Evaluating the IAQ and energy performance of ventilation systems in multifamily buildings

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Abstract. Buildings must provide Indoor Air Quality (IAQ) to the best of their ability while maintaining high energy efficiency. Mechanical ventilation systems are central to this concern. Despite the promises of innovative technologies in the market, a simple simulation tool for comparing their effects is not available. This article presents a TRNSYS-CONTAM co-simulation tool that enables the calculation of interdependent effects of temperature, moisture, and airflow on contaminant transport, and energy use on the building scale. The impact of the outdoor conditions, airtightness of building envelopes, neighboring environments, and the building's wind exposure is also considered. IAQ is assessed by humidity, CO2 concentration in the building, and the exposure of its occupants to PM2.5 and formaldehyde concentrations to comply with available recommendations. This paper presents the methodology employed to evaluate the global performance of ventilation systems in terms of energy efficiency and IAQ.

1. Introduction

People spend most of their life in buildings (residential, commercial, educational…). As a result, they are exposed daily to indoor pollutants that can produce adverse effects on their health such as headaches, allergies, and respiratory diseases [1], and affect their productivity [2, 3]. Exposures to indoor pollutants in residential buildings are particularly important. Research showed that 60 to 95% of our total lifetime exposures to airborne pollutants occur in homes, with 30% of that being during sleeping time. [4] Moreover, World Health Organization data [5] indicated that 180,000 deaths in Europe and the Americas were attributable to household (indoor) air pollution.

Indoor air pollution in residential buildings is generated by pollutants introduced into the built environment along with outdoor air and by indoor emissions from occupants and their activities (heating, cooking, cleaning …) and from furnishing and building materials used. Since source control can only be done to a certain extent, improving air quality within residential buildings relies on bringing in more fresh air to dilute the concentration of pollutants. This means increased ventilation, which is a cost-energy solution for temperate/cold climates even when no mechanical device is used.

The level of pollution inside a building is determined by many other factors than the pollutants' load, which can be related to the building itself (configuration, envelope leakage, internal partitioning), to the ventilation system (type, outdoor air intake, supply and/or return airflow rates, operating mode…) and to the neighboring environment (weather, urban density, outdoor pollution…). Despite these different factors impacting the air quality of the built environment, current standards, and regulations [6, 7] generally characterize indoor pollution using a prescriptive approach based on ventilation rates requirements set according to comfort considerations, instead of on pollutants' concentration levels for fulfilling both comfort and health criteria. A performance-based approach, able to predict the concentrations of pollutants within the built environment via numerical simulation and evaluate them against acceptable values to prevent health risks, seems then to be a more appropriate methodology to assess Indoor Air Quality (IAQ) in buildings than the predictive approach since a same ventilation rate can conduct to different levels of indoor pollution. However, modeling pollutant mass transfer in residential buildings is a complex task: numerous pollutants are found in the residential indoor environment [4]; pollutants can be transported by convective and diffusive airflow between the different spaces of the built environment and through the building envelope; particulate matters, inorganic gases, and organic compounds interact differently with the solid surfaces (wall and furnishings); pollutants can be extracted from the indoor environment by different ventilation and filtration systems and input data are needed regarding the emissions from the indoor sources (building and furniture materials and occupants' activities) and the outdoor air pollution.

Therefore, to perform predictions with reasonable computational time only a small number of pollutants can be considered in the numerical simulations. Simplifications must also be adopted concerning some physical phenomena, whose modeling can be time-consuming and/or dependent on parameters hard to obtain. Moreover, accurate and realistic input data are needed to provide reliable simulations.

According to previous work [7] performance-based approaches applied to indoor air quality have recently been used for compliance of ventilation control strategies in residential buildings. Their study showed that most of them were based on mass transfer calculations using a multizone building partitioning, considering occupants' exposure to CO_2 and condensation risk criteria. Lv and Yang [8] have used a performance-based approach for indoor decoration pollution control, whose mass transfer calculations (in a single or multizone building partitioning) include the pollutant-material interaction for volatile organic compounds (VOC). The authors have shown that the referred approach could correctly predict exposure to formaldehyde in real buildings. A performance-based approach based on multizone heat and mass transfer calculations has been proposed by Cony-Renaud-Salis et al. [9] to evaluate ventilation systems in dwellings. The approach accounts for humidity, inorganic gases (CO_2, SO_2, NO_2, O_3), particulate matters ($PM_{2.5}$ and PM_{10}) and organic compounds (formaldehyde, acrolein, benzene, toluene, and trichloroethylene), ignoring the sorption effects of the latter. According to the authors, except for benzene whose values are overestimated, levels of pollution in mechanically ventilated dwellings agree with values from a national French measurement survey.

The objective of this paper is to introduce a tool to assess the performance of ventilation systems operating in multifamily buildings, considering both energy efficiency (EE) and IAQ criteria. The tool is based on TRNSYS-CONTAM building simulations for a set of residential buildings equipped with different mechanical ventilation systems operating under various conditions. This means that the global performance (EE and IAQ) of ventilation systems is assessed in this tool by means of dynamic calculations of heat and mass (air, moisture, and

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pollutants) transfer according to a multizone building partitioning, considering humidity and a representative pollutant of each pollutant category (CO_2, $PM_{2.5}$ and formaldehyde). Sorption effects and particle size distribution are neglected. This tool constitutes therefore a numerical framework that allows users to assess the global performance of a given ventilation system considering its neighboring environment, without the need to model in detail the building and its ventilation system. In order to show the applicability of the tool, the performances of a pressure-controlled balanced ventilation system in a two-story multifamily building are evaluated.

2. Methodology

The proposed TRNSYS-CONTAM tool, named HEAVENLY (Holistic Evaluation tool for Air VENtiLation sYstems), was conceived to evaluate the performance of ventilation systems with airflow rates ranging from 1,000 m^3/h to 18,500 m^3/h and structured into two main components: a building test bed and a graphical user interface.

2.1.Building test bed

The building test bed encompasses TRNSYS-CONTAM building performance simulations. This means dynamic computations of heat, moisture, and pollutants (CO_2, HCHO, and $PM_{2.5}$) transport within a selected set of buildings equipped with user-adjustable ventilation systems, employing TRNSYS [10] and CONTAM [11] tools coupled to each other according to a multizone approach.

As illustrated in Figure 1, there are three distinct data blocks within the building test bed: 1) Archetype block, housing data unalterable by the user; 2) User selection block, incorporating data modifiable by the user; and 3) Influential factors block, containing data that can automatically vary during calculations to assess the performance of the tested ventilation system under various operational conditions.

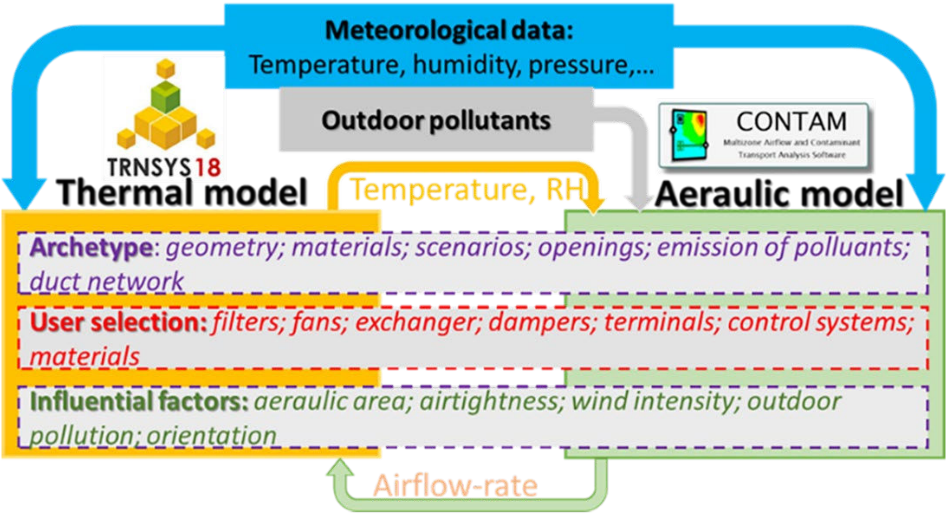
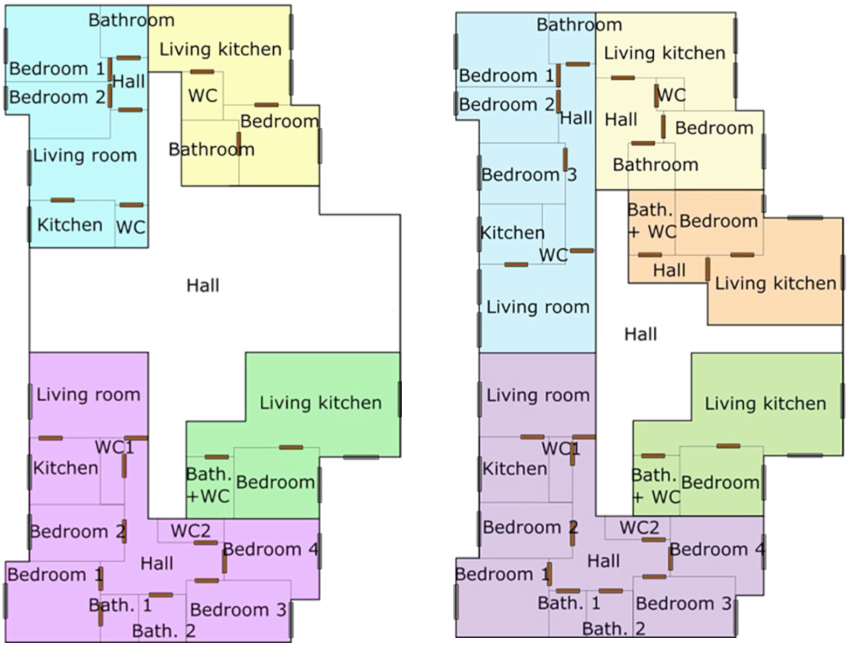


Fig. 1. TRNSYS-CONTAM building performance simulations: data blocks and data flow.

Archetype block

The archetype block comprises data about the characteristics of building-ventilation system sets, specifically: 1) The geometry of the buildings; 2) The hygrothermal properties of the envelope materials of the buildings; 3) The design of the duct network (including duct shape, duct diameter, duct length, and fittings parameters); 4) Internal loads, encompassing heat gains, humidity production, and pollutants' emissions; 5) The heating system; and 6) Opening scenarios for windows and doors.

With respect to the geometry of the buildings, the archetypes are rectangular buildings 26.8 m long and 16.6 m wide, with 1 to 10 floors of 3 m high each. The ground and upper floors have different typologies including flats from 1 to 4 bedrooms, with closed or open kitchens and toilets integrated or separated from the bathrooms, as indicated in Figure 2.



a) b)

Fig. 2. Schematic representation of the a) ground floor and b) upper floors.

User selection block

The user selection block primarily encompasses the data related to the control and operational performance of the components that constitute the ventilation systems. The list of parameters that can be adjusted by the user is shown in Table 1 by category of component.

Influential factor block

The influential factors block encompasses two categories of data: 1) Characteristics of the test bed's buildings in relation to their neighboring environment: a) The airtightness of the building envelope, categorized as airtight or leaky and b) The building's wind exposure, classified as facing or covered; 2) Characteristics of the neighboring environment, considering: a) The outdoor $PM_{2.5}$ pollution level, categorized as <10 µg/m^3 or >20 µg/m3,

b) Wind intensity, categorized as low or strong and c) Urban density, categorized as urban or semi-urban.

By combining these various factors, a total of 32 distinct boundary conditions are established (see Table 2), representing the operation conditions into which the ventilation systems are tested.

2.2 Graphical user interface

The graphical user interface of HEAVENLY is organized into three main blocks: pre-processor, processor, and post-processor.

Table 1. Building test bed: user-adjustable parameters of the ventilation systems components.

Category	Type	User-adjustable parameter
Venting terminals	Pressure-controlled (diffusers and vents)	Performance curve ($Qx\Delta P$)
	Humidity controlled (vents)	Performance curve ($Qx\Delta P$) ($RH_{max}xQ_{max}$) ($RH_{min}xQ_{min}$)
Boxes, plenums, and systems	Fans	Performance curve ($Qx\Delta P$)
	Air-handling units	
Wall and zones	Pressure-controlled (intakes)	Performance curve ($Qx\Delta P$)
	Humidity controlled (intakes)	
Ducts	Fittings	Material (roughness), leakage class
	Straight ducts	
Exchangers	Plate heat exchanger	Energy efficiency Airflow rate and initial pressure drop at nominal conditions
Filters	$PM_{2.5}$ filter	Filtering efficiency, Airflow rate and initial pressure drop at nominal conditions
Controls	Passive (manual, time clock & presence detection)	Control mode choice: manual, time clock, or presence detection mode according to pre-defined schedules
	Active (On/Off, proportional, PID)	Control mode choice: On/Off, proportional or PID Probe position choice: in a particular zone (remote measurement) or on the return air Controlled quantity choice: H_2O, CO_2, HCHO, $PM_{2.5}$ Setpoint schedule choice: according to a target IAQ performance level (excellent, very good or good)

Pre-processor block

The pre-processor block has three functions:

a) Select automatically from the archetypes (building-ventilation system sets) of the building test bed, those corresponding to the type and airflow rate range of the ventilation system whose performance the user wants to evaluate.

b) Collect the user's operational performance data concerning the component(s) of the ventilation system whose performance will be assessed, and change automatically the building performance simulations accordingly; and

c) Define the weather data for which the building performance simulations relative to the user-tailored building-ventilation sets will be run. The user will be able to choose among three European weather data corresponding to the cities of Athens, Helsinki, and Strasbourg.

Table 2. Building test bed: influential factors set.

Influential factor set	**Outdoor environment**		**Building**		
Number	**Wind intensity**	**$PM_{2.5}$ pollution**	**Wind-exposure***	**Tightness**	**Location**
#1	Strong	<10	Facing	Airtight	Urban
#2	Strong	<10	Facing	Airtight	Semi-urban
#3	Strong	<10	Facing	Leaky	Urban
#4	Strong	<10	Facing	Leaky	Semi-urban
#5	Strong	<10	Covered	Airtight	Urban
#6	Strong	<10	Covered	Airtight	Semi-urban
#7	Strong	<10	Covered	Leaky	Urban
#8	Strong	<10	Covered	Leaky	Semi-urban
#9	Strong	>20	Facing	Airtight	Urban
#10	Strong	>20	Facing	Airtight	Semi-urban
#11	Strong	>20	Facing	Leaky	Urban
#12	Strong	>20	Facing	Leaky	Semi-urban
#13	Strong	>20	Covered	Airtight	Urban
#14	Strong	>20	Covered	Airtight	Semi-urban
#15	Strong	>20	Covered	Leaky	Urban
#16	Strong	>20	Covered	Leaky	Semi-urban
#17	Low	<10	Facing	Airtight	Urban
#18	Low	<10	Facing	Airtight	Semi-urban
#19	Low	<10	Facing	Leaky	Urban
#20	Low	<10	Facing	Leaky	Semi-urban
#21	Low	<10	Covered	Airtight	Urban
#22	Low	<10	Covered	Airtight	Semi-urban
#23	Low	<10	Covered	Leaky	Urban
#24	Low	<10	Covered	Leaky	Semi-urban
#25	Low	>20	Facing	Airtight	Urban
#26	Low	>20	Facing	Airtight	Semi-urban
#27	Low	>20	Facing	Leaky	Urban
#28	Low	>20	Facing	Leaky	Semi-urban
#29	Low	>20	Covered	Airtight	Urban
#30	Low	>20	Covered	Airtight	Semi-urban
#31	Low	>20	Covered	Leaky	Urban
#32	Low	>20	Covered	Leaky	Semi-urban

**The wind-exposures are characterized by the rotation of the building relative to its original orientation. In the facing exposure, the buildings are in their original positions (Figure 2) while in the covered exposure the buildings are 180° rotated*

Processor block

The processor block has the following functions:

a) Run the set of TRNSYS-CONTAM building performance simulations resulting from the user's specifications given in the pre-processor block.
b) Calculate the levels of relative humidity and CO_2 in all rooms of the building according to a scale from 1 to 5, as explained in the post-processor sub-section.
c) Calculate HCHO and $PM_{2.5}$ exposure levels for all occupants of the building according to a scale from 1 to 5, as explained in the post-processor sub-section.

Post-processor block

The global performance of a ventilation system in HEAVENLY is defined by the most unfavorable grade between the grades resulting from two indicators: the energy efficiency (EE) indicator and the indoor air quality (IAQ) indicator.

The objective of the post-processor block is therefore to treat the processor block outputs, calculate the EE and IAQ indicators as defined below, and indicate the global performance for each set of user-tailored building-ventilation systems.

2.3 Indoor Air quality indicator

The IAQ considers the concentrations of humidity (H_2O) and three contaminants found within buildings: carbon dioxide (CO_2), formaldehyde (HCHO), and fine particulate matter ($PM_{2.5}$). The formulation of this indicator primarily adheres to the requirements outlined in NF EN 16798-1:2019 [12] for humidity and each specific contaminant. As per NF EN 16798-1:2019 [12] ventilation systems can be designed to achieve levels of environmental air quality that align with four distinct categories, as detailed in Table 3.

Table 3. Categories of indoor environmental quality [12].

Category	Level of expectation
IEQ_I	High
IEQ_{II}	Medium
IEQ_{III}	Moderate
IEQ_{IV}	Low

Hence, the criteria for humidity and pollutants can differ based on the expected level of air quality in a specific space, as outlined in Table 4.

Table 4. Humidity, CO_2, $PM_{2.5}$, and formaldehyde requirements [13].

Pollutant	Category	Reference value			Reference period
		Living room/others	Rooms	Workspace	
Humidity	IEQ_I	30% - 50% et <12g/kg			-
	IEQ_{II}	25% - 60% et <12g/kg			
	IEQ_{III}	20% - 70% et <12g/kg			
	IEQ_{IV}	20% - 70% et <12g/kg			
CO_2 [ppm]	IEQ_I	<550	<380	<350	
	IEQ_{II}	<800	<550	<500	
	IEQ_{III}	<1350	<950	<800	
	IEQ_{IV}	<1350	<950	-	
$PM_{2.5}$ [µg/m^3]	-	<10			annual average
		<25			24-hour average
HCHO [µg/m^3]		<100			average over 30 min

The reference values for humidity and CO2 are associated with the room, whereas the reference values for PM2.5 [1] and formaldehyde [14] are linked to the occupants' exposure i.e. the time spent in each room. Note that PM2.5 exposure limit values have been reduced recently to 5 (annual) and 15 (24hr) µg/m³ by WHO, those values will be used in future assessments.

Using the normative requirements delineated in Table 4 and allowing for acceptable deviations of 3% and 5% (see Table 5), a 5-level scale has been devised for humidity and each pollutant (CO_2, $PM_{2.5}$, and HCHO), in order to identify the level of pollution within buildings. The resulting 5-level scale for humidity is depicted in Table 6.

Table 5. Acceptable deviation corresponding to 3% and 5% of the time [12].

		Daily [min][1]	**Weekly[h]**	**Monthly [h]**	**Annually[h]**
% of total hours	3 %	45	5	22	259
	5 %	75	9	26	432
% of working hours	3 %	15	1	5	61
	5 %	30	2	9	108

Table 6. 5-level scale for humidity.

IAQ level	**Humidity**[1]	**Acceptable deviation (AD)**
	Relative (RH)	**% of the total number of hours or % of the number of working hours**
Excellent	>30% - <50%	AD < 3%
Good	>25% - <60%	AD < 3%
Acceptable	>20% - <70%	AD < 3%
Bad	>20% - <70%	AD < 5%
Very bad	>20% - <70%	AD > 5%

[1] *It is advisable to restrict the absolute humidity to 12g/kg [13]*

The sub-index for each pollutant and the overall IAQ index for the entire building are determined using the methodology outlined in Figure 4. In the context of residential collective buildings, pollutant sub-indexes, as well as a global IAQ index, can also be indicated at the dwelling level.

As depicted in Figure 4, the global indoor air quality indicator for the entire building is constructed based on the most unfavorable sub-index [15] among the sub-indices for humidity, CO_2, $PM_{2.5}$, and HCHO.

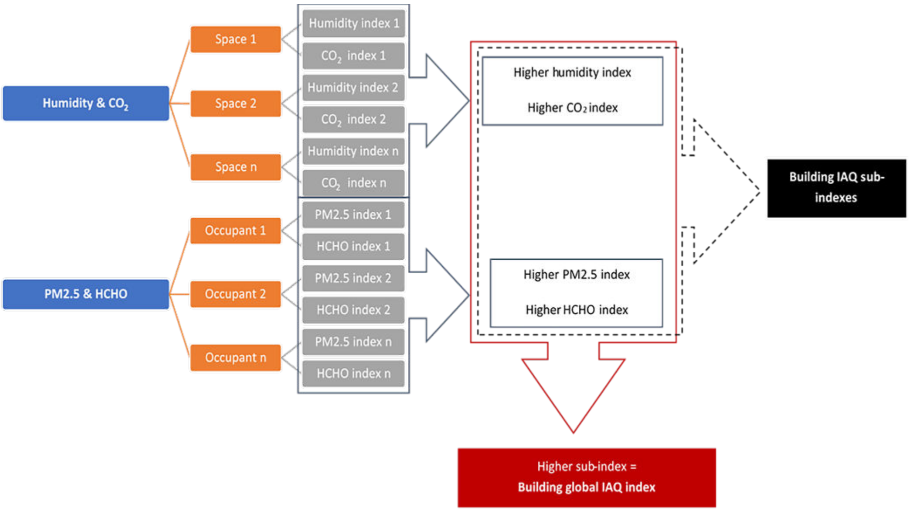


Fig. 3. Methodology for determining the IAQ level in a building: global and by pollutant.

2.4 Energy efficiency indicator

The EE indicator (BEP) takes into account: 1) the energy consumed by fans and 2) the energy consumed due to thermal losses related to air renewal.

Therefore, the resulting annual energy consumption [Wh], in terms of primary energy, is expressed by:

$$EP = \sum_{t=0}^{t=t_{ht}} \left(\frac{P_{th}}{3.6} + 2.5 P_{elec} \right) \Delta t \tag{1}$$

with t_{ht} $[h]$ being the number of hours of the heating season, Δt [h] the simulation time step, P_{elec} [W] the electric fan power, and P_{th} [kJ/h] the thermal power due to air renewing thermal losses.

The thermal power due to air renewal thermal losses, P_{th} [kJ/h], being related to “non-intentional” ventilation, i.e., infiltrations and airflow patterns through opening windows, opening doors and intakes, and to the "intentional" ventilation, i.e., the airflow patterns between outdoor and indoor environments provided by mechanical equipment, it is calculated based on both contributions:

$$P_{th} = \sum_{room\ i} \left(P_{vent,i} + P_{inf,i} \right) \tag{2}$$

where $P_{inf,i}$ [kJ/h] stands for the infiltration gains and $P_{vent,i}$ [kJ/h] for the ventilation gains of room i, given by:

$$P_{vent,i} = \rho C_p Q_{vent,i} \left(T_{sp,i} - T_{in,i} \right) \tag{3}$$

$$P_{inf_i} = \rho C_p Q_{inf,i}(T_{out} - T_{in,i}) \tag{4}$$

with ρ [kg/m^3] and C_p [kJ/(kg.K)] being respectively the density and the specific heat of the air, T_{sp} $[K]$ the supplied air temperature, $Q_{inf,i}$ [m^3/h] and $Q_{vent,i}$ [m^3/h] the airflow rate by infiltrations and by mechanical ventilation respectively.

The energy performance of non-conditioned residential buildings can then be assessed by comparing the energy consumed on ventilation for the building being tested, EP [Wh], with that for the corresponding reference building, EP_{ref} [Wh], according to a 5-level scale of Table 7.

The energy consumption of a reference building equipped with a balanced ventilation system is defined via TRNSYS-CONTAM calculations for each boundary condition indicated in Table 2, considering the following assumptions: class of conduit tightness: B, control mode: always on, fan efficiency: 80%, filters' efficiency class: B [16] and heat exchanger efficiency: 70%.

Table 7. Building energetic performance level.

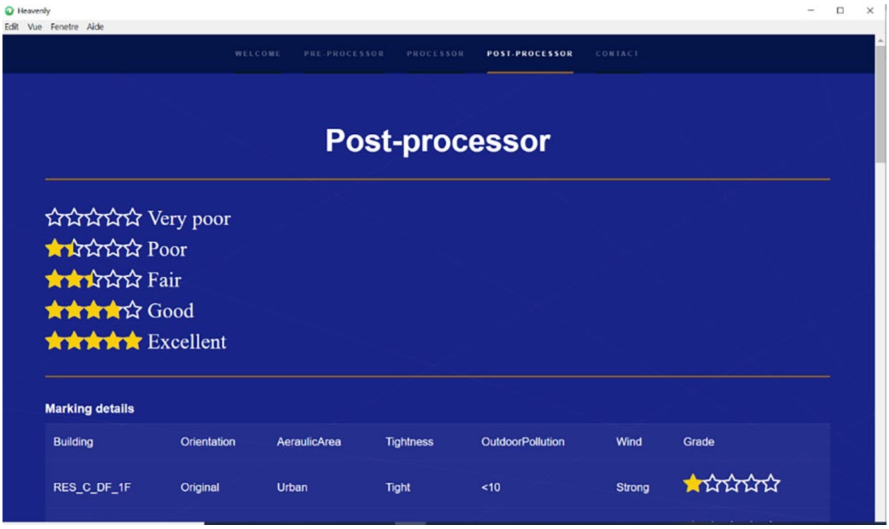
BEP level	$\boldsymbol{BEP = \frac{EP}{EP_{ref}}}$ [−]
5. Excellent	BEP ≤ 0.825
4. Good	0.825 < BEP ≤ 0.875
3. Acceptable	0.875 < BEP ≤ 0.925
2. Bad	0.925 < BEP ≤ 0.975
1. Very bad	0.975 < BEP ≤ 1.025

3. Results and discussion

To show the applicability of HEAVENLY, the results for a two-story residential building equipped with a balanced ventilation system with pressure-controlled extraction vents are presented.

As illustrated in Figure 4, the global performance grades are displayed for the user in the post-processor window for each configuration indicated in Table 2, according to a 5-level star scale. It can be inferred from Figure 4 that the balanced ventilation system performs poorly in the indicated operation conditions since they have a 1-star grade for global performance.

Results for a specific configuration are also available regarding the grades associated with the EE and IAQ indicators (Figure 5a), with the latter being detailed by type of pollutant (Figure 5b). According to Figure 5, the balanced ventilation system with pressure-controlled outlets operating under the boundary conditions corresponding to case #13 (Table 2) demonstrates excellent energy efficiency but poor indoor air quality. Specifically, Figure 5b reveals that the suboptimal indoor air quality is attributed to elevated levels of $PM_{2.5}$ and formaldehyde (HCHO) pollutants. However, in terms of humidity and CO_2, IAQ levels are assessed as excellent and good, respectively.



Post-processor

☆☆☆☆☆ Very poor
⯪☆☆☆☆ Poor
★★⯪☆☆ Fair
★★★★☆ Good
★★★★★ Excellent

Marking details

Building	Orientation	AeraulicArea	Tightness	OutdoorPollution	Wind	Grade
RES_C_DF_1F	Original	Urban	Tight	<10	Strong	★☆☆☆☆

a)

Building	Orientation	AeraulicArea	Tightness	OutdoorPollution	Wind	Grade
RES_C_DF_1F	Original	Urban	Tight	<10	Strong	★☆☆☆☆
RES_C_DF_1F	Original	Urban	Tight	<10	Low	★☆☆☆☆
RES_C_DF_1F	Original	Urban	Tight	>20	Strong	★☆☆☆☆
RES_C_DF_1F	Original	Urban	Tight	>20	Low	★☆☆☆☆
RES_C_DF_1F	Original	Urban	Permeable	<10	Strong	★☆☆☆☆
RES_C_DF_1F	Original	Urban	Permeable	<10	Low	★☆☆☆☆
RES_C_DF_1F	Original	Urban	Permeable	>20	Strong	★☆☆☆☆
RES_C_DF_1F	Original	Urban	Permeable	>20	Low	★☆☆☆☆
RES_C_DF_1F	Original	Semi-Urban	Tight	<10	Strong	★☆☆☆☆

b)

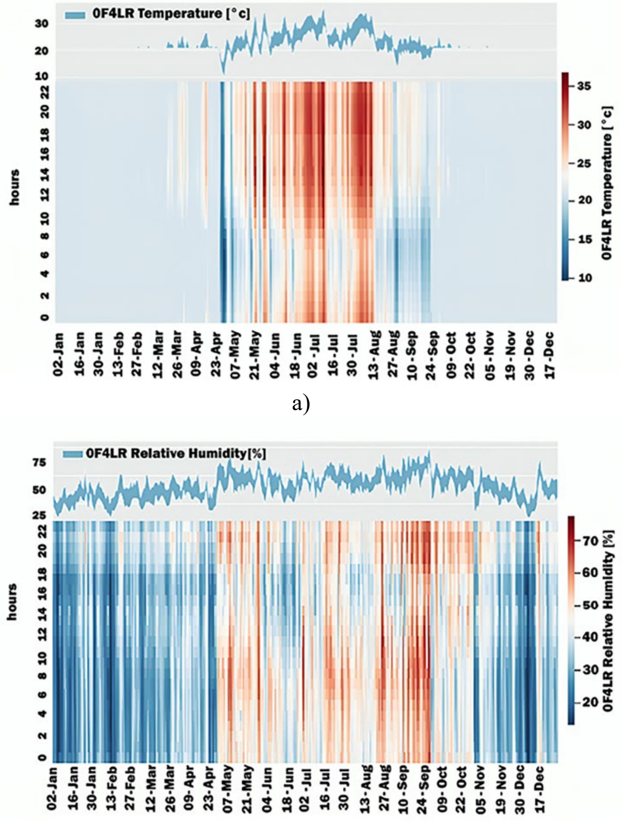
Fig. 4. Post-processor window: a) Global performance indicator - 5-level start scale for and b) Archetypes' global performance grades - a two-story residential building equipped with a balanced ventilation system with pressure-controlled outlets.

Detailed information about temperature, humidity, pollutant concentration, and airflow rates at the room level can also be provided by the tool for each configuration of the building test bed. The evolution of temperature and relative humidity over a year in the living room of the 4-bedroom flat located on the ground floor is illustrated in Figure 6. Figure 6a shows that the heating system, controlled by means of a proportional controller based on the outside air temperature, can maintain the temperature of the concerned living room at around 20°C during winter. Figure 6a also shows that, since the building is non-conditioned and no overnight cooling is programmed, the temperature in this room can be higher than 25°C, mostly in the afternoons and nights, during quite long periods in the summer season.

a) b)

Fig. 5. Post-processor window: a) EE and IAQ grades and b) IAQ grade by type of pollutant for a specific configuration.

Concerning humidity, Figure 6b indicates that the relative humidity in the referred living room is most of the time maintained between 25% and 50%, which agrees with NF EN 16798-1:2019 requirement for the IEQ$_{II}$ category (see Table 3 and Table 4). Short periods of very low relative humidity (< 20%) can however be observed during wintertime.

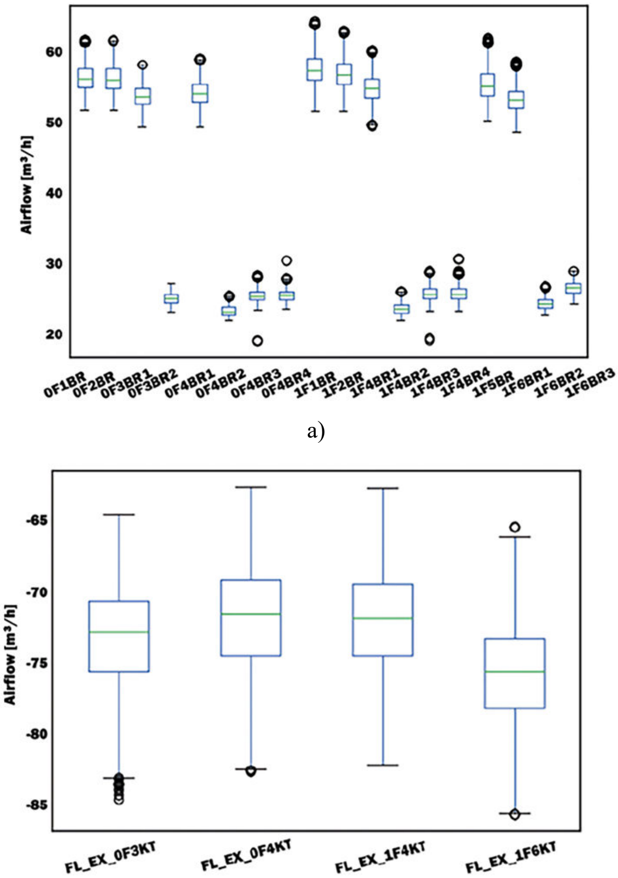


a)

b)

Fig. 6. Temperature (a) and Relative humidity (b) distributions for the 4-bedroom flat located on the ground floor.

The airflow rates supplied in the bedrooms and extracted in the kitchens of the two-story building are shown in Figure 7. Two levels of supply airflow rates can be observed in Figure 7a. A first level, between 50 m^3/h and 60 m^3/h, for double rooms, and a second level, between 20 m^3/h and 30 m^3/h, for single rooms. Dispersion is quite limited but tends towards the upper limit. As illustrated in Figure 7b, the extraction vents of the kitchens operate with airflow rates between 65 m^3/h and 85 m^3/h, presenting therefore a larger dispersion than the supply inlets that also tend towards the upper limit.



a)

b)

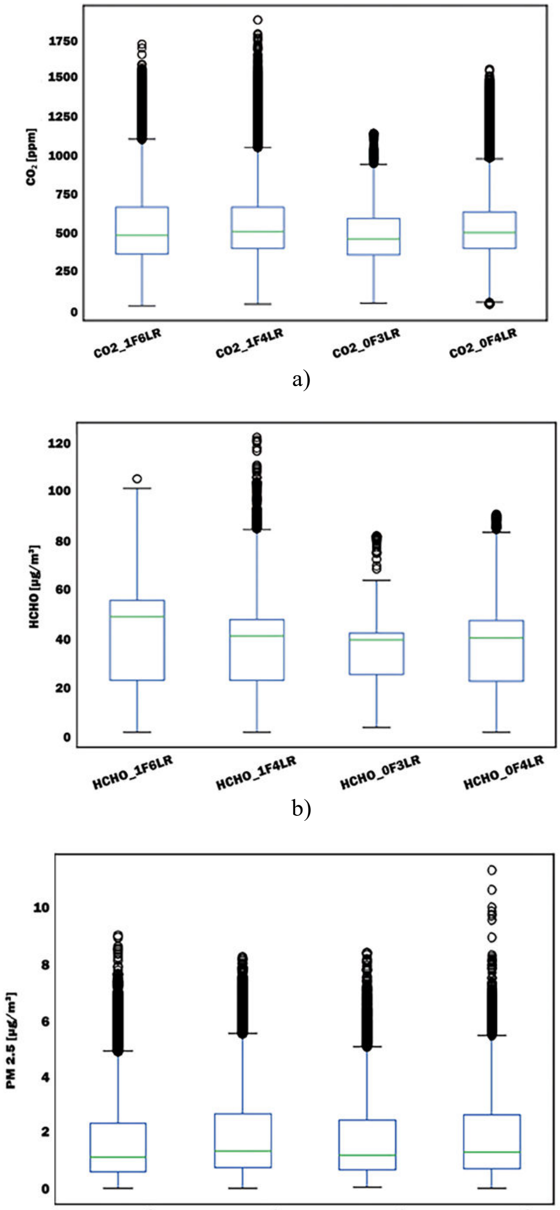
Fig. 7. Airflow rates supplied in the bedrooms (a) and extracted in the kitchens (b).

With respect to the pollutant concentrations, Figure 8 shows the concentrations of CO2, formaldehyde, and PM2.5 in different living rooms of the two-story building in question. According to Figure 8a, the level of CO2 in the living rooms is mainly maintained below 800 ppm as requested for the IEQII category (see Table 3). Nevertheless, except for the 0F3LR living room, the level of CO2 could be higher than 1350 ppm, which is the limit requested for the IEQIV category corresponding to a low level of environmental air quality.

Like CO_2, the level of formaldehyde in the living rooms is mainly kept below 100 μg/m^3 (Figure 8b), complying with NF EN 16798-1:2019. The only exception is the living room of the 4-bedroom flat located on the top floor (1F4LR), where this limit value is exceeded several times and, depending on the duration, could lead to a poor assessment of the indoor air quality for the entire building.

Regarding particulate matter pollution, in spite of the large dispersion, the $PM_{2.5}$ concentration found in the different living rooms (Figure 8c) is always below 25 µg/m^3, as requested by NF EN 16798-1:2019.

These different results illustrate the potential of HEAVENLY as a support tool for improving the performance of ventilation systems and/or their components, since it provides comprehensive insights about their operation during realistic conditions.



a)

b)

c)

Fig. 8. Concentration in the living rooms regarding CO_2 (a) Formaldehyde (b) and $PM_{2.5}$ (c).

4. Conclusions

The presented TRNSYS-CONTAM co-simulation tool, named HEAVENLY, offers a comprehensive approach to evaluating the performance of ventilation systems in residential buildings. The study focused on balanced ventilation systems in two-story multifamily buildings, considering energy efficiency and Indoor Air Quality indicators.

The methodology outlined in the paper, involving the building test bed and graphical user interface, provides a framework for assessing ventilation system performance. The user-adjustable parameters and influential factors allow for a thorough examination of diverse operational conditions.

The IAQ indicator considers humidity, CO_2, $PM_{2.5}$, and formaldehyde concentrations, aligning with recommendations. The 5-level scale for IAQ, with criteria based on guideline values, offers a nuanced evaluation of pollution levels within buildings.

The applicability of HEAVENLY was demonstrated for a two-story residential building with a balanced ventilation system. The global performance grades, presented on a 5-level star scale, indicate the system's performance under different boundary conditions.

Overall, HEAVENLY is a valuable tool for assessing the interdependent effects of temperature, moisture, airflow, and energy use on contaminant transport in buildings. It offers a practical means of evaluating energy efficiency and IAQ, enabling informed decision-making in the design and operation of ventilation systems for residential buildings.

Nomenclature

EP	Annual energy consumption, Wh
t_{ht}	Number of hours of the heating season, *h*
Δt	Simulation time step, *h*
P_{elec}	Electric fan power, *W*
P_{th}	Thermal power due to air renewing thermal losses, *kJ/h*
$P_{vent,i}$	Ventilation gains for room i, *kJ/h*
$P_{inf,i}$	Infiltration gains for room i, *kJ/h*
P	Density of air, kg/m^3
C_p	Specific heat of air, *kJ/(kg.K)*
T_{sp}	Supplied air temperature, *K*
$Q_{inf,i}$	Airflow rate by infiltrations for room i, m^3/h
$Q_{vent,i}$	Airflow rate by mechanical ventilation for room i, m^3/h

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