Impact of the building airtightness and natural driving forces on the operation of an exhaust ventilation system in social housing in Chile.

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ABSTRACT

Chile has 1,626 social housing complexes with a total of 350,880 dwellings. Several studies have demonstrated a low thermal performance and high air permeability of the envelope of social houses throughout the country, causing surface condensation on walls, high heat losses in winter and low levels of thermal comfort for their occupants. The presence of high levels of indoor pollutants and/or indoor humidity has also been observed, causing respiratory and cardiovascular diseases in the occupants. This highlights the urgent need to renovate social housing in Chile to achieve better standards of habitability, well-being and quality of life for its inhabitants. Current retrofitting programs for social housing focus mainly on reducing heat losses and condensation problems inside the dwellings, although they also include the installation of a mechanical exhaust ventilation system with natural air inlets. However, there is currently no evaluation of the performance of such ventilation systems in the country. In fact, we do not know if the natural air inlets provide the required airflow rates to the different living areas of the dwelling and how the airflow rates are affected by the airtightness of the building envelope and the natural external driving forces (wind and thermal buoyancy).

This study has evaluated the performance of a commonly used mechanical exhaust ventilation system in a representative social house in Chile, for two sets of climatic data, using the airflow and contaminant transport calculation software CONTAM. It has highlighted the significant effect of the building airtightness and the natural driving forces, mainly the wind effect, on the performance of the ventilation system. For the house investigated in this research and considering a n_{50}-value of $10h^{-1}$, the supplied airflow in one of the bedrooms is drastically reduced to almost the half of the value obtained for a perfectly airtight house when all the interior doors are open. When the doors are closed, the effect is even more pronounced. The decrease in the supplied airflows in the bedrooms leads to a significant increase in the CO_2-exposure of the occupants. In the most unfavourable case analysed – n_{50} of $10h^{-1}$ with closed interior doors – the child of the family spent only 35% of his time in an indoor environment with a CO_2 concentration below 950 ppm.

These results emphasize the need to work also on improving the airtightness of social housing for a better operation of the exhaust ventilation system. They contribute to a better knowledge of the performance of the ventilation systems currently installed in the renovation of social housing in Chile, as well as to the identification of ways to improve these systems so that they can guarantee sufficient indoor air quality to the occupants.

KEYWORDS

Mechanical exhaust ventilation, indoor air quality, social housing, airtightness, wind pressure.

1 INTRODUCTION

According to the 2017 census, the total number of dwellings in Chile reaches 6.5 million. It is estimated that only 2% of the buildings meet minimum thermal performance standards (OECD, 2014) and 66% have thermal comfort problems (RedPE, 2019). Social housing is not an exception. Chile has 1,626 social housing complexes built between 1936 and 2016, with a total of 350,880 dwellings. Several studies have demonstrated a low thermal performance and high air permeability of the envelope of social housing throughout the country, causing surface condensation on walls, high heat losses in winter and low levels of thermal comfort for their occupants (de la Barrera et al., 2021). The presence of high levels of indoor pollutants and/or indoor humidity has also been observed, causing respiratory and cardiovascular diseases in the occupants. Based on a post-occupancy evaluation carried out in social housing complexes built in 2013 in the city of Concepción, Gonzalez-Caceres et al. identified 76 apartments affected by damage produced by high moisture levels out of the 400 apartments evaluated. Inadequate ventilation was identified as one of the multiple causes of this situation (Gonzalez-Caceres et al., 2019).

This highlights the enormous challenge and need to retrofit social housing in Chile to achieve better standards of habitability, well-being and quality of life for its inhabitants. Current retrofitting programs for social housing focus mainly on reducing heat losses and condensation problems inside the dwellings, although they also include the installation of a mechanical exhaust ventilation system with natural air inlets in accordance with the Chilean Ventilation Standard NCh3309 (INN, 2022). However, there is currently no evaluation of the performance of such ventilation systems in the country. In fact, we do not know if the natural air inlets provide the required airflow rates to the different living areas of the dwelling and how the airflow rates are affected by the airtightness level of the building envelope and the natural external driving forces (wind and thermal buoyancy).

This study aims to evaluate by simulation the performances of a commonly used mechanical exhaust ventilation system in a representative social housing in Chile. Specifically, the effects of the airtightness level of the building envelope and the natural driving forces on the indoor air quality are assessed using the airflow and contaminant transport calculation software CONTAM for two different outdoor climate data sets.

2 METHODS

2.1 House description

The investigated social house is a real one-story detached dwelling with a total floor area of 43m², which is typical for a Chilean social house. The house has a living-dining room with an open kitchen, two bedrooms and a bathroom, as shown in Figure 1. Bedroom 1 is assumed to face north.

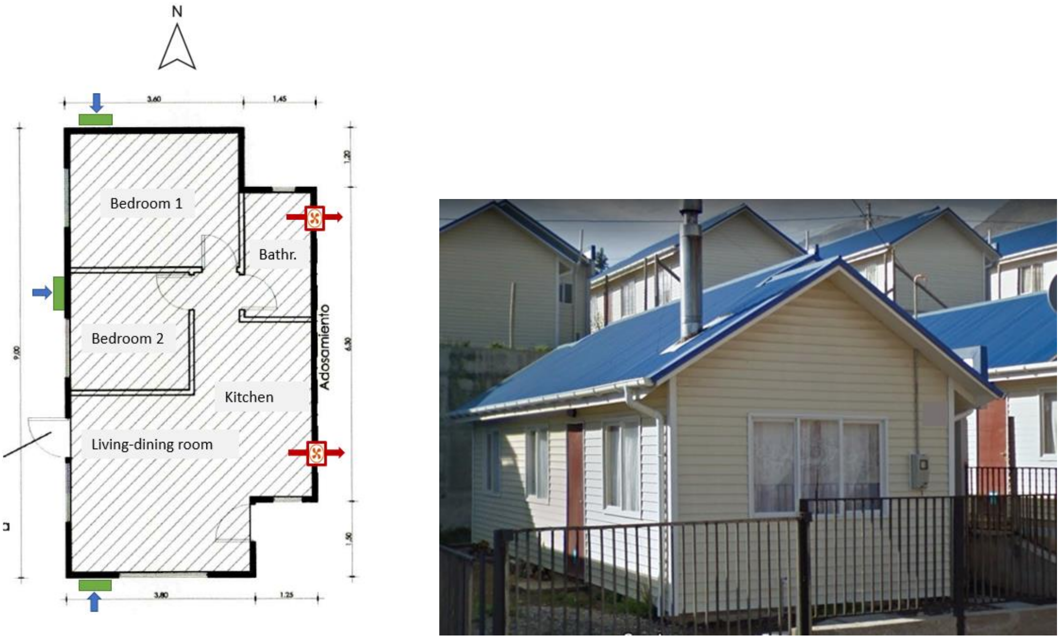

Figure 1: Plan and picture of the house investigated in this study.

2.2 Climatic data

The performance of the exhaust ventilation system was evaluated for two sets of climatic data (IWEC) corresponding to the two main cities in Chile: Santiago and Concepción. The wind speed in the IWEC data file for Santiago was modified to better match the data provided by the *General Directorate of Civil Aeronautics* for the period 2018-2022. Santiago, the capital city, is located in the central zone of Chile (~33°S), in the Central Valley, while Concepción is a coastal city located 500 km further south (~37°S). Both cities have similar average daily temperatures in winter, but different wind speeds and directions. The wind roses are shown in Figure 2 for the heating period considered in this study: from May 1 till September 30.

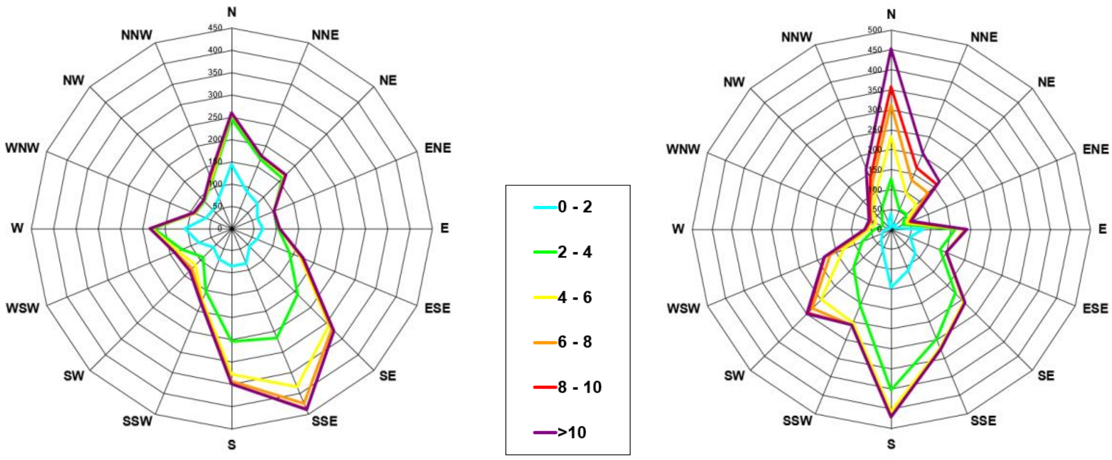

Figure 2: Wind roses for the Santiago (left) and Concepción (right) climates (wind speed in m/s).

2.3 Exhaust ventilation system

A mechanical exhaust ventilation system with constant airflow is assumed. Each bedroom and the living room are equipped with supply vents (also called 'inlet vents' or 'trickle vents') sized to provide 25 m³/h per person (category II in EN16798-1) (CEN, 2019) at 10Pa, considering two adults in the master bedroom, two children in the second bedroom and three people in the living room. The air is exhausted in the bathroom and in the kitchen with a total airflow equal to the total airflow supplied by the vents, in order to have a balanced ventilation system. As a result, the supplied airflow rates are: 50 m³/h for bedroom 1, 50 m³/h for bedroom 2, 76 m³/h for the living room; the exhaust airflow are: 50 m³/h in the bathroom and 126 m³/h in the kitchen. The location of the supply vents and exhaust fans is shown in Figure 1.

2.4 Model and assumptions

The simulations in this study used the multizone indoor air quality and ventilation analysis program CONTAM to evaluate the airflows, contaminant concentrations, and occupant exposure in the investigated building. It requires numerous input data to represent the elements of the building model, including air leakage paths (cracks, windows, doors), ventilation system elements (fans, vents), contaminant sources, etc. The main input variables are given below. A 5-minute timestep was used for the calculation and 15 minutes for the outputs.

In the absence of a detailed study of the distribution of air leakage in Chilean houses, it was assumed that air leakage is uniformly distributed over all vertical walls exposed to the ambient environment. Airflow paths were located at 3 different heights of each wall - top, middel and bottom - and modelled using the power law model with a flow exponent of 0.65. Three levels of envelope airtightness, expressed as air exchange rate at 50Pa (n_{50}-values), were considered: $10h^{-1}$ corresponding to the mean value for recently built houses in Chile, $5h^{-1}$, which is the current requirement applied in some cities where *Air Quality Management Plans* are in force, and $0h^{-1}$ as an ideal case. Interior doors were modelled based on a two-way flow model when open, and a 1cm high air gap under the door when closed. Supply vents were modelled as a one-way flow using a powerlaw with exponent n equal to 0.5. Figure 3 illustrates the developed CONTAM model.

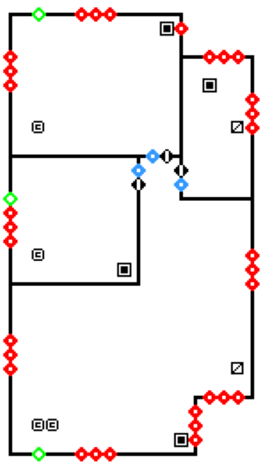

Figure 3: CONTAM model.

The wind pressure on each building surface was calculated using wind pressure coefficients from the Swami and Chandra model (Florida Solar Energy Center, 1987) and a wind speed

modifier coefficient to account for 'suburban' terrain. A constant indoor air temperature of 20°C was assumed.
The carbon dioxide emission rate from human respiration was calculated according to Persily (Persily & de Jonge, 2017), considering two 40-year-old adults, and 5- and 10-year-old children. The average values were: 18 L/h and 14L/h for the adults and children when they are awake, and 12 L/h and 8 L/h when they are asleep.
Due to the lack of data at the national level, a daily occupancy profile was developed, specifying the location and activity of each household member in the dwelling at each timestep, as shown in Figure 4. A permanent occupation of the dwelling by family members was assumed.

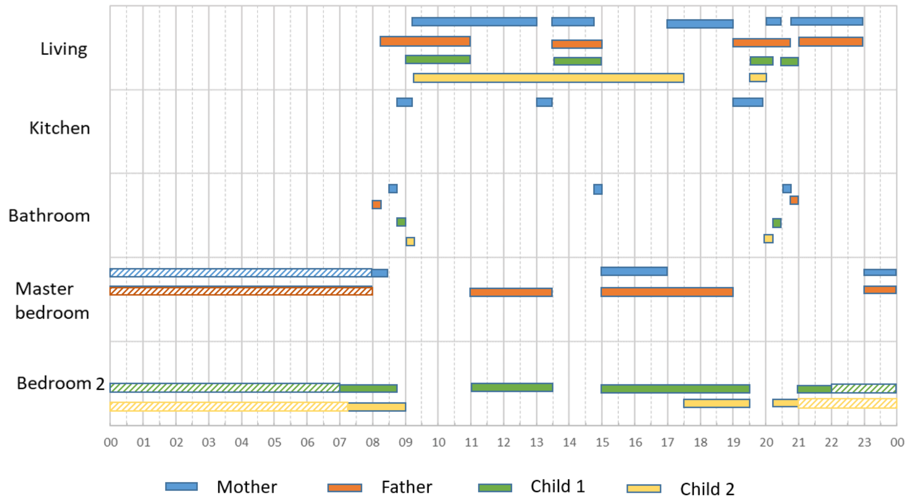

Figure 4: Occupancy profile.

2.5 Indoor Air Quality criteria

The evaluation of the performance of the ventilation system is based on the outdoor (fresh) airflow rates (AR) obtained in each room of the dwelling and the occupant's exposure to carbon dioxide. Specifically, two CO_2-related indicators commonly used in performance-based approaches were used in this study:

- The cumulative exceeding exposure above 1000 ppm, assuming an outdoor concentration of 400 ppm
- The percentage of time spent in four CO_2 concentration classes (EN16798-1): < 950 ppm, 950-1200 ppm, 1200-1750 ppm, > 1750ppm.

Note: All average AR values mentioned in this paper are calculated per room based on all hours (occupied and unoccupied) of the heating period.

3 RESULTS AND DISCUSSION

3.1 Airflow rates

Santiago

Figure 5 illustrates the average AR over the heating period for the living room ('Liv'), the master bedroom ('bedr.1') and the children's bedroom ('bedr.2'). When all interior doors are open, the average ARs are very close to the design values for a perfectly airtight house (n_{50}=0 h^{-1}): 49 m³/h for both bedrooms and 77 m³/h for the living room. The instantaneous AR (15-minute timestep) over the entire heating period fluctuates around the average values due to the effects of natural driving forces, mainly the wind forces, as shown in Figure 6. The effect of air infiltration (n_{50}=5 and 10 h^{-1}) through the building envelope is different depending on the type of room. The living room is more affected by air infiltration than the bedrooms due to its higher heat losses area. In addition, the wind coming mainly from the south and southeast generates an overpressure on the facades of the living room, which explains the increase of the total fresh airflow with respect to the n_{50} for this room. On the contrary, the air infiltration for bedroom 2 represents a lower fraction of the total fresh air (infiltration + ventilation), and this room is mostly exposed to under pressure due to the wind effects. Consequently, the total outdoor air supply is drastically reduced compared to the design value: from 50 m³/h to 28 m³/h on average, when n_{50}=10 h^{-1}. A higher variation of the instantaneous AR is observed for a leaky building than for an airtight one (Figure 7 versus Figure 6).

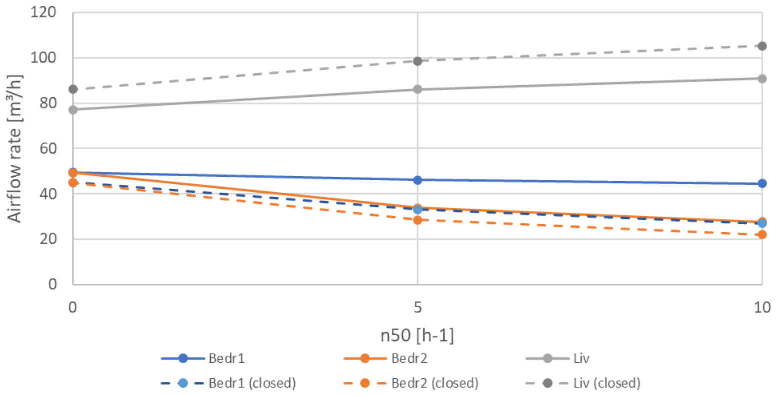

Figure 5: Average airflow rates in the living room and bedrooms over the heating period. Solid lines indicate the case with open interior doors and dotted lines the case with closed doors.

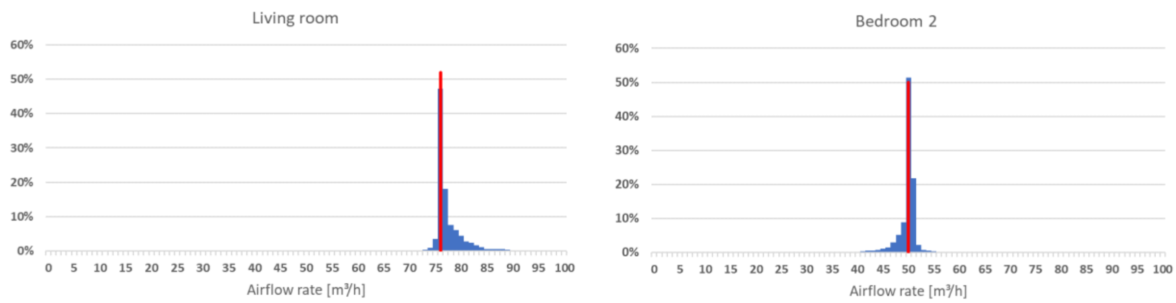

Figure 6: Frequency distribution of the outdoor airflow rates in the living room (left) and bedroom 2 (right). Perfectly airtight house, open interior doors. Vertical red line indicates the design airflow rate.

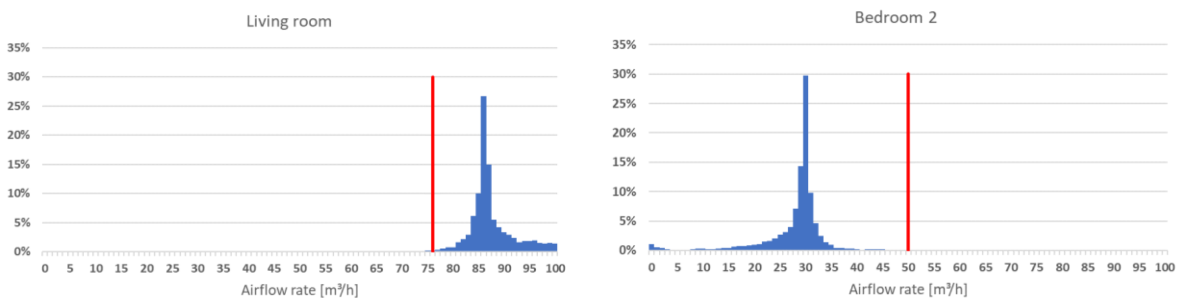

Figure 7: Frequency distribution of the outdoor airflow rates in the living room (left) and bedroom 2 (right). Leaky house (n_{50}=10h^{-1}), open interior doors. Vertical red line indicates the design airflow rate.

When all the interior doors are closed, the above effects are further accentuated. For the house under analysis, the interior doors of the two bedrooms create an additional air resistance in comparison with the living room, which facilitates the supply of air through the openings of the living room (supply vent and cracks). The average AR for bedroom 2 is only 22 m³/h at n_{50}=10 h^{-1}, less than half of the nominal airflow.

Concepción

Figure 8 shows the average AR over the heating period for the living room, master bedroom and children's bedroom. The trends observed for the living room and bedroom 2 for the climate of the city of Concepción are similar to those of the city of Santiago. However, the average ARs are higher for bedroom 1, because it is more exposed to winds – sometimes of high speed – coming from the north.

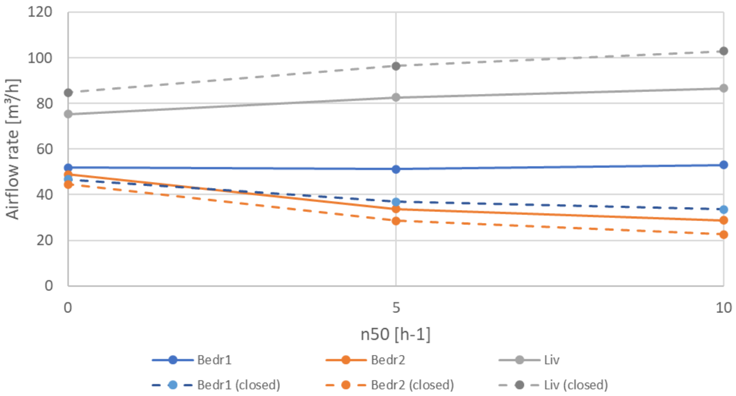

Figure 8: Average airflow rates in the living room and bedrooms over the heating period. Climatic data of Concepción. Solid lines indicate the case with open interior doors and dotted lines the case with closed doors.

In the cases simulated so far, a fixed orientation was assumed with the bedroom 1 facing north. Additional simulations were performed for other building orientations. Figure 9 illustrates the effect of the building orientation on the average AR in each room. Variations of 22%, 38%, and 7% are observed for Bedroom 1, Bedroom 2, and Living room, respectively.

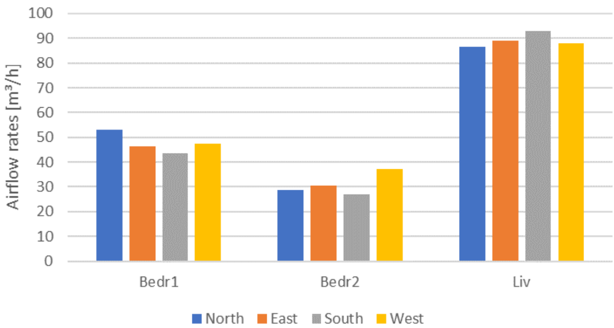

Figure 9: Effect of the building orientation on the average airflow rates. Orientation indicated in the legend of the chart refers to the bedroom 1 orientation.

3.2 CO_2-based indicators

Only the results for Santiago are presented, but the results are similar for the climate of Concepción. The cumulative exceeding exposure above 1000 ppm during the entire heating period is given in Figure 10 for the father and child_1. We also plotted the percentage of time spent in the four CO_2 concentration classes specified in EN16798-1 for the three levels of airtightness, with the interior doors open and closed (Figure 11).

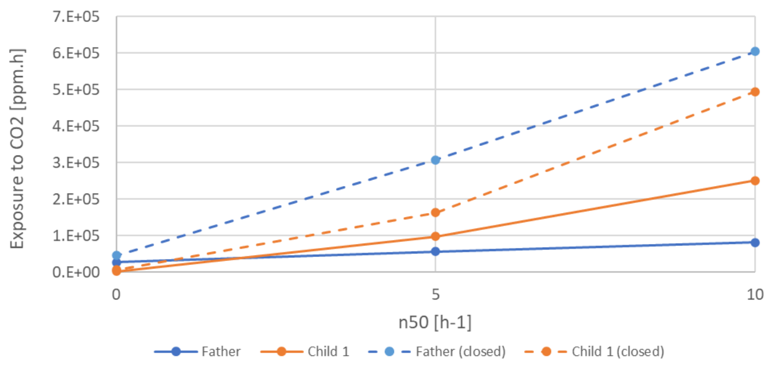

Figure 10: Cumulative exceeding exposure to CO_2 for the father and child_1.

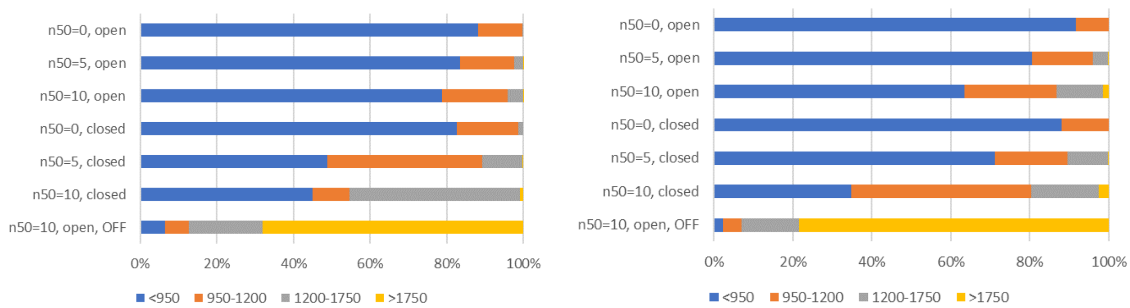

Figure 11: Percentage of time spent in four CO_2 concentration (ppm) classes for the father (left) and child_1 (right).

The decrease of the supplied airflows in both bedrooms for a leaky house leads to a significant increase of the CO_2-exposure for both father and child_1. The highest exposure values are observed for the least airtight house (n_{50}=10h^{-1}) with closed doors, which is consistent with the trends found for the airflows. In this case, the father and the child spent only 45% and 35% of their time, respectively, in an indoor space with a CO_2 concentration lower than 950 ppm, while the ventilation system was in continuous operation. On the other hand, a very good airtightness (n_{50}=0h^{-1} in our study) makes it possible to provide the design values of the airflows most of the time and, consequently, to maintain the CO_2 concentration below 950 ppm during 92% of the time for child_1 when the doors are open and 88% when they are closed. As a basis for comparison, the case of a poorly airtight house (n_{50}=10h^{-1}) with open doors was also considered, but this time without any exhaust ventilation system (bottom bar in the figure). In this case, the indoor air quality is not guaranteed at all, as the occupant is exposed to CO_2 concentrations above 1750 ppm most of the time.

4 CONCLUSION

This study has shown the significant effect of the building airtightness and the natural driving forces, mainly the wind effect, on the performance of a mechanical exhaust ventilation system with constant airflow rate in a representative social house in Chile. For the house investigated in this research and considering a n_{50}-value of $10h^{-1}$, the supplied airflow in the living room is increased by 17% on average compared to a perfectly airtight house, while in one of the bedrooms it is drastically reduced to almost the half of the value. If all the interior doors in the house are closed, the effect is even more pronounced. The decrease in the supplied airflows in the bedrooms leads to a significant increase in the CO_2-exposure of the occupants. In the most unfavourable case analysed – n_{50} of $10h^{-1}$ with closed interior doors – the child of the family spent only 35% of his time in an indoor environment with a CO_2 concentration below 950 ppm. These results underline the need to work also on improving the airtightness of social houses for a better operation of the exhaust ventilation system.

5 ACKNOWLEDGEMENTS

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