Performance evaluation of humidity controlled decentralized ventilation systems in social housing in Chile

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ABSTRACT

More than 70% of the dwellings in Chile were built before 2000, when the use of thermal insulation in the roofs of residential buildings became mandatory. This explains why less than 2% of dwellings are considered energy efficient. Social housing is no exception. Several studies have shown poor thermal performance of the envelope of social housing throughout the country, with low levels of thermal comfort and indoor air quality that affect the health of its occupants. Retrofitting programs for social housing launched by the government in recent years have implemented more rigorous thermal standards, along with the installation of humidity controlled decentralized mechanical exhaust ventilation systems. However, it is not known whether such ventilation system can effectively guarantee air quality in homes.

This study evaluated the indoor air quality and ventilation heat losses of a typical social house in Chile equipped with a humidity-controlled ventilation system using the airflow and pollutant transport calculation software CONTAM. It was shown that such a system does not at all guarantee the indoor air quality, especially in the bedrooms during the night hours. Several alternative ventilation systems and strategies were identified and evaluated. Two of them showed good performance in terms of indoor air quality while limiting ventilation heat losses, for the moderate and high occupancy profiles considered in this study. They include demand-based ventilation using CO_2 concentration detection. The first system is based on the extended cascade ventilation principle, while the second includes the addition of an exhaust system specific to bedrooms. They reduce the ventilation heat losses by about 32% and 37% on average, respectively, compared to a continuously operating ventilation system, while ensuring an equivalent level of indoor air quality.

By proposing better solutions than those currently used in social housing, this study will contribute to the development of public policies aimed at improving the comfort and health of social housing occupants while limiting the dwelling's energy use.

KEYWORDS

Mechanical exhaust ventilation, demand-based control, indoor air quality, ventilation heat losses, social housing.

1 INTRODUCTION

More than 70% of the dwellings in Chile were built before 2000, when the use of thermal insulation in the roofs of residential buildings became mandatory. This explains why, according to OECD figures, less than 2% of dwellings are considered energy efficient (OECD, 2014). Social housing is no exception. Several studies have shown that the thermal performance of the envelope of social housing is poor throughout the country, leading to problems of surface condensation on walls, high heat losses in winter and low levels of thermal comfort for their occupants (de la Barrera et al., 2021; Vives et al., 2023). In addition, social housing also has indoor air quality (IAQ) problems that affect the health of its occupants. The above shows the enormous challenge and the need to renovate existing housing in order to achieve adequate standards of habitability, better comfort, wellbeing and quality of life for its occupants. Retrofitting programs for social housing launched by the government in recent years have implemented more rigorous thermal standards, along with the installation of decentralized mechanical exhaust ventilation systems (MINVU, 2017). Exhaust fans in wet rooms are usually activated when the light is turned on, by means of a manual ON/OFF switch or based on the relative humidity level of the room.

Previous studies have shown that the control strategy based on relative humidity was less suited to maintain the IAQ compared to a constant flow exhaust ventilation (e.g. Laverge et al., 2011). Based on the analysis of monitoring data, Pecceu et al. concluded that relative humidity seemed to be a poor control variable for detecting people in demand-controlled ventilation (Pecceu et al., 2018). A comparison of different ventilation control algorithms showed that control based only on relative humidity in humid spaces was not effective (Caillou et al., 2014). However, to date, no study in Chile has shown the performance of this type of humidity-based control for the specific outdoor climates found in Chile and how it could be improved.

The aim of this study was to evaluate the IAQ and ventilation heat losses of a typical social housing unit in Chile equipped with the most common humidity-controlled decentralized ventilation system currently in use. In a subsequent phase, alternative ventilation strategies and solutions were proposed, evaluated, and compared with the base case solution. Given the importance of simple, robust and cost-effective ventilation solutions, especially for social housing, only relatively simple solutions based on existing decentralized ventilation systems were considered in this study. Such ventilation solutions are also easier to implement in renovation projects than more complex centralized systems. All systems were evaluated using the airflow and pollutant transport calculation software CONTAM.

2 METHODS

2.1 Description of the case-study

The dwelling under investigation is a one-story detached social house with a total floor area of 43m², which is typical for Chilean social houses. It consists of a living-dining room with an open kitchen, two bedrooms, and a bathroom, as shown in Figure 1. It is assumed that bedroom 1 faces north. The house is fitted with exhaust fans in wet rooms (bathroom, kitchen) that are activated when the light is turned on, by means of a manual ON/OFF switch or based on the relative humidity level of the room, and with supply vents in the dry rooms (living room and bedrooms) sized to provide 25 m³/h per person at 10Pa (category II in EN16798-1) (CEN, 2019). The total exhaust airflow is 176 m³/h, with 50 m³/h in the bathroom and 126 m³/h in the kitchen (Flamant et al., 2023). Figure 1 shows the location of the two exhaust fans and supply vents.

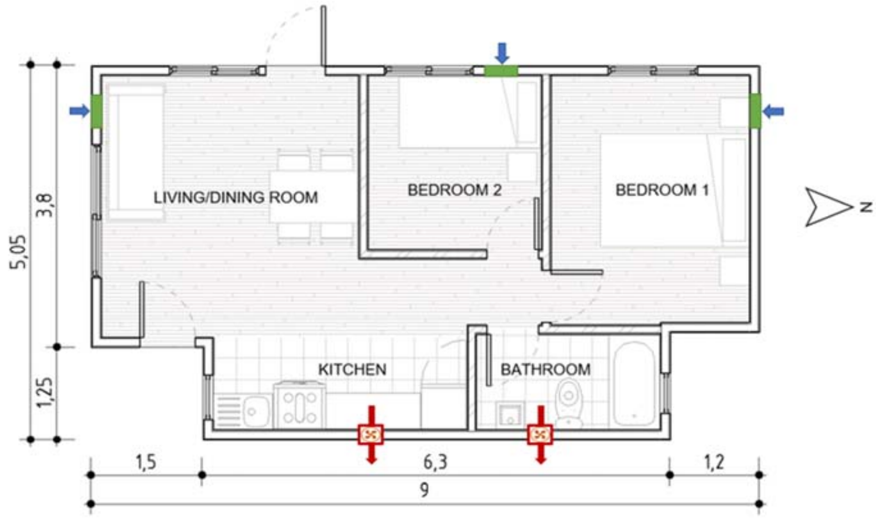

Figure 1: Layout of the house investigated in this study. Air inlets are pictured in green and exhaust fans in red.

2.2 Climatic data

This study considers two sets of climatic data (IWEC datafile) corresponding to the two main cities in Chile: Santiago and Concepción. Despite being classified under the same climate type 'Csb' according to the Köppen classification, the two cities exhibit clear differences. Santiago, located in the central valley, has a Mediterranean climate with mild temperatures. Concepción is a coastal town with a maritime climate characterised by heavy rainfall and high levels of air relative humidity during the winter. Table 1 presents the monthly average air temperature, air relative humidity and wind speed for the heating period considered in this study, which spans from May 1 to September 30. The average absolute humidity during this period is approximately 0.0054 kg/kg in Santiago and 0.0066 kg/kg in Concepción.

Table 1 : climatic data considered in this study

Month	Santiago			Concepción		
	Temp. [°C]	RH [%]	Wind sp. [m/s]	Temp. [°C]	RH [%]	Wind sp. [m/s]
May	12.8	61	2.4	11.3	88	3.1
June	8.5	70	1.8	9.7	88	3.2
July	8.4	75	1.7	9.2	86	3.9
August	10.1	67	2.4	10.1	84	4.3
September	13.2	64	2.7	10.8	80	4.1

2.3 Model and assumptions

To evaluate the performances of the ventilation systems and strategies considered in this study, simulations were performed using the multizone airflow network model CONTAM. A 5-minute timestep was used for the calculation and the outputs. 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. We assume an airtightness of the building envelope n_{50} of $5h^{-1}$, which is the

number of air changes per hour for a pressure difference of 50 Pa between indoor and outdoor. n_{50}=5 is the compulsory value for new and renovated houses in some cities in Chile where *Air Quality Management Plans* (PDA) are in force (Ministerio del Medio Ambiente, 2020). This value has also been recommended in the proposal to update the thermal building code in Chile (MINVU, 2020). The 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, middle and bottom - and modelled using the power law model with a flow exponent of 0.65. All internal doors are closed with an undercut of 1cm. Supply vents were modelled as a one-way flow using a power law with exponent n equal to 0.5. The indoor air temperature is set at 18°C in all rooms throughout the entire simulation period.
A family of 4 people is assumed considering two 40-year-old adults, and 5- and 10-year-old children. Occupants produce moisture by breathing and sweating according to their level of activity. Metabolism moisture emissions rates of 55 g/h for an awake adult, and 40 g/h for a sleeping adult were considered (CEN, 2006). Taking into account a 25% reduction in moisture production for children (Johansson et al., 2015), the following rates were used: 41 g/h for an awake child, and 30 g/h for a sleeping child. Based on a literature review, the quantity of water vapor generated by the different household activities is indicated in Table 2.

Table 2 : Total water vapor generation by the household activities

Activity	**Rate**	**Duration**	**Frequency**	**Total amount (g/day)**	**Location**
Shower	250 g/event	5 min/event	1 event/ pers./day	1000	Bathroom
Cooking	2380 g/day	60 min/day	3 meals, every day	2380	Kitchen
Dishwashing	450 g/day	25 min	3 washings/day (3 meals), every day	450	Kitchen

The carbon dioxide emission rate from human respiration is (Persily & de Jonge, 2017):

- Adult: 18 L/h for an awake person, and 12 L/h for a sleeping person
- Child: 14 L/h for an awake person, and 7 L/h for a sleeping person

Two daily occupancy profiles were developed, specifying the location and activity of each household member of the family in the dwelling every 15 minutes, as shown in Figure 2. The first one corresponds to a high (permanent) occupancy of the house, the other to a moderate occupancy. The two profiles were built by taking into account the '*Use of Time National Survey*' conducted in 2015 in Chile, which provided some activity data from a randomly selected group of 15,312 households (Molina et al., 2021).

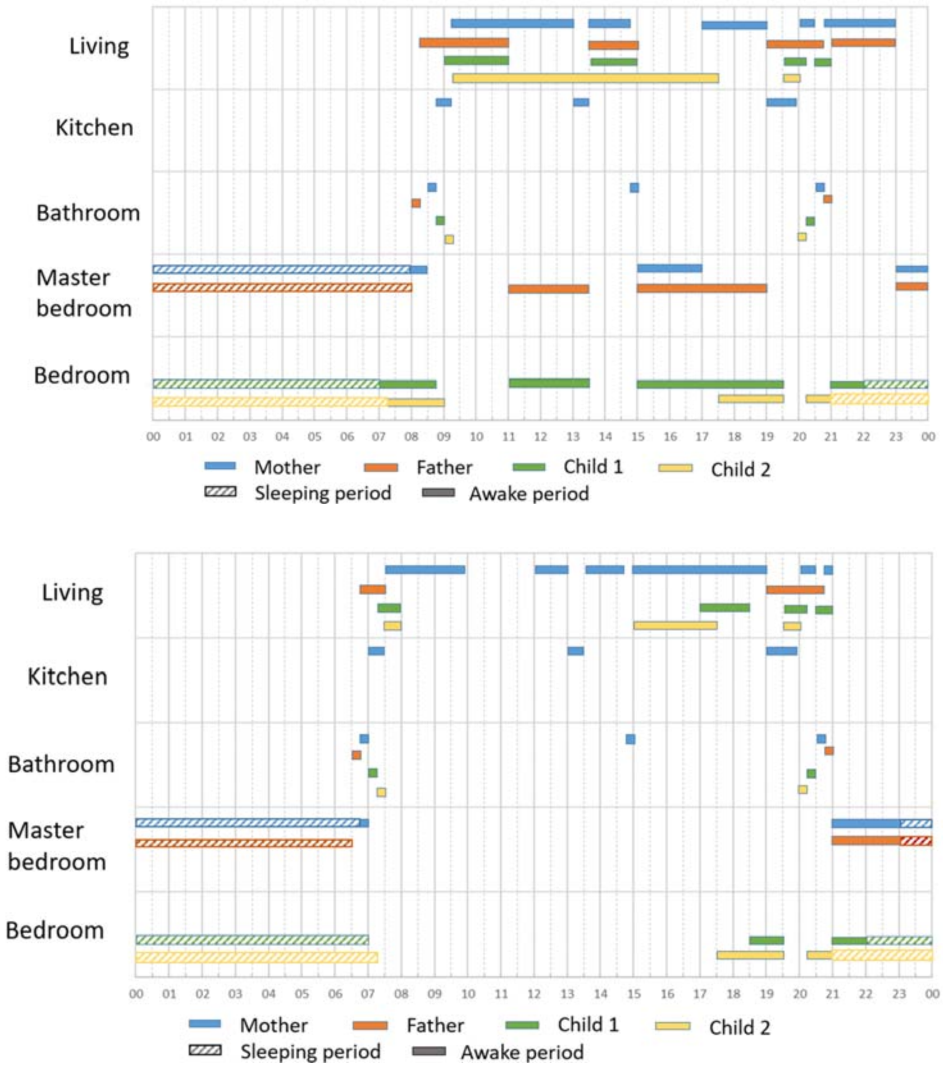

Figure 2: Occupancy profiles. Above: high occupancy, down: moderate occupancy.

2.4 Ventilation systems evaluated

Seven different ventilation systems were simulated. Some of them were evaluated with different settings. Table 3 provides a brief explanation for each of them.

System A is a decentralized ventilation system that corresponds to the base configuration (see §2.1), but assuming continuous operation 24/7: the exhaust fans in the kitchen and bathroom extract the maximum airflow rates every moment of the day. This system serves as the reference case. System B is the most commonly installed system today in new or retrofitted houses in Chile, where exhaust fans are activated when the relative humidity of the indoor air exceeds a setpoint (ON-OFF mode). The bathroom fan also detects the presence of the occupant and continues to operate for 15 minutes after the occupant leaves the room. Three RH setpoints were considered: RH = 70% (B1), 65% (B2) and 60% (B3). System C is similar to B, but with the additional requirement that the exhaust fans operate continuously every hour of the night (22h-7h) to provide ventilation during sleeping hours. The exhaust fans in System D can operate at two different speeds to provide different airflow rates. When operating at normal speed, System D is the same as B1, but it maintains a minimum exhaust airflow rate equal to half of the maximum value when operating at low speed. Systems E and F are identical to B1, but with an additional centralized exhaust system for the two bedrooms only. The maximum total airflow of the exhaust system is 100 m³/h, with 50 m³/h per bedroom. This exhaust system operates only during the night for system E and based on the average CO_2 concentration over the bedrooms for system F, with a flowrate directly proportional to the CO_2 concentration. System G operates according to the *extended cascade ventilation principle* (Rojas et al., 2015) and has no supply air inlet in the living room. The bathroom fan is activated based on the relative humidity of the air, similar to B1. The kitchen fan has two speeds. The high-speed setting corresponds to the maximum airflow rate of 126 m³/h. It runs all night to maintain a minimum airflow in the bedrooms and when the CO_2 concentration in the open kitchen (equivalent to the one in the living) exceeds 1000 ppm during the day. The low-speed setting runs the rest of the time, corresponding to 1/3 of the maximum value to guarantee a minimal ventilation rate in the house.

Table 3 : List of the ventilation systems compared in the study

ID	Description
A	ON, 100% of the time
B1	ON/OFF, RH=70% in both bathroom and kitchen & presence detection in the bathroom
B2	ON/OFF, RH=65% in both bathroom and kitchen & presence detection in the bathroom
B3	ON/OFF, RH=60% in both bathroom and kitchen & presence detection in the bathroom
C1	ON/OFF, RH=70% in both bathroom and kitchen & presence detection in the bathroom + ON 100% during night (clock)
C2	ON/OFF, RH=65% in both bathroom and kitchen & presence detection in the bathroom + ON 100% during night (clock)
D	2 speeds (low/normal), RH=70% in both bathroom and kitchen & presence detection in the bathroom + Minimum airflow = ½ maximum value.
E	ON/OFF, RH=70% in both bathroom and kitchen & presence detection in the bathroom + centralized exhaust system only for bedrooms operating at 100% during the night (clock)
F	ON/OFF, RH=70% in both bathroom and kitchen & presence detection in the bathroom + centralized exhaust system only for bedrooms with airflow proportional to CO_2 concentration in bedrooms
G	'Extended' cascade ventilation. Bathroom: ON/OFF, RH=70% & presence detection. Kitchen: ON 100% during night (clock) and when CO_2 concentration > 1000 ppm during day + Minimum airflow = 1/3 maximum value.

2.5 Assessment criteria

The ventilation systems were evaluated based on the following criteria:

1. Ventilation and infiltration heat losses during the heating period from May 1 to September 30 (kWh). In the remainder of this document, the term "Ventilation Losses" is used to refer to "Ventilation and Infiltration Losses".
2. CO_2 cumulative exceeding exposure above 1000 ppm, assuming an outdoor concentration of 400 ppm, expressed as ppm.h per hour of occupancy. CO_2 is a good marker of occupant-related emissions, including bio-effluents and odours. It characterizes the perceived indoor air quality experienced by building occupants and is good indicator of ventilation rate per person (Poirier et al., 2021). Complementary indicators are needed, however, to achieve a comprehensive air quality assessment.
3. Risk of mould growth, supposed to occur when the monthly average relative humidity on a typical thermal bridge with a temperature factor of 0.7 exceeded 80% (Caillou et al., 2014).

3 RESULTS AND DISCUSSION

3.1 Climate of Santiago

Figure 3 shows the exceeding CO_2 exposure above 1000 ppm versus the ventilation losses for the different ventilation systems investigated in this study, for the moderate occupancy scenario. As a 'reference case', ventilation system A allows to guarantee a good IAQ with a low exceeding CO_2 exposure, but at the expense of high ventilation heat losses due to the continuous air exhaust. Despite the continuous operation of the system, the design values for supply airflow are not reached in the bedrooms due to the influence of air leakage and wind forces (Flamant et al., 2023). This results in CO_2 concentrations that are slightly above 1000 ppm during the night, mainly in the bedroom 1. Systems B, the most commonly installed systems today, show the worst performance in terms of IAQ, with high CO_2 concentrations mainly in the two bedrooms during the night, as shown in Figure 4. The HR-based algorithm is effective to evacuate the water vapour peaks from the household activities in the kitchen and bathroom, but is not suitable to remove the pollutants generated by the occupants in the bedrooms. In addition, Systems B1 and B2 do not meet the criterion for the risk of mould growth. Compared to systems B, System C allows for a significant reduction of excess CO_2 exposure, especially in the bedrooms, by enforcing continuous ventilation during the night. The bathroom and kitchen exhaust fans in System C2 operate 58% and 61% of the time, respectively, compared to 51% and 30% in System B2. Such an increase in the use of exhaust fans also results in much higher ventilation losses. Maintaining a minimum exhaust airflow rate (in this case half of the maximum value) throughout the whole day (System D) improves the IAQ compared to Systems B, but without reaching the performance of Systems C. The additional installation of a dedicated exhaust system for the bedrooms – Systems E & F -, in addition to the bathroom and kitchen exhaust fans, offers the highest performance in terms of IAQ, with a ~50% reduction in ventilation losses compared to the reference case A. The *cascade ventilation system* G offers another interesting alternative in terms of IAQ and energy. The continuous use of the kitchen exhaust fan during the night maintains a low CO_2 concentration in the bedrooms, and the absence of air intake in the living room reduces the ventilation heat losses in this room compared to the other systems studied. Thanks to its daytime CO_2-based detection, the kitchen/living fan adjusts the ventilation flow rate according to the needs of the room. This System G has the advantage of not requiring the installation of an additional exhaust system. However, it requires a more sophisticated detection and control system than the exhaust fans usually used. It is particularly suitable for the house configuration considered in this study, with a kitchen opened onto the living room (Rojas et al., 2015). With the exception of Systems B1 and B2, all other systems meet the criterion for the risk of mould growth. It must be noted that the control parameters of the various ventilation solutions were selected following a limited optimization process; it is possible that further optimization may lead to even more favourable results.

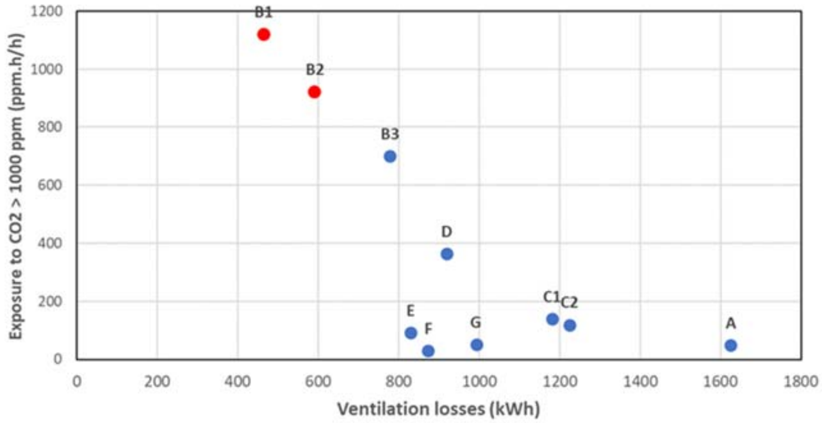

Figure 3: Exposure to CO_2 vs ventilation losses (kWh) for the different ventilation systems under analysis. Moderate occupancy. Climate of Santiago.

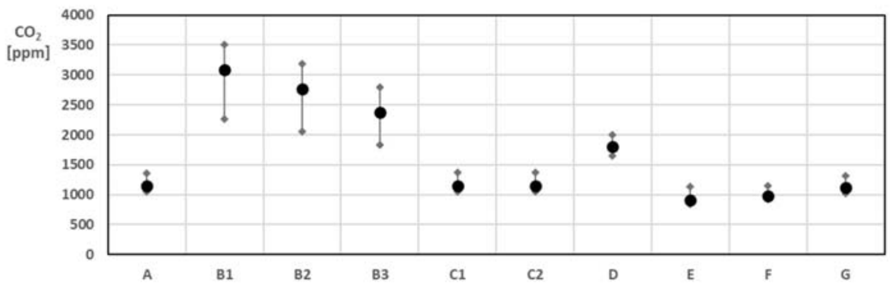

Figure 4: Minimum, mean and maximum values of CO_2 concentration in bedroom 1 during the night hours for the different ventilation systems under analysis. Moderate occupancy. Climate of Santiago.

Figure 5 illustrates the exposure to CO_2 versus ventilation losses for the different ventilation systems, but this time for the high occupancy scenario of the house. Compared to the case of moderate occupancy, the main difference concerns the performance of the clock-based control systems (night hours), i.e. Systems C and E. Both systems fail to maintain air quality in bedrooms and living rooms during the day. Only Systems F and G perform well for both occupancy scenarios.

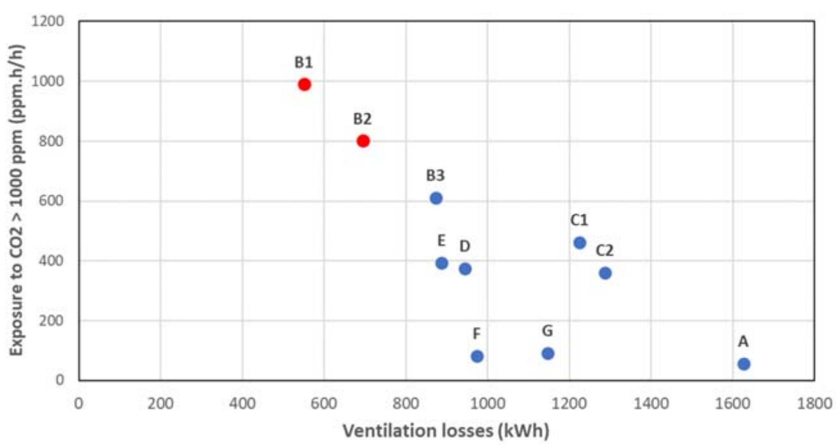

Figure 5: Exposure to CO_2 vs ventilation losses (kWh) for the different ventilation systems under analysis. High occupancy. Climate of Santiago.

3.2 Climate of Concepción

Figure 6 shows the exposure to CO_2 versus ventilation losses for the climate of Concepción in the case of the high occupancy scenario. The points are closer together in terms of excess CO_2. Indeed, since the absolute humidity of the outdoor air in Concepción is higher than in Santiago, the ventilation systems, whose control is based on the relative humidity of the indoor air, have to run longer to maintain a given RH level. This leads to an improvement in indoor air quality at the expense of higher ventilation losses. None of the systems B meets the criterion for the risk of mould growth. Systems C1, D, E and F, whose control is partly based on RH=70%, also present a risk, but this can be avoided by lowering the RH setpoint to a lower level (e.g. RH=65%). Again, systems F and G offer the best performance in terms of IAQ, with energy savings of about 25% compared to reference case A.

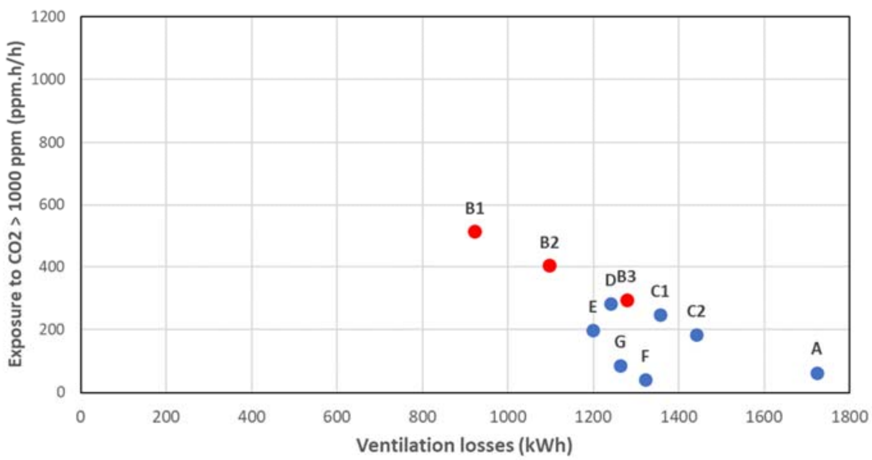

Figure 6: Exposure to CO_2 vs ventilation losses (kWh) for the different ventilation systems under analysis. High occupancy. Climate of Concepción.

4 CONCLUSIONS

This study showed that a decentralized ventilation system controlled by the relative humidity of the indoor air does not at all guarantee the IAQ in the dwelling under consideration, particularly in the bedrooms during the night hours. This finding is particularly important given that this system is currently the most widely used in Chile in both new construction and renovation projects. The study identified and evaluated several alternative ventilation systems and strategies that significantly improved IAQ. In particular, two systems showed good performance in terms of IAQ while limiting ventilation heat losses, for the two occupancy profiles considered. They include demand ventilation control based on local CO_2 concentration detection. The first is based on the *extended cascade ventilation principle*, while the second involves the addition of an exhaust system specific to bedrooms. They reduce the ventilation heat losses by about 32% and 37% on average, respectively, compared to a ventilation system operating continuously, while ensuring an equivalent level of IAQ.

Further research will focus on evaluating a wider variety of cost-effective ventilation systems and strategies, for a series of typical social housing typologies. Air quality will be assessed not only in terms of CO_2 concentration, but also considering other pollutants such as formaldehyde and particulate matter $PM_{2.5}$.

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