms. Figure 1 provides a visual representation of the locations of the ventilation components, while Table 1 outlines their specific characteristics.

Table 1. Characteristics of ventilation components in each room.

Room	Characteristics Ventilation Components
Bathroom	Self-adjusting exhaust unit / / $30 \text{ m}^3\text{h}^{-1}$
WC	Self-adjusting exhaust unit / / $15 \text{ m}^3\text{h}^{-1}$
Kitchen	Self-adjusting exhaust unit / / $45/120 \text{ m}^3\text{h}^{-1}$
Living room	1 trickle vent EA 45
Bedrooms	1 trickle vent EA 30

As part of the MANAG'R project, a particular focus on air quality in housing is necessary. A device with integrated sensors was installed in the apartment to conduct this analysis. The initial measurement allows us to adjust the experimental procedure and provide an up-to-date air quality assessment. This device includes sensors for monitoring carbon dioxide (CO_2), total volatile organic compounds (TVOCs), formaldehyde, relative humidity (RH), temperature (T), fine particles ($\text{PM}_{2.5}$), nitrogen dioxide (NO_2), brightness, and sound in real time. It was positioned above the door between the living room and the hall in a central location in the apartment, close to one of the most important sources of indoor air pollution (the kitchen) and maintaining an unconditional airflow. As presented in Figure 1, this device enables the continuous monitoring of these parameters. Furthermore, measurements were conducted in this apartment to assess envelope air leakage and ventilation exhaust airflows.

A supplementary monitoring campaign was conducted during winter, from 28 March to 13 April 2022, to tackle the following parameters: T, RH, CO_2 , and $\text{PM}_{2.5}$. Each parameter was measured every 10 min at two indoor locations (the living room and bedroom 2, the parental and occupied room) and outdoors (Figure 1). For this purpose, several additional measuring devices are employed and detailed in Tables 2 and 3:

- NODE sensors of the Airvisual brand measure CO_2 , RH, T and $\text{PM}_{2.5}$;
- NEMO registers CO_2 and PM, as well as T and RH simultaneously;
- NEMO Outdoor records PM concentrations, T, and RH simultaneously.

Table 2. Devices of measurement and their height positions in each room.

Room	Device Height [cm]	CO_2	RH	T	$\text{PM}_{2.5}$
Living room	95	Nemo + Node	Nemo + Node	Nemo + Node	Nemo + Node
Bedrooms	55	Nemo	Nemo	Nemo	Nemo
Outdoor	110	/	Nemo	Nemo	Nemo

Inter-comparison intermediate and low-cost measuring devices with laboratory devices allowed us to verify the accuracy of these devices in measurement [58]. Notably, the devices used in this study also monitored formaldehyde, NO_2 , and TVOC, as detailed in [12], for this apartment and two others in the same building during the monitoring period. Although the concentration data for these contaminants could provide valuable insights for analyzing the effectiveness of ventilation systems, their impact on IAQ is not discussed. We focus on modeling CO_2 and $\text{PM}_{2.5}$ to explore the influence of smart ventilation strategies.

Table 3. Description of measurement devices.

Device Name	Device Symbol *	Device Type	CO ₂	PM	RH	T	Reference
Node	●	Low-cost (near REF.)	NDIR 400–10,000 ppm, ±0.02%	Light scattering accuracy Precision of ±15%	Non- condensing sensor over a range of 0–95%	Sensor allowance is between −10 °C and +40 °C	[59]
Nemo	●	Intermediate (near REF.)	NDIR, 0–5000 ppm, ±50 ppm	0 to 1000 µg·m ^{−3} , ±10%	Capacitive, 0–95%, ±3% de 11 °C à 89 °C	CMOS, −55 to +125 °C, ±2 °C de −25 °C à 100 °C	[60]
Nemo outdoor	●	Intermediate (near REF.)	/	0 to 1000 µg·m ^{−3} , ±10%	Capacitive, 0–95%, ±3% de 11 °C à 89 °C	CMOS, −55 to +125 °C, ±2 °C de −25 °C à 100 °C	[60]

* Each device position is located in Figure 1 with the respective device color symbol.

We employed a questionnaire and time–budget activity records to understand the characteristics of the studied site and describe the behaviors and population within it. These tools draw insights from a national survey on indoor air quality in French dwellings [61]. Investigators were tasked with completing the questionnaire, while occupants were responsible for filling in the time activity records. This survey aimed to gather comprehensive information about the building environment, room description, and behavior of the occupants. It covers various aspects, including the maintenance of the ventilation system, window/door usage, and daily activities. Time activity records, covering the entire campaign period, document the time spent in each room and activities that could impact indoor air quality. These activities include incense, candles, air fresheners, fragrances, pesticides, and cleaning products. With inquiries focusing on location, types of activities, participants involved, and specific products used, the survey provides a nuanced view of the daily routines of the occupants. For example, the occupier goes out to work a few days a week at different, irregular times. Bedroom 2 is the occupier’s room and was therefore chosen for this study. The occupier used candles daily. The two domestic animals spend most of their time in the living room and hall but go outside twice daily.

2.2. Modeling

DOMUS and CONTAM are based on multizone models, i.e., valid for the well-mixed assumption of a uniform and homogenous distribution of air temperature, species concentrations, and air momentum effects. On the other hand, CFD codes can handle non-uniformities and heterogeneities but with a substantial computational effort regarding the multizone models. This section outlines the main governing equations and numerical methods for each model and the simulation procedure.

2.2.1. DOMUS—For Energy and Hygrothermal Modeling

DOMUS applies lumped models to calculate temperatures and humidity in each building zone. The energy balance can be written as follows:

$$\dot{E} = \dot{E}_{\text{walls}} + \dot{E}_{\text{airflow}} + \dot{E}_{\text{sources}}, \quad (1)$$

where $\dot{E}$ is the rate of the energy transfer of a zone, $\dot{E}_{\text{walls}}$ is the rate of energy transfer related to surfaces, $\dot{E}_{\text{airflow}}$ is the rate of energy transfer regarding airflow sources, and $\dot{E}_{\text{sources}}$ is the rate of energy generation.

The zone mass balance can be written as follows:

$$\dot{M} = \dot{M}_{\text{airflow}} + \dot{J}, \quad (2)$$

where $\dot{M}$ is the vapor mass transfer rate, $\dot{M}_{\text{airflow}}$ is the mass flow from air sources, and $\dot{J}$ is the water vapor flow.

The conservation equations (Equations (1) and (2)) are discretized using the control volume formulation method, with a central difference scheme and linearized vapor concentration difference at the boundaries in terms of temperature and moisture content. The MTDMA (multi-tridiagonal matrix algorithm) is used to solve the discretized equations [62]. More information about DOMUS can be found in [63–65].

2.2.2. CONTAM—For Airflow and Pollutant Modeling

CONTAM operates based on a multizone airflow network model. This model assumes well-mixed conditions within each zone, where air momentum effects, pressure, and species concentration are uniformly and homogeneously distributed. The contaminant flow balance is mathematically represented by

$$\frac{dm_{\text{cont},i}^{\alpha}}{dt} = \sum_j \dot{m}_{\text{air},j \rightarrow i} (1 - \eta_j^{\alpha}) C_j^{\alpha} + G_i^{\alpha} + m_{\text{air},i} \sum_{\beta} K_i^{\alpha,\beta} C_i^{\beta} - \sum_j \dot{m}_{\text{air},i \rightarrow j} C_i^{\alpha} - R_i^{\alpha} C_i^{\alpha}, \quad (3)$$

where $m_{\text{cont},i}^{\alpha}$ is the mass of contaminant α in zone i , $\dot{m}_{\text{air},j \rightarrow i}$ is the rate of air mass flow from zone j to zone i , η_j^{α} is the filter efficiency of contaminant α through the path between zones j and i , C_j^{α} is the concentration of contaminant α in zone j , G_i^{α} is the α contaminant generation rate, $m_{\text{air},i}$ is the air mass in zone i , $K_i^{\alpha,\beta}$ is the kinetic reaction coefficient in zone i between species α and β , C_i^{β} is the concentration of component β in zone i , $\dot{m}_{\text{air},i \rightarrow j}$ is the rate of air mass flow from zone i to zone j , C_i^{α} is the concentration of contaminant α in zone i , and R_i^{α} is the removal coefficient of component α in zone i .

A control volume model employing the standard implicit method discretizes the mass balance equation. The resulting set of discretized equations is solved using both an iterative biconjugate gradient (BCG) algorithm and an iterative successive over-relaxation (SOR) algorithm, as described in Dols and Polidoro (2020) [55].

2.2.3. CFD0—For Pressure Coefficients

CFD codes can handle non-uniformities and heterogeneities in fluid flow, although at a higher computational cost when dealing with multizone models. The mass and momentum equations for steady-state fluid flow can be expressed in the following general form, as shown in [66]:

$$\nabla \cdot (\rho \mathbf{u} \varphi) - \Gamma_{\varphi} \nabla \cdot (\nabla \varphi) = S_{\varphi}, \quad (4)$$

where ρ is the air density, $\mathbf{u}$ is the air velocity, φ is the transported property (mass or a velocity component), Γ_{φ} is the generalized diffusion coefficient, and S_{φ} is a source or sink term.

Analytical solutions for the partial differential equations described in Equation (4) exist in certain simplified cases, such as some laminar flows. However, for most flow problems, including airflow around bluff bodies, empirical and/or numerical solutions are necessary. The finite volume method (FVM) is commonly employed among the various numerical discretization methods. This method discretizes the domain into smaller control volumes and integrates the transport equations for each volume. Numerical schemes solve the convective, diffusive, and gradient terms arising from the FVM. Additionally, addressing the turbulence closure problem requires numerical modeling, such as the Reynolds-Averaged Navier–Stokes (RANS) methods, which involve modeling eddies of all sizes through the Reynolds decomposition.

For dealing with incompressible airflow, the “CFD0 Editor” from CONTAM comes into play [67]. This software implements the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm to determine the airflow field [68]. The liner eddy viscosity model standard $k-\varepsilon$ [69] is employed as the High-Reynolds number turbulence model. Lastly, the convective terms are discretized using the power law scheme.

2.2.4. Simulation Procedure

The energy and hygrothermal DOMUS model of this study focused on simulating the winter season, i.e., the heating period, in Lyon (France) for two weeks from 28 March to 13 April, employing a time-step of 60 s. The boundary conditions were set as adiabatic and impermeable roofs and floors. Façades comprised a 14 cm glass wool layer and a 45 cm concrete block layer, while the internal walls featured a 14 cm glass wool layer, a 15 cm brick, and a 2 cm plaster; all windows were double-glazed (4/12/4 cm).

Temperature settings were maintained at $23\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ for the living room (LV) zone and $22\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ for bedroom 2 (BD2), utilizing a 5 kW on/off heating system. Mechanical ventilation was carried out by an exhaust-only system, operating at 4 h^{-1} in the bathroom and WC, and 2 h^{-1} in the kitchen and hall (Table 1). Initial conditions for relative humidity and temperature in the monitored zones (LV and BD2) were set to mean measured values, with simulations run three times to refine the initial conditions before presenting the outcomes in this study. The Lyon TMY weather file was adjusted based on outdoor measurements during this period. The DOMUS model did not explicitly consider neighborhood effects in this study, although outdoor parameters sourced from the measured data may have encompassed some aspects of the urban microclimate in the simulation.

Contaminant concentrations and pressure differentials were obtained using CONTAM modeling aligned with the same period, time-step, and ventilation rates as the DOMUS model. Building air leakage was modeled with the power law equation [70]:

$$Q = c\Delta P^n, \quad (5)$$

where Q is the volumetric airflow and ΔP is the pressure drop across the opening. The flow coefficient c and the pressure exponent n were determined experimentally as $6.9 \times 10^{-3}\text{ m}^3\cdot\text{s}^{-1}\cdot\text{Pa}^{-n}$ and 0.72, respectively.

In the CONTAM simulation, doors and windows remained closed. Indoor contaminant sources were based on [71], with the apartment housing only one occupant who spent 20% of the daytime in the living room and 30% in bedroom 2 (Figure 1) during weekdays (on weekends, the apartment was unoccupied), according to the experiment survey. CO_2 emissions by the occupant were set at $18\text{ L}\cdot\text{h}^{-1}$ (wake) and $15\text{ L}\cdot\text{h}^{-1}$ (sleeping). Due to scheduling discrepancies in the survey, a CONTAM Discrete Values File (DVF) [55] was created to reflect the measured CO_2 emissions. This study did not account for indoor $\text{PM}_{2.5}$ generation due to a lack of precise information. Furthermore, considering the layout of the apartment and the airflow patterns created by the mechanical extraction ventilation system of the kitchen, it was assumed that particle emissions in the kitchen would be effectively removed and would not significantly impact the overall IAQ in the monitored areas. Outdoor CO_2 was estimated at 447 ppm during the absence of the occupant (one weekend), while outdoor $\text{PM}_{2.5}$ measurements were used in the simulation. Pressure coefficients were derived from the CFD results, as later described.

The local wind pressure coefficient is defined by [72]

$$C_{p,i} = \frac{P_i - P_{\infty}}{\frac{1}{2}\rho_{\infty}u_{\infty}^2}, \quad (6)$$

where ρ_{∞} is the outdoor air density, u_{∞} is the approaching wind speed at upwind wall height, P_{∞} is the local outdoor atmospheric pressure, and P_i is the pressure in point i for a given wall surface under wind action.

Equation (6) provides a straightforward definition; however, determining the wind pressure coefficient depends on factors such as the building shape, wind direction, and surrounding environment. This study employed a wind direction increment of 15° to obtain a comprehensive representation of the wall-averaged pressure coefficient for the building façades.

This study applied a CFD tool from CONTAM, the CFD0, to conduct CFD simulations. Following Blocken (2015) [73], a grid sensitivity study initially resulted in a hexahedral mesh with a resolution of $120 \times 215 \times 53$ nodes, as presented in Figure 2a. The length scale considered was 1:100 of a 6-story building ($10 \text{ m} \times 20 \text{ m} \times 90 \text{ m}$) accounting for the influence of the neighboring building ($10 \text{ m} \times 20 \text{ m} \times 45 \text{ m}$), with a wind velocity of 5 m/s at building height ($Re_H = 6.8 \times 10^6$). Boundary conditions included a no-slip wall at the ground, a slip wall at the top of the domain, and open sides mimicking an atmospheric boundary layer profile, varying with wind direction. Figure 2b illustrates airflow streamlines for a wind direction of 150° and pressure coefficients at a plane near the apartment floor.

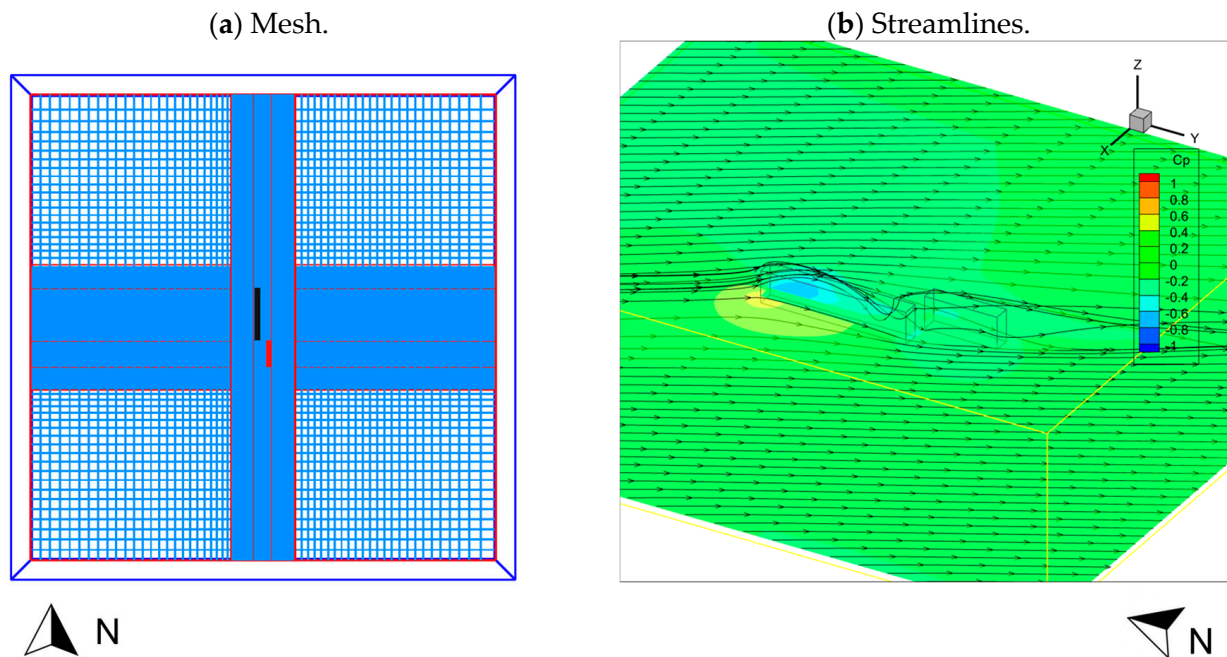


Figure 2. CFD0 at plane $z = 10 \text{ m}$: (a) mesh with $120 \times 215 \times 53$ nodes and (b) streamlines and wind-averaged pressure coefficient (C_p) of the airflow around the building for a wind direction of 150° from CFD0.

3. Results and Discussion

3.1. Temperature and Humidity

The temperatures recorded during the campaign, along with the DOMUS-modeled temperatures for the living room (LV) and bedroom 2 (BD2), are illustrated in Figure 3, in which the outdoor temperature was measured and applied as boundary conditions in DOMUS modeling. Notably, the LV consistently maintained a slightly higher temperature compared to BD2. Specifically, the mean LV temperature remained approximately 1.3°C higher during the experiment and increased to about 1.6°C in the modeling phase compared to BD2.

Examining the discrepancies between the measured and DOMUS temperatures, the average error in the LV stood at -0.2°C , whereas BD2 exhibited a slightly higher average error of -0.5°C , and these errors were below the uncertainty of the equipment ($\pm 1^\circ\text{C}$). Despite these variations, the temperatures exhibited a close correlation, particularly during the warmest period outdoors, spanning from 29 March to 1 April.

A finding emerged regarding the impact of heating control on temperature stability. Particularly, turning off the heating in BD2 amplified its susceptibility to external temperature fluctuations. In contrast, the LV, where heating remained consistent throughout the campaign, displayed comparatively less sensitivity to external temperature changes.

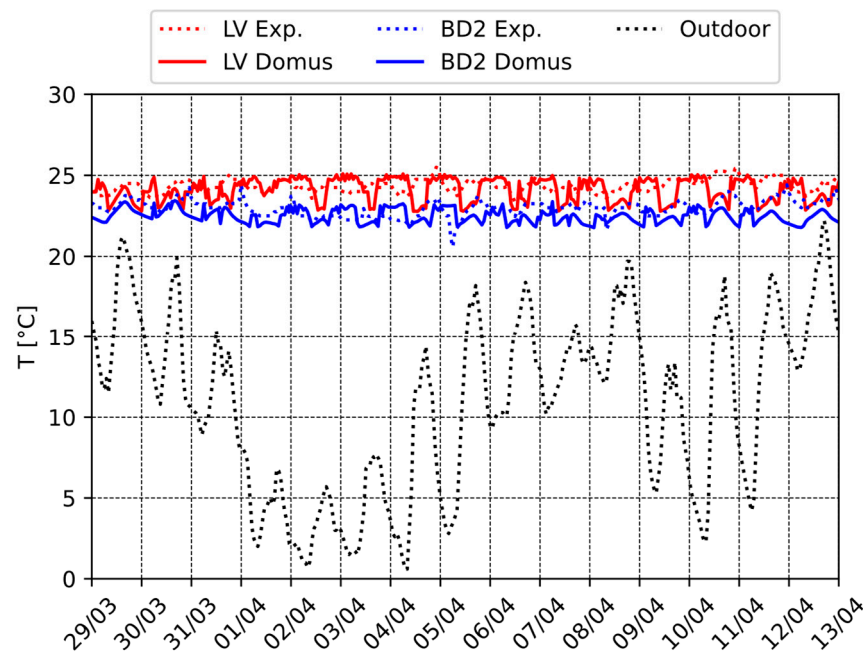


Figure 3. Temperature from experimental data (Exp.) against numerical modeling (DOMUS) in two zones: living room (LV) and bedroom 2 (BD2).

The monitoring of relative humidity during the campaign was complemented by DOMUS modeling, as illustrated in Figure 4. Without moisture control equipment, the only regulated parameter in both zones was the dry bulb temperature via the electric heating system. Consequently, variations in moisture content arose from a confluence of factors, including occupancy patterns, building materials, and prevailing weather conditions. Throughout the campaign, outdoor relative humidity ranged from 14% to 93%, averaging 60%, while outdoor temperatures fluctuated between 0.6 °C and 24.5 °C, averaging 12.2 °C. On average, the outdoor environment stayed around 12 °C and 60% relative humidity ($5.4 \text{ g}_{\text{vapor}}/\text{kg}_{\text{air}}$), contrasting with the LV at approximately 24 °C and 31% ($5.9 \text{ g}_{\text{vapor}}/\text{kg}_{\text{air}}$), and BD2 at nearly 23 °C and 36% ($6.5 \text{ g}_{\text{vapor}}/\text{kg}_{\text{air}}$). On average, both zones had a higher moisture content than the outdoor environment. BD2 exhibited more moisture than the LV, possibly due to the occupant spending more time in BD2.

An assessment of average relative humidity errors between the measurements and DOMUS modeling yielded a marginal deviation of +0.8% and −0.9% for the LV and BD2, respectively, underscoring the accuracy of the DOMUS model, especially considering the inherent uncertainty of the equipment at $\pm 5\%$. However, discrepancies arose when comparing the model and experimental data curve behaviors. Notably, deactivating heating in BD2 amplified relative humidity, making it more susceptible to outdoor humidity influence, which deviated from the anticipated model behavior.

Boxplots compare the measured and modeled temperature data for the LV and BD2 spaces in Figure 5. All boxplots of this study represent the first (Q1) and third (Q3) quartiles at the bottom and the top of the box, respectively. The whiskers extend from the box by 150%, the interquartile range, circles represent the outliers, and the line inside the box illustrates the median value.

Both zones exhibit similar temperature variation amplitudes of around 2.5 °C, indicating a consistent alignment between the measured observations and model simulations with DOMUS. However, distinct differences emerge in the contrasting temperature between the LV and BD2, evident in the measured and modeled datasets. The median measured temperature was 24.2 °C and 23.0 °C for the LV and BD2, respectively, and the relative errors of the median modeled temperatures were up to 2%.

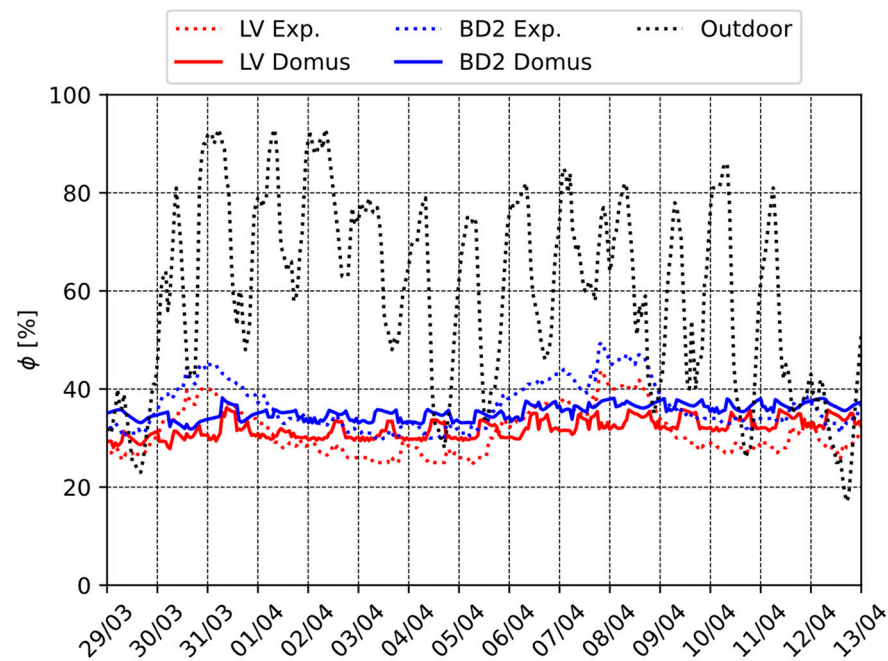


Figure 4. Relative humidity from experimental data (Exp.) against numerical modeling (DOMUS) in two zones: living room (LV) and bedroom 2 (BD2).

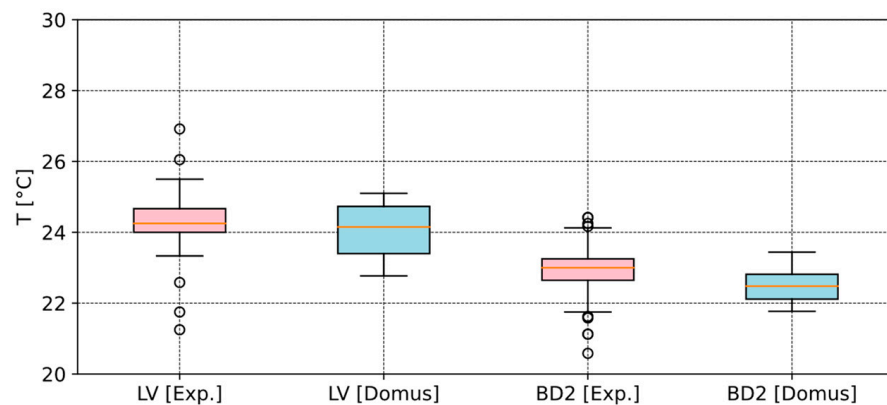


Figure 5. Boxplot of the temperature from experimental data (Exp.) against numerical modeling (DOMUS) in two zones: living room (LV) and bedroom 2 (BD2).

The measured temperatures in the LV predominantly ranged between 23.0 °C and 25.7 °C, while in BD2, they fell within the range of 21.7 °C to 24.2 °C. Modeled temperatures mirror these trends, maintaining ranges of 21.4 °C to 26.7 °C in the LV and 21.1 °C to 23.9 °C in BD2. Notably, BD2 consistently registered colder minimum temperatures, reaching close to 21.0 °C (with Q1 of 22.6 °C), and the LV registered hotter maximum temperatures close to 27.0 °C (with Q3 of 24.7 °C).

A comparative distribution of indoor measured and modeled relative humidity data in the LV and BD2 is depicted in Figure 6. The measured relative humidity variations exhibit similar amplitudes in the LV and BD2 of around 30%, while the modeled relative humidity was around 10% for both zones. In contrast, the modeled relative humidity variations differ notably between these two spaces. The measured relative humidity ranged from 15% to 44% in the LV and 22% to 51% in BD2, with a median of 29% and 35%, respectively. Meanwhile, the modeled relative humidity stayed between 25% and 38% in the LV and 31% and 40% in BD2, with a median of 32% and 35%, respectively.

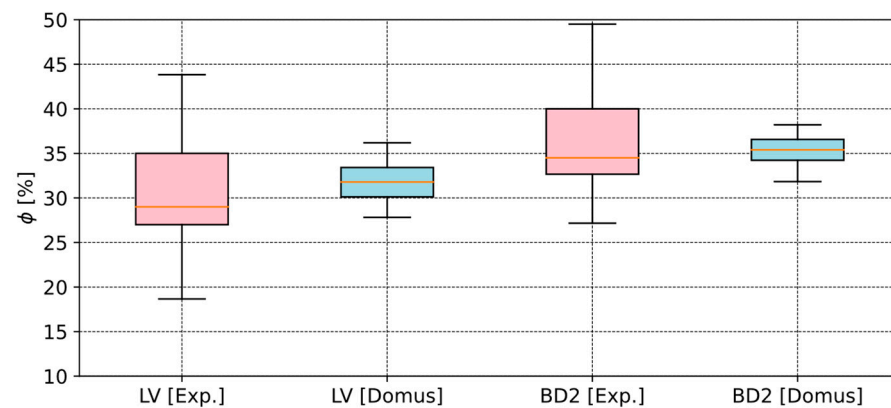


Figure 6. Boxplot of the relative humidity from experimental data (Exp.) against numerical modeling (DOMUS) in two zones: living room (LV) and bedroom 2 (BD2).

The duration when relative humidity fell below 30%, representing a health risk [74,75], accounted for approximately 42% of the time in the LV, where the minimum measured relative humidity was registered at 19% with Q1 of 27%.

Notably, no condensation risks were observed in the different rooms, as the duration when relative humidity exceeded 70%—indicative of a condensation risk [74,75]—was not recorded in both the LV and BD2 and assuming the surface temperature of the interior walls were kept above the dew-point temperature.

Although the numerical modeling results fell within the sensor error margins for temperature (Figure 3) and humidity (Figure 4), and showed good agreement with the median and data dispersion presented in the boxplots (Figures 5 and 6), the verification was conducted over a short period of only two weeks. The accuracy of the numerical model may decrease in a whole-year simulation due to the necessary simplifications of boundary conditions and the need for a more accurate representation of occupant behavior over a longer timeframe.

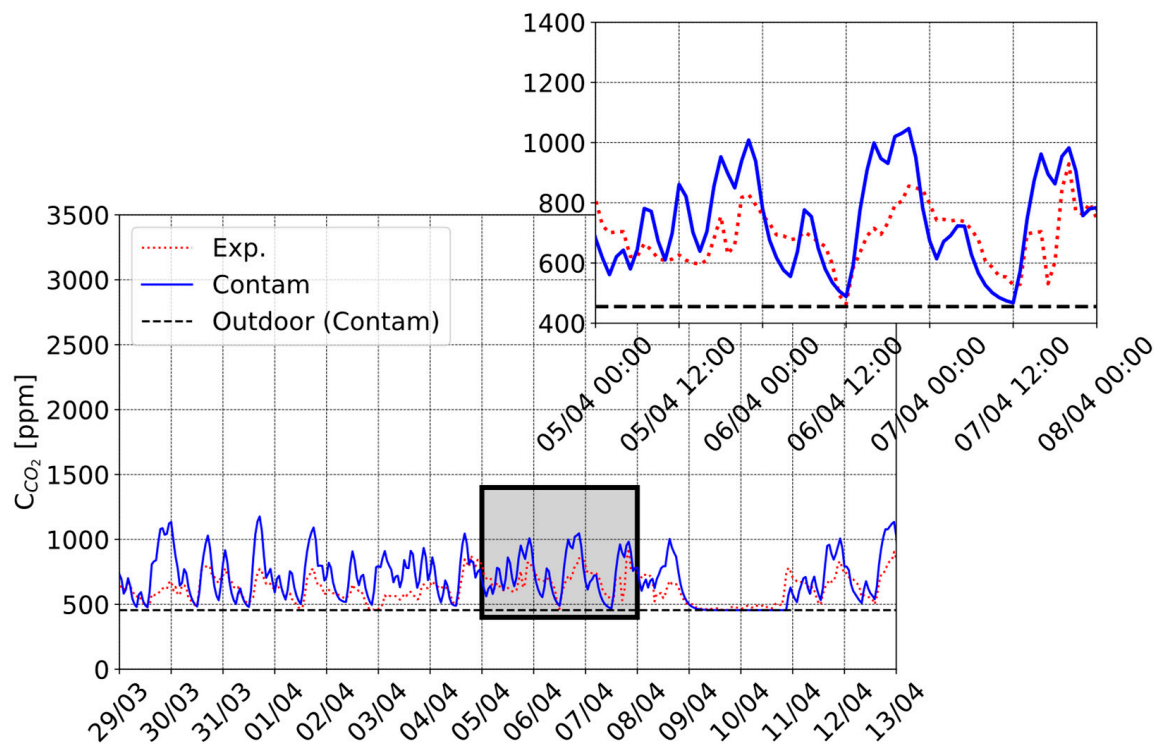
3.2. Contaminant Concentration

The divergence in measured and CONTAM-modeled CO₂ concentrations in the living room (LV) and bedroom 2 (BD2) is illustrated in Figure 7. The modeled CO₂ concentration notably rises above 1000 ppm, with BD2 exhibiting higher levels than the LV. Remarkably, maintaining BD2's door open overnight, as observed during the experiment, resulted in similar concentrations in both BD2 and the LV, while in the simulation, the door remained closed. A more explicit agreement between the measured and modeled CO₂ concentrations was observed in the LV compared to BD2, particularly evident from April 5th to 8th.

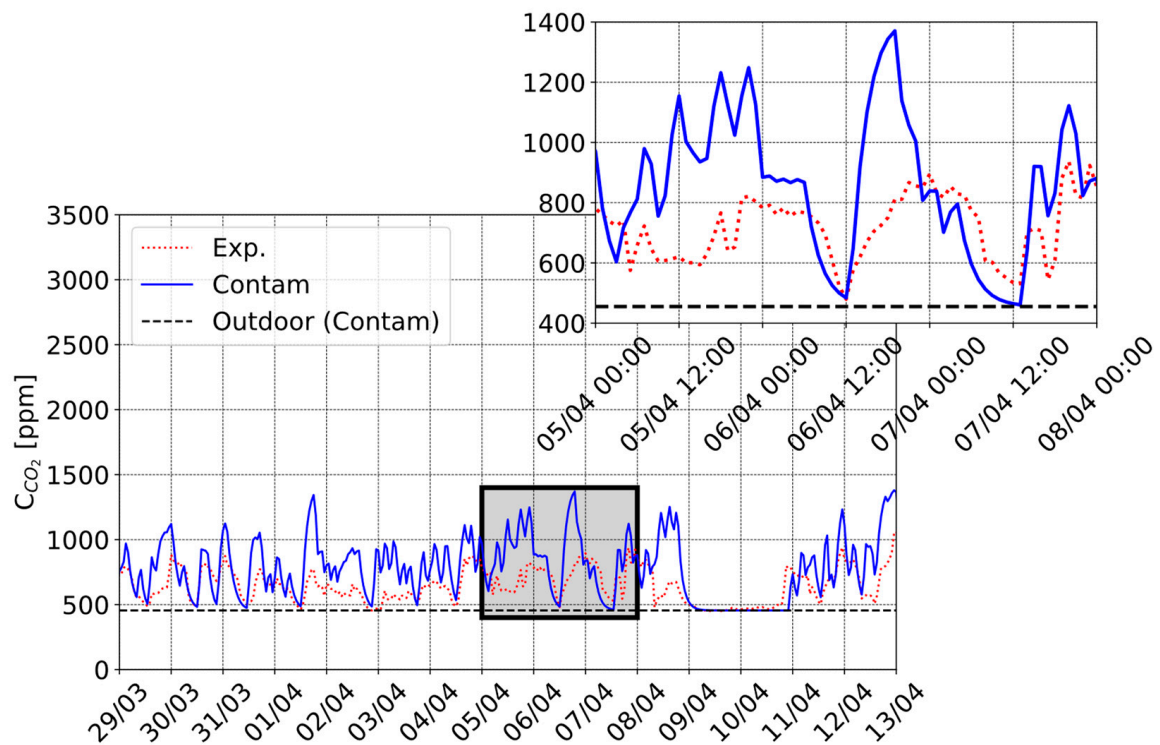
The modeled CO₂ behavior closely matched the measurements in Figure 7 due to the boundary conditions set in the CONTAM DVF schedule, which included typical day and night emissions for a single occupant [71]. Due to limited information on actual apartment occupancy, we estimated room occupancy by aligning it with the CO₂ growth observed in the experimental curve. While this method produced some overpredicted and underpredicted values, most deviations were within the sensor error range.

Figure 8 highlights the distribution of measured and modeled CO₂ concentrations in the LV and BD2. A similar variation in CO₂ concentrations is observed in both the LV and BD2. The average CO₂ concentration in the living room was measured at 620 ppm, 11% lower than the modeled concentration at 698 ppm. In BD2, the measured CO₂ concentration averaged 630 ppm, 18% lower than the modeled concentration averaged 767 ppm. These values fall within the ranges of 454–930 ppm and 447–1062 ppm for measured CO₂ in the LV and BD2, respectively, and 454–1177 ppm and 454–1380 ppm for modeled CO₂ in the LV and BD2, respectively. The median values for measured and modeled CO₂ concentrations were 620 ppm and 674 ppm (−8%), respectively, in the LV and 630 ppm and 767 ppm (−18%), respectively, in BD2. Moreover, the median error between measured and

modeled CO₂ concentrations was +54 ppm in the LV and +137 ppm in BD2, higher than the equipment uncertainty of ± 50 ppm.



(a) Living room (LV)



(b) Bedroom 2 (BD2)

Figure 7. CO₂ concentration from experimental data (Exp.) against numerical modeling (CONTAM) in two zones: (a) living room (LV) and (b) bedroom 2 (BD2).

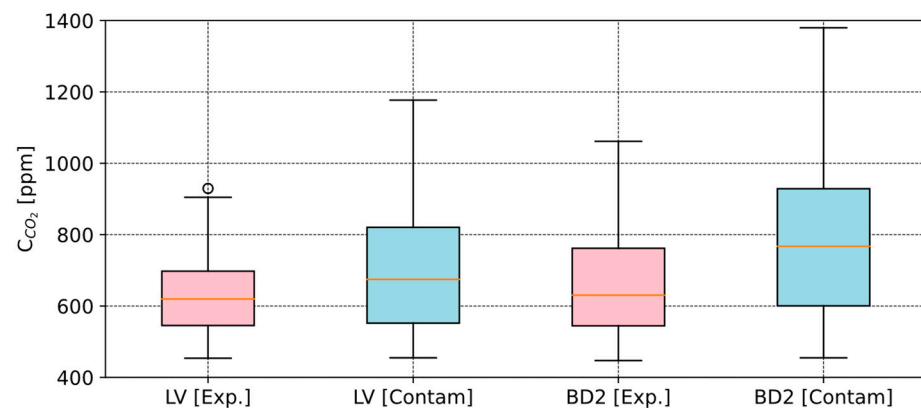


Figure 8. Boxplot of the CO₂ concentration from experimental data (Exp.) against numerical modeling (CONTAM) in two zones: living room (LV) and bedroom 2 (BD2).

Figure 9 represents the outdoor and indoor PM_{2.5} concentrations in the LV and BD2, as measured and modeled by CONTAM. The outdoor concentration was in the range 0–18 $\mu\text{g}\cdot\text{m}^{-3}$. Each external peak corresponded to an internal peak in the measured and modeled concentrations. Notably, PM_{2.5} concentrations exceeding 10 $\mu\text{g}\cdot\text{m}^{-3}$ were more prevalent in the living room than in BD2, especially in the measured data where internal sources existed (contrary to the simulation). This discrepancy can be attributed to the proximity of the kitchen for the measured data, an internal source of fine-particle generation, affecting the living room more prominently than the bedroom. These indoor sources are not modeled in CONTAM, so it is assumed that the peaks observed inside are not obtained in the simulations and that the simulated indoor PM concentration follows the outdoor concentrations with a time lag. The higher emission rates observed in the measurements on April 5th and 6th afternoons were attributed to candle burning, as noted in the survey, highlighting a limitation of the modeling, which struggles to accurately represent these and other indoor emission rates resulting from occupant behavior.

Figure 10 compares the measured and modeled PM_{2.5} concentrations in the LV and BD2 using boxplots. In the LV, the median value for measured PM_{2.5} concentration was 3.7 $\mu\text{g}\cdot\text{m}^{-3}$, while the modeled concentration was 4.7 $\mu\text{g}\cdot\text{m}^{-3}$ (+27%). On the other hand, in BD2, the median values were 4.2 $\mu\text{g}\cdot\text{m}^{-3}$ for the measured PM_{2.5} concentration and 4.7 $\mu\text{g}\cdot\text{m}^{-3}$ (+12%) for the modeled PM_{2.5} concentration. On average, the LV recorded PM_{2.5} concentrations of 5.8 $\mu\text{g}\cdot\text{m}^{-3}$ (measured) and 6.2 $\mu\text{g}\cdot\text{m}^{-3}$ (modeled), while BD2 showed concentrations of 5.3 $\mu\text{g}\cdot\text{m}^{-3}$ (measured) and 6.2 $\mu\text{g}\cdot\text{m}^{-3}$ (modeled). These concentrations fall within 0–15 $\mu\text{g}\cdot\text{m}^{-3}$ for the measured PM_{2.5} in the LV and 1–19 $\mu\text{g}\cdot\text{m}^{-3}$ for the modeled PM_{2.5} in BD2.

3.3. Other Smart Ventilation Strategies

The ventilation system in the renovated apartment can be classified as MEV-cav, which stands for mechanical exhaust-only ventilation with constant air volume, as detailed in Section 2. To evaluate the effects of alternative ventilation systems, we selected two advanced configurations based on [51]. First, the MEV-rh, one of the French reference systems for dwellings that integrates humidity control, has been described in [76]. It includes exhaust components in humid rooms and trickle vents in bedrooms and the living room, both controlled by humidity. Secondly, the MEV-rb combines CO₂ and humidity regulation at the room level. The airflow variations for these enhanced systems are presented in Figure 11. Specifically, the MEV-rh system operates at its lowest airflow rate of 20% relative humidity in the kitchen and 40% in the bathroom/WC. The humidity in these rooms is highest at 60% and 80% relative humidity, respectively (Figure 11a). For the system MEV-rb, a gradual modulation of airflows is observed from 800 ppm to 900 ppm for CO₂ concentration and from 57% to 77% for relative humidity, ensuring that the system adjusts the airflow between defined minimum and maximum thresholds to

meet the ventilation demands of all apartment rooms, as demonstrated by the smooth transition control in Figure 11b. The system MEV-rb is installed in more than 90% of the new buildings in France [77] because it provides energy savings estimated at 30% to 50% of the heating energy compared to MEV-cav [76].

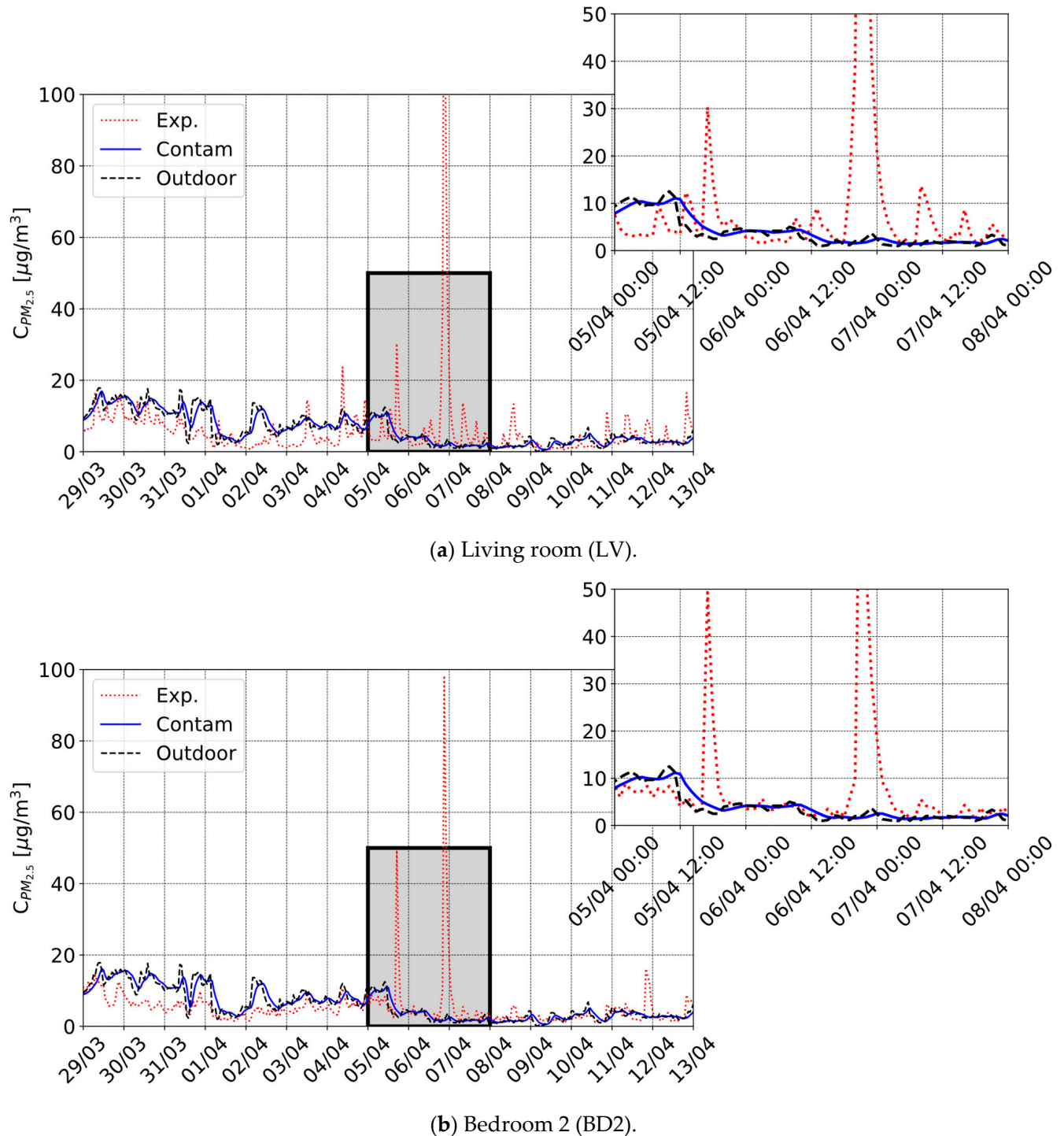


Figure 9. PM_{2.5} concentration from experimental data (Exp.) against numerical modeling (CONTAM) in two zones: (a) living room (LV) and (b) bedroom 2 (BD2).

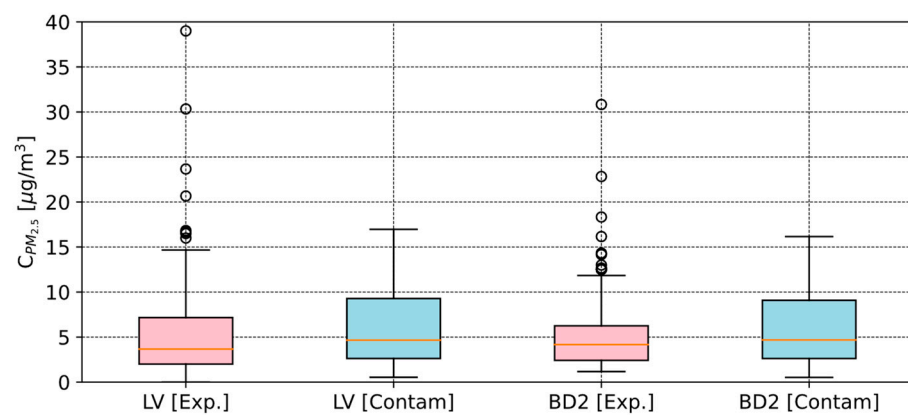


Figure 10. Boxplot of the $PM_{2.5}$ concentration from experimental data (Exp.) against numerical modeling (CONTAM) in two zones: living room (LV) and bedroom 2 (BD2).

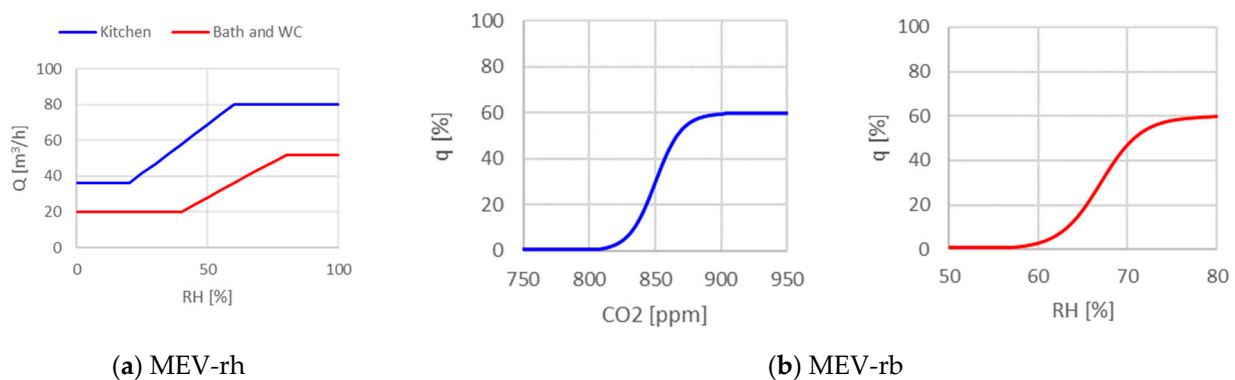


Figure 11. Smart ventilation systems: (a) mechanical exhaust-only ventilation and humidity control (MEV-rh) and (b) mechanical exhaust-only ventilation and CO_2 and humidity control at the room level (MEV-rb).

We present the CO_2 and $PM_{2.5}$ concentrations across two zones within an apartment, comparing the efficacy of various ventilation strategies in Figures A1 and A2. Figure A1 reveals that smart ventilation strategies, specifically MEV-rh and MEV-rb, reduce CO_2 , showcasing the superior performance of MEV-rb over the MEV-cav system in managing CO_2 concentrations. However, it can be noted in Figure A2 that these improvements do not extend to $PM_{2.5}$ concentration levels, despite a slight reduction observed with the smart ventilation strategies compared to the reference ventilation. These results show that the variation in airflows in the two smart systems does not influence the transfer of the outdoor pollution to indoors, which is an interesting result: the periods when the ventilation airflows are higher (due to high indoor humidity and/or CO_2) do not correspond to outdoor pollution peaks, so we cannot observe an effect on $PM_{2.5}$.

We provide a detailed boxplot analysis of average CO_2 and $PM_{2.5}$ concentrations in Figures 12 and 13, respectively, comparing the performance of a reference ventilation strategy (MEV-cav) against smart ventilation strategies (MEV-rh and MEV-rb) within two distinct zones of this apartment: the living room (LV) and bedroom 2 (BD2).

The median concentrations of CO_2 for MEV-cav, MEV-rh, and MEV-rb were observed at 673 ppm, 549 ppm, and 526 ppm, respectively, in the LV and at 768 ppm, 592 ppm, and 585 ppm, respectively, in BD2. These results indicate an enhancement in CO_2 management through the implementation of intelligent ventilation strategies, with reductions in median CO_2 concentrations of 18% (MEV-rh) and 22% (MEV-rb) in the LV and 23% (MEV-rh) and 24% (MEV-rb) in BD2, respectively.

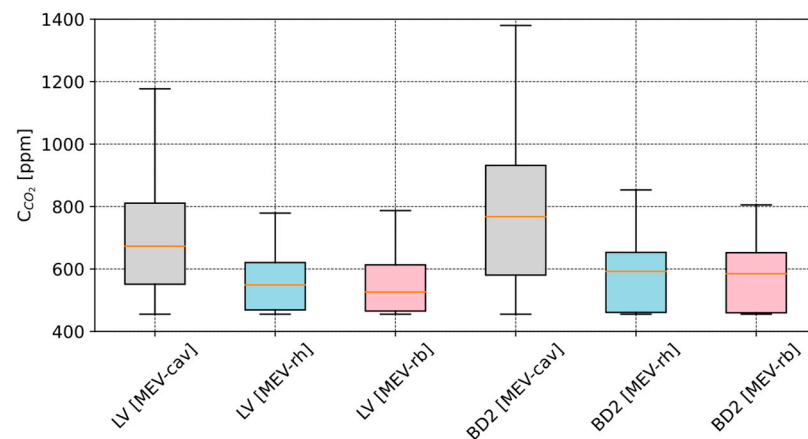


Figure 12. Boxplot of the CO₂ concentration from reference ventilation strategy (MEV-cav) against smart ventilation strategies (MEV-rh and MEV-rb) in two zones: living room (LV) and bedroom 2 (BD2).

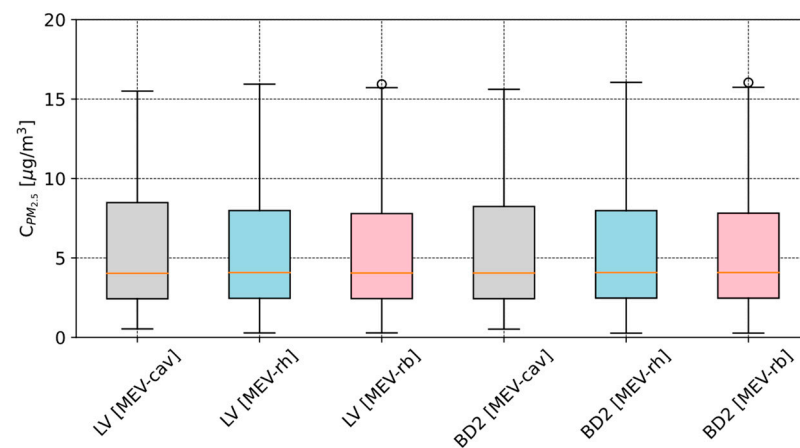


Figure 13. Boxplot of the PM_{2.5} concentration from reference ventilation strategy (MEV-cav) against smart ventilation strategies (MEV-rh and MEV-rb) in two zones: living room (LV) and bedroom 2 (BD2).

Furthermore, the efficacy of smart ventilation systems is more pronounced when analyzing the upper-quartile (Q3) CO₂ concentrations. In the LV, the concentrations were recorded at 881 ppm, 621 ppm, and 613 ppm for MEV-cav, MEV-rh, and MEV-rb, respectively. In contrast, in BD2, the concentrations were 932 ppm, 653 ppm, and 652 ppm for MEV-cav, MEV-rh, and MEV-rb, respectively. This corresponds to an approximate 30% reduction in CO₂ levels for both smart ventilation systems across both zones. This analysis underscores the substantial impact of smart ventilation systems on improving air quality by effectively managing and reducing CO₂ concentrations within residential environments.

The PM_{2.5} concentration levels revealed minimal variation across all ventilation systems, maintaining a median value of approximately 4.0 µg·m⁻³. When analyzing the third-quartile values, a modest enhancement was observed, with concentrations of 8.5 µg·m⁻³, 8.0 µg·m⁻³, and 7.8 µg·m⁻³ for MEV-cav, MEV-rh, and MEV-rb in the LV, respectively. Similarly, in BD2, the concentrations were recorded at 8.2 µg·m⁻³, 8.0 µg·m⁻³, and 7.8 µg·m⁻³ for MEV-cav, MEV-rh, and MEV-rb, respectively. This indicates a slight improvement in PM_{2.5} management in the higher-concentration quartiles across the examined ventilation systems, with a reduction of approximately 5% of the PM_{2.5} concentration.

These results highlight a potential area for enhancement in smart ventilation systems by reducing CO₂ concentrations. Nevertheless, we should consider indoor PM_{2.5} sources

due to cooking in the following steps to further improve IAQ by addressing particulate matter alongside CO₂ levels.

Finally, the average air change rates in the bathroom and WC were 3.6 h⁻¹ for the MEV-rh system and 1.4 h⁻¹ for the MEV-rb system, leading to energy savings of approximately 10% and 65%, respectively. In addition, there was a reduction in extract ventilation rates in the kitchen and hall, with average rates of 1.7 h⁻¹ for the MEV-rh system and 1.3 h⁻¹ for the MEV-rb system, while still maintaining acceptable IAQ levels, as shown in Figure 12. Although further monitoring is required to confirm these energy savings over a year, both systems show potential for reducing energy consumption while improving overall IAQ.

4. Conclusions

This research evaluates IAQ in an apartment in Lyon, France, a region known for its poor air quality index. By integrating innovative methods, this study assesses temperature, relative humidity, CO₂, and PM_{2.5} concentrations in the living room and bedroom. A key contribution of this research is verifying the experimental data against multizone simulation models (DOMUS and CONTAM), which are coupled with a CFD tool to refine pressure coefficients on the building façade. This novel coupling approach enhances the accuracy of IAQ simulations by providing a more precise representation of the building's microclimate.

The main findings of this research are as follows:

- The study compared two advanced energy-efficient ventilation strategies—mechanical exhaust-only with humidity control (MEV-rh) and room-based mechanical exhaust-only with combined CO₂ and humidity control (MEV-rb)—against a traditional mechanical exhaust-only strategy with constant airflows (MEV-cav).
- The analysis, employing temporal series and boxplots, showed that the measurement device (Nemo) had minimal errors: 0.2 °C for temperature, 0.8% for relative humidity, 54 ppm for CO₂, and 0.2 µg/m³ for PM_{2.5}.
- The results revealed improvements in IAQ, particularly a 20% reduction in the average CO₂ concentration and a 5% reduction in the third-quartile PM_{2.5} concentration, demonstrating that these smart ventilation strategies enhance room ventilation and pollutant dilution.

The novelty of this research lies in its use of coupled simulation models and CFD tools to refine IAQ predictions and its comparative analysis of innovative ventilation strategies in an urban microclimate. Future research should incorporate indoor sources of particulate matter, such as those from cooking, and expand the study to include additional zones like the kitchen and bathroom. Additionally, investigating performance during heatwaves could further refine numerical modeling and improve boundary conditions for multizone models, contributing valuable insights to the field of urban microclimate and air pollution management.

Author Contributions: Conceptualization, M.B.L., N.K., B.P., G.G., N.M., M.O. and E.G.; methodology, M.B.L., N.K., B.P., G.G., M.O. and E.G.; software, M.B.L., N.K. and B.P.; experimental campaign, N.K.; validation, M.B.L., N.K., G.G., M.O. and E.G.; formal analysis, M.B.L. and N.K.; investigation, M.B.L., N.K., G.G., M.O. and E.G.; data curation, M.B.L. and N.K.; writing—original draft, M.B.L., N.K. and G.G.; writing—review and editing, G.G., N.M., M.O. and E.G.; supervision, G.G., N.M., M.O. and E.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CAPES, grant number #898/18, and the CNPq/Araucaria Foundation, grant number #19/2022.

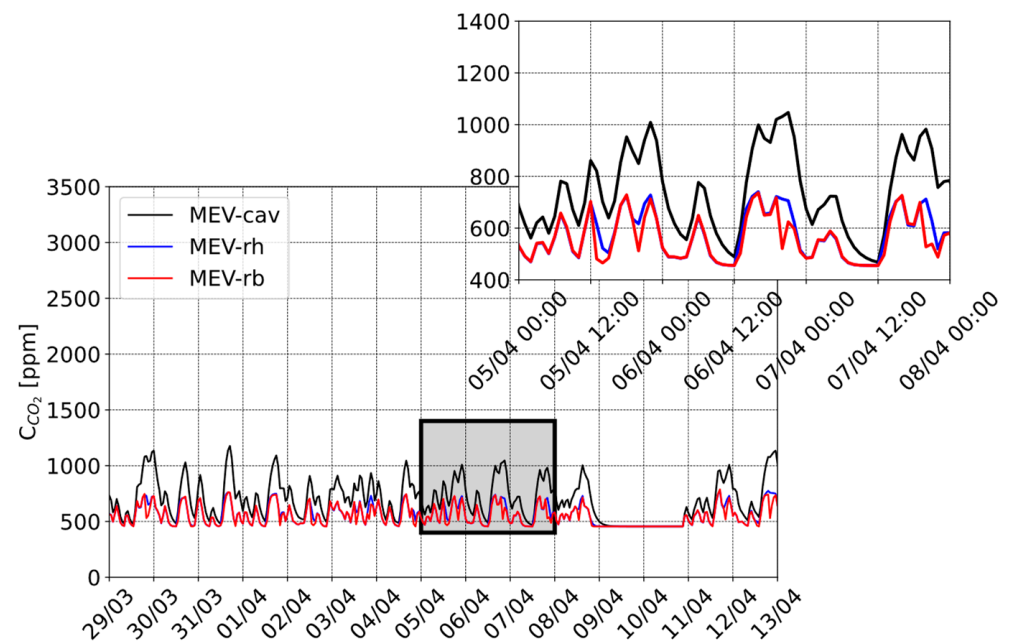
Data Availability Statement: The data that have been used are confidential.

Acknowledgments: The authors would like to thank the Brazilian agency CAPES (the Brazilian Federal Agency for the Support and Evaluation of Graduate Education) of the Ministry of Education for the financial support, the Binational Cooperation Program CAPES/COFECUB (Grant # 898/18), in collaboration with the laboratory LOCIE at the Université Savoie Mont-Blanc, France, the Brazilian

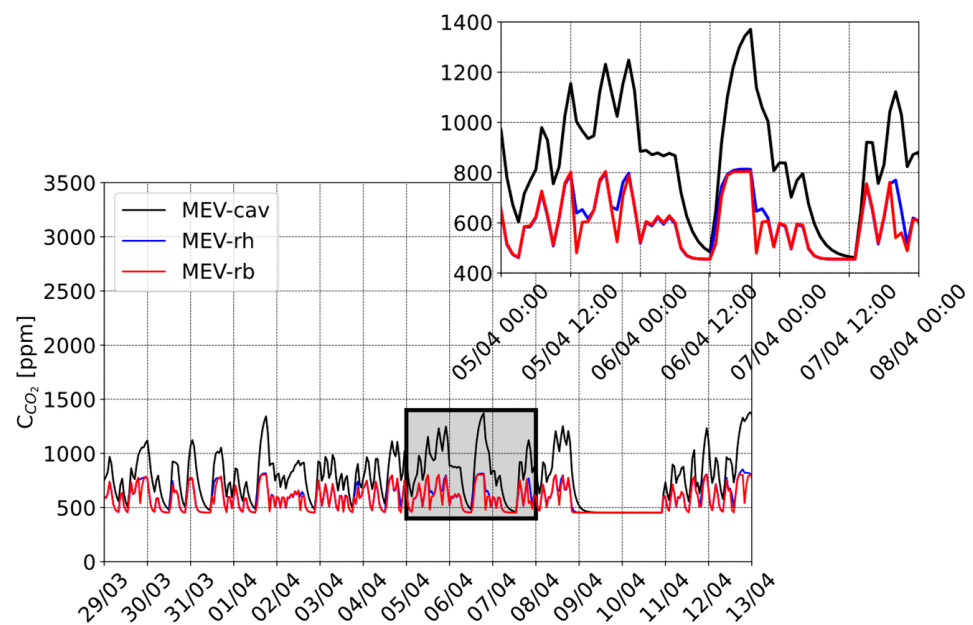
Research Council (CNPq) of the Ministry of Science, Technology and Innovation, and the Araucaria Foundation (Grant # 19/2022).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A



(a) Living room (LV).



(b) Bedroom 2 (BD2).

Figure A1. CO₂ from reference ventilation strategy (MEV-cav) against smart ventilation strategies (MEV-rh and MEV-rb) in two zones: (a) living room (LV) and (b) bedroom 2 (BD2).

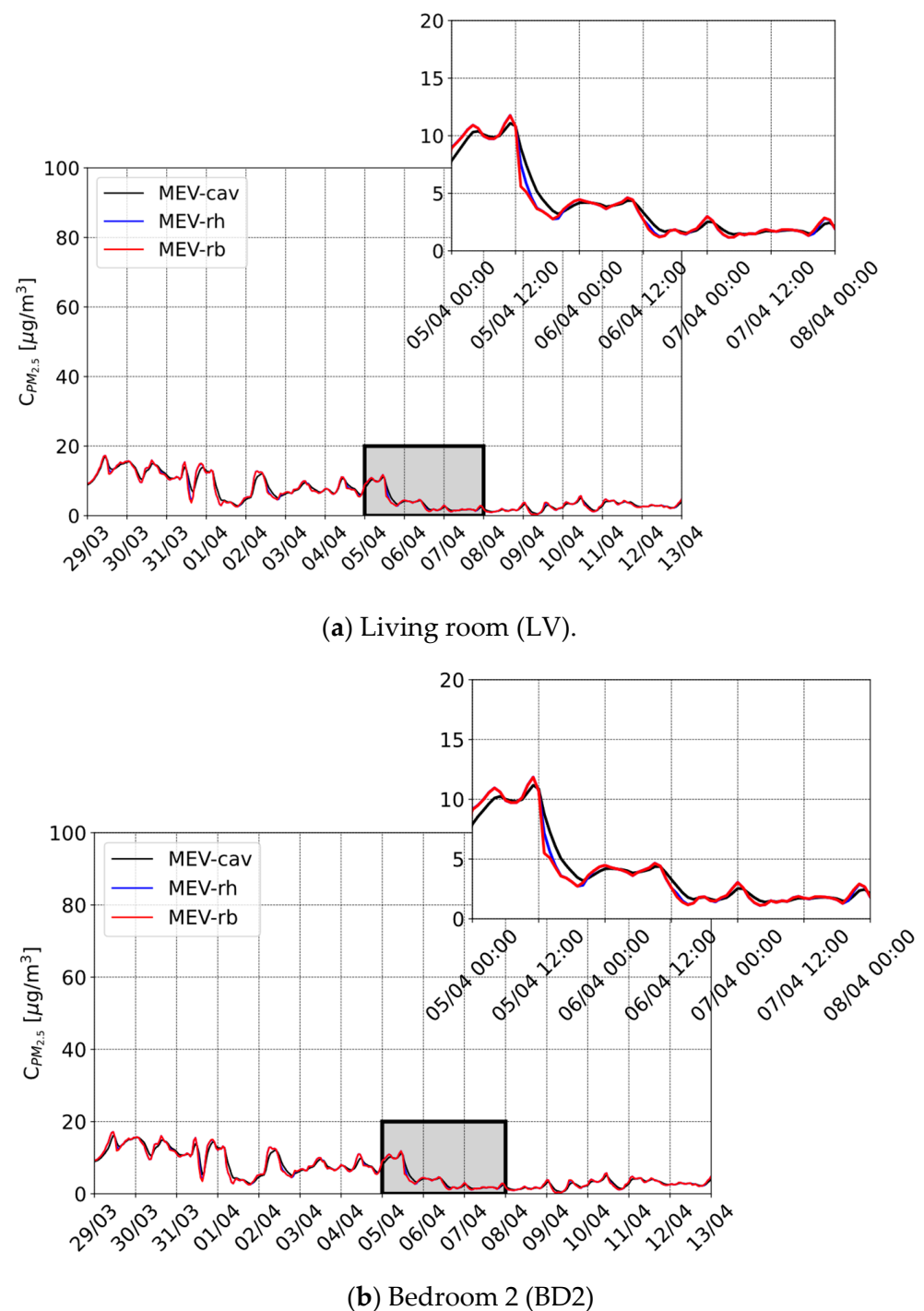


Figure A2. PM_{2.5} from reference ventilation strategy (MEV-cav) against smart ventilation strategies (MEV-rh and MEV-rb) in two zones: (a) living room (LV) and (b) bedroom 2 (BD2).

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