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Estimation of heating system energy modeling profiles based on environmental monitoring records in Central-Southern Chile

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ABSTRACT

Data simulated for occupancy profiles, usually based on standard occupancy schedules, must be validated against real measurements, and many studies have pointed out the gap between them. This problem is more pronounced in homes that are not heated by grid-connected energy sources, such as wood-burning stoves, because the meter cannot provide a real-time estimate. In Central-South Chile, 74% of homes are heated by wood stoves, causing an acute problem of air pollution in several urban areas. The government is trying to solve this problem, but at the moment there is no data on occupancy profiles, hence it is not possible to estimate the energy intensity for heating. This exploratory study aims to clarify to what extent occupancy profiles can be estimated from $PM_{2.5}$ pollution levels. To this end, publicly available data on $PM_{2.5}$ concentrations in 17 cities in central-south Chile was used as a proxy to build occupancy schedules for homes heated by wood stoves. The results show that there is a clear relationship between pollution levels and occupancy intensity, and that the latter does not follow the schedules outlined in international standards or building codes. The results and methodology can be replicated in cities where air pollution is driven by wood stoves, allowing public authorities to have access to accurate occupancy schedules and providing them with reliable data to address local air pollution problems.

1. Introduction

In recent years, a considerable amount of research has focused on generating more accurate operating schedules for buildings by quantifying parameters related to the users' behavior. Different techniques include monitoring electricity and gas consumption, the opening of windows, hot water, air cooling, heating devices, and other electrical appliances. Some researchers have addressed data quality uncertainty using probabilistic models [1], whereas others have proposed calibration outlines for models using real data obtained from different sources, such as occupation proxies incorporated in Wi-Fi connections [2], or the use of connected thermostats [3]. Although the adjustments using calibration processes are somewhat normal, they require real-time information on monitored buildings, which is usually difficult to obtain due to privacy issues, and is also time-consuming [4] Given these difficulties, designers end up relying on a simplified operation schedule based on the local regulatory framework or international standards when the former is not available, which can also lead to increasing the performance gap between the design and operation stages. This, in the end, may reduce the credibility and increase skepticism about the reliability of these schedules when designing high-performance buildings [5].

As an example, several studies in European countries have questioned the savings estimates in energy retrofits, considering the gap between simulated and on-site measured data. Filippidou et al. (2019) showed that the more energy savings measures (ESMs) are applied to existing dwellings in the Netherlands, the larger the gap between expected and real gas consumption savings is; for 7 ESMs, the actual savings can reach a mere 40% of the expected values [6]. Similarly, Galvin et al. (2016) studied the gap between simulated and real data for the renovation of German homes. Their study concluded that occupants use, on average, 30% less heating energy than expected [7]. This gap is known as the prebound and rebound effect and has been addressed from a theoretical point of view by other authors, who emphasize that potential savings are usually overestimated [7]. Moreover, existing

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Table 1
Summary of the features of the communes and monitoring points evaluated.

Zone	Atmospheric Decontamination Plan (PDA)	Commune	Latitude/Longitude				Temperature	
			Commune Coord.		Monitoring Point Coord.		Min.	Max.
Zone 1	Plan for the Central Valley of the O'Higgins Region	Graneros	−34.0646	−70.7261			4.5	29.6
		Rancagua	−34.1701	−70.7407	−34.1623	−70.7139	4.5	29.6
					−34.1439	−70.7371		
		Doñihue	−34.1896	−70.8903			4.7	30.0
		Olivar	−34.2093	−70.8171			4.5	30.0
		Coltauco	−34.2931	−71.0809			4.8	29.9
		Coinco	−34.2702	−70.9517			4.6	30.0
		Quinta de Tilcoco	−34.2701	−70.9517			4.5	29.8
		San Vicente de Tagua Tagua	−34.4393	−71.0770			4.7	30.1
		Placilla	−34.6386	−71.1175			4.5	30.0
		Mostazal	−33.9799	−70.7121			3.2	26.6
		Codegua	−34.0390	−70.6678			2.9	26.2
		Machalí	−34.1825	−70.6511			1.1	22.8
		Malloa	−34.4465	−70.9464			3.2	27.6
		Rengo	−34.4090	−70.8614	−34.3945	−70.8530	2.3	25.8
		Requínoa	−34.2848	−70.8174			3.3	27.1
		San Fernando	−34.5839	−70.9892	−34.5799	−70.9897	1.9	25.1
		Chimbarongo	−34.7088	−71.0404			3.4	28.2
Zone 2	Plan for the Central Valley of the Province of Curicó	Curico	−34.9857	−71.2391	−34.9749	−71.2340	2.3	26.1
		Teno	−34.8667	−71.1609			3.4	28.0
		Rauco	−34.9264	−71.3189			5.1	30.2
		Romeral	−34.9602	−71.1251			2.2	26.1
		Sagrada Familia	−34.9988	−71.3817			4.9	30.0
		Molina	−35.1140	−71.2800			2.5	26.3
Zone 3	Plan for the communes of Talca and Maule	Talca	−35.4264	−71.6660	−35.4066	−71.6333	4.8	29.6
					−35.4358	−71.6195		
		Maule	−35.5236	−71.6923			4.3	28.8
Zone 4	Plan for the communes of Chillán and Chillán Viejo	Chillán	−36.6066	−72.1034	−36.5948	−72.0893	3.8	27.8
					−36.6162	−72.0931		
		Chillán Viejo	−36.6229	−72.1318			3.9	27.7
Zone 5	Plan for the communes of the Concepción Metropolitan area	Lota	−37.0944	−73.1563			5.9	20.8
		Coronel	−37.0292	−73.1453			5.7	21.7
		San Pedro de la Paz	−36.8413	−73.1037			5.8	21.3
		Penco	−36.7386	−72.9938			5.8	21.4
		Talcahuano	−36.7144	−73.1142	−36.7237	−73.1237	5.7	20.3
					−36.7362	−73.1189		
					−36.7373	−73.1044		
		Hualpén	−36.7879	−73.0878	−36.7700	−73.1138	5.6	20.1
					−36.7807	−73.1156		
					−36.7914	−73.1191		
					−36.8031	−73.1204		
		Tomé	−36.6169	−72.9575			5.9	21.8
		Chiguayante	−36.9073	−73.0292	−36.9233	−73.0361	5.6	22.8
		Hualqui	−36.9759	−72.9383	−36.9775	−72.9319	5.3	24.7
		Concepción	−36.8272	−73.0502	−36.7846	−73.0521	5.6	22.4
Zone 6	Plan for the commune of Los Ángeles	Los Ángeles	−37.4706	−72.3517	−37.4631	−72.3246	3.6	26.5
					−37.4712	−72.3615		
Zone 7	Plan for the communes of Temuco and Padre las Casas	Temuco	−38.7400	−72.5901	−38.7269	−72.5799	4.3	25.1
					−38.7487	−72.6207		
		Padre las Casas	−38.7731	−72.5971	−38.7647	−72.5988	3.9	24.5
Zone 8	Plan for the commune of Valdivia	Valdivia	−39.8141	−73.2459	−39.8055	−73.2587	4.6	22.3
Zone 9	Plan for the commune of Osorno	Osorno	−40.5738	−73.1358	−40.5845	−73.1187	4.6	21.3
Zone 10	Plan for the city of Coyhaique and its surrounding area	Coyhaique	−45.5711	−72.0685	−45.5790	−72.0500	−2.9	14.8
					−45.5799	−72.0611		

literature has shown that occupancy profiles compared with income levels can be drivers of energy consumption and CO_2 emissions. A study in China clarified that income level exerts a stronger influence on energy consumption than heating equipment, floor area, or heating method [8]. From a sociological point of view, economic inequality on a macro scale has been linked to a decrease in home ownership, which in turn, leads to higher levels of fuel poverty [9]. A study on a macro scale within the 27 EU countries has also concluded that increased income for low-income groups could entail higher CO_2 emissions, yet highlights that technological improvements can compensate for this increase [10]. Meanwhile, a study on a global scale showed that emissions per GDP drive the decarbonization of residential buildings [11].

The great majority of these studies have been carried out under very specific conditions: Developed countries with a long history of energy-efficiency policies for the building industry, and buildings whose main source of energy is either electricity or gas. In those cases, energy consumption is directly estimated through the readings of the meters. But this is not always the case, and that is precisely the main motivation for this study. In countries like Chile, many regions have cold winters and are covered by vast forest areas, hence wood is easily available as an economic energy source for heating. In Central-Southern Chile the culture associated with the use of wood burners in homes is popular. According to official estimations, this covers 74% of the energy the residential sector uses [12]. This has led to different environmental contamination issues in the form of high levels of Particulate Matter 2.5 ($PM_{2.5}$), mainly in the country's central-southern cities [13]. Although the use of other less contaminating sources has been promoted, wood continues to be the most popular, albeit for cultural, economic, or availability reasons. As a response to reduce the negative effects on air quality, the Government has established specific regulations for cities

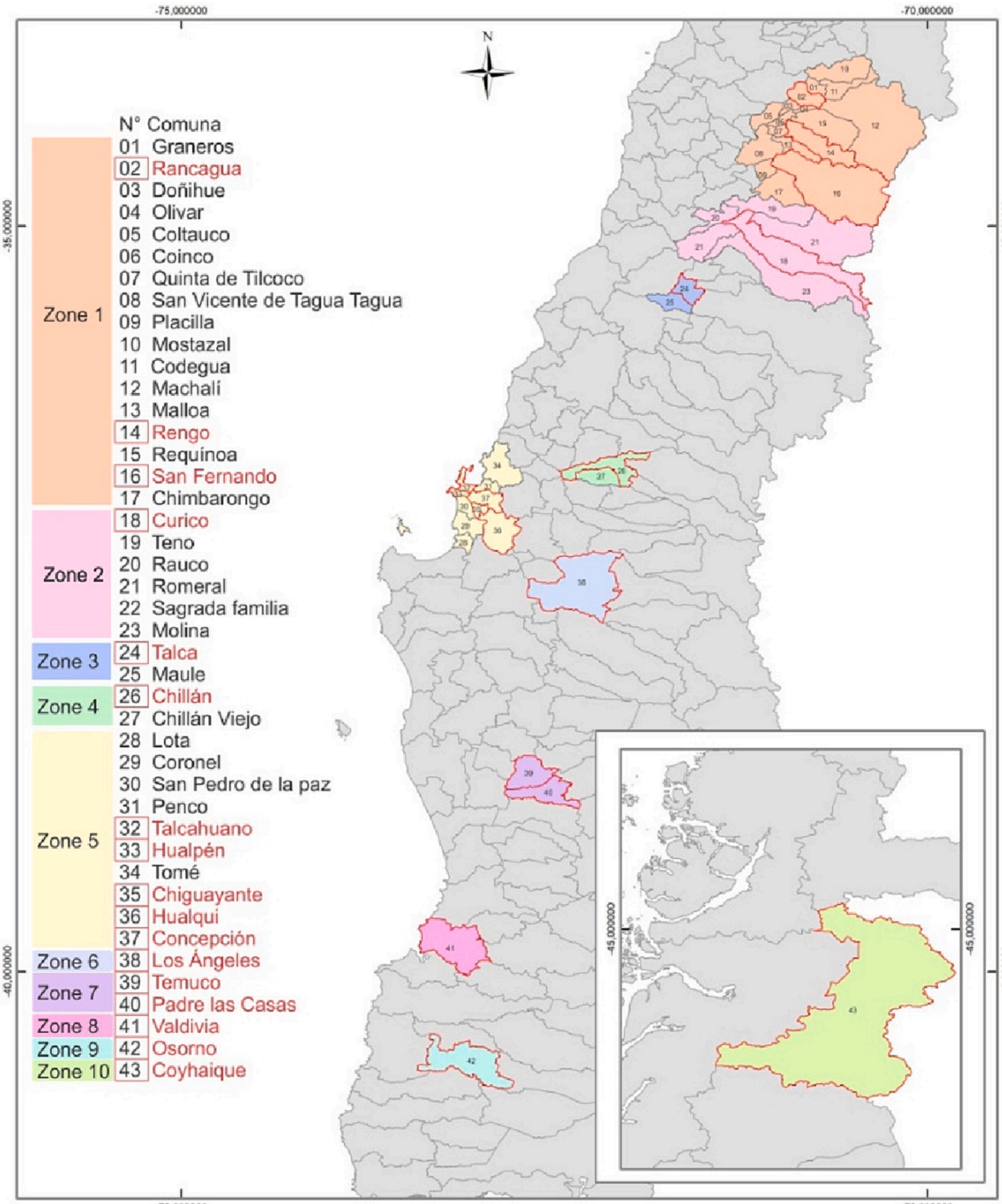

Fig. 1. Zones with Atmospheric Decontamination Plans and Communes, in red, that have an environmental monitoring system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with high contamination levels. These are called Atmospheric Decontamination Plans (PDA, in Spanish) and include measures such as an increase in building standards, and restrictions for the main contaminant generating sources. Numerous environmental monitoring points have been set up in this context to identify critical contaminant concentration episodes [14].

The shortcomings described are more evident in developing countries that have started to address the issue of energy efficiency in the building industry very recently. Chile, the country that this study focuses on, is one of these. The country has established a regulatory framework to achieve carbon neutrality by 2050 [15], and residential building energy labeling is one of the cornerstones of this program. However, since there is a lack of locally generated data regarding occupancy profiles for heating and cooling use in residential buildings, they resort to standard profiles from Appendix C of the residential chapter of ASHRAE, which do not provide profiles that consider different intensities in heating use, therefore disregarding the actual occupation schedule for dwellings [16].

Given this situation, this study aims to fill a research gap when it comes to generating heating occupancy schedules for homes heated by wooden burners during wintertime. Since the PDAs specifically mention that atmospheric contamination in Southern Chilean cities is strongly influenced by the extensive use of wooden burners in dwellings during wintertime, this exploratory study was set up to clarify two main aspects: First, whether occupancy schedules for houses heated by wood burners can be estimated using the local atmospheric contamination levels as proxy data. Second, to what extent this estimation is reliable and accurate.

The results from this study can contribute from two perspectives. First, from a more general and methodological point of view, the study aims at exploring a methodology that can be reproduced in urban areas affected by high air pollution levels. Second, from a more local approach, this research will generate new data to produce accurate heating schedules for a type of home usually disregarded in simulation software. This will allow stakeholders, and specifically Chilean public agencies, to devise policies that specifically represent the local reality and also tackle the issue of atmospheric contamination, which is an acute problem in several cities in Southern Chile.

2. Methodology

This research used a quantitative approach to prepare the heating system use schedules, collecting, classifying, and analyzing information published by the National Air Quality Information System (SINCA, in Spanish). For this, data from all the metering centers of the communes governed by Atmospheric Decontamination Plans (PDA, in Spanish) in central-southern Chile were considered. The heating use calendars were ultimately validated through the relationship with outdoor temperatures, and the surveying of housing occupation in one of the study areas.

2.1. Definition of information sources

The population analyzed is part of 8 regions of Chile and comprises 43 communes, where 36 monitoring points were identified. As inclusion criteria, those monitoring stations that had records of 2018, 2019, and 2020, and reported data on Particulate Matter 2.5 ($PM_{2.5}$) indices, were considered. Regarding the records, measurements updated every hour during the entire year were used. From the revision, 28 monitoring points were obtained in 17 communes that complied with the inclusion requirements. The information collected covers data from 75% of the total population in the PDA zones evaluated [17]. Table 1 shows the location of the monitoring points used, along with the maximum and minimum annual temperatures of those zones (10 Zones), and of the communes evaluated (17 communes).

2.2. Data grouping criteria

The study considers 10 zones in central-southern Chile with Atmospheric Decontamination Plans, as those were the areas of the country that had $PM_{2.5}$ records (Fig. 1).

The weather conditions are affected by the latitude and longitude of each zone. Some PDAs are formed by several communes and measuring points (See Table 1). However, their weather conditions are representative of the zone they are in, with most having very similar features. Considering this, the results are analyzed by the median values of 2018, 2019, and 2020 (hourly or monthly) from the records of the communes in each PDA. Years after 2020 are not included to avoid bias associated with the lockdowns implemented in Chile under the Covid-19 pandemic. In addition, the data was divided by weekdays (Monday to Friday) and weekends (Saturday and Sunday).

2.3. Identification of background contamination and data adjustment

Once the information was defined and grouped, the emissions were analyzed to identify the typical background contamination of each zone, linked to traffic, industrial processes, and wood-burning stoves, among others. An important part of these sources has relatively constant levels throughout the year, as they do not necessarily depend on the weather, but rather on the work-related and productive operations of each city. As a result, the study period's hourly data were stratified into quartiles for weekdays and weekends, to analyze their variability and identify similar trends associated with contamination sources, that were relatively constant throughout the study periods.

The data were then submitted to a fit process that comprised discounting the background contamination identified to differentiate the months where there is a relevant use of heating.

2.4. Weighting and data grouping

With the data defined and adjusted, the weighting of the average hourly measurements was established for 2018, 2019, and 2020 compared to the annual maximum registries. With this information, the months and schedules with higher emissions levels were identified, separating them into the following three groups depending on the intensity of concentrations reflected in the average monthly schedule, taking into account that said conditions had to be met by both the weekly and weekend records, and by the weather harshness of the month (considering that winter begins in Chile on June 21st, and ends on September 23rd).

- Months, where the average monthly hourly $PM_{2.5}$ emissions percentage compared to the annual maximum, were less than 2%.
- Months where the average monthly hourly $PM_{2.5}$ emissions percentage, compared to the annual maximum, were between 2% and 15% considering the annual maximum value (medium intensity).
- Months where the average monthly hourly $PM_{2.5}$ emissions percentage, compared to the annual maximum, exceeded 15% (high intensity).
- The first group considered months without heating use, the second group was called "Cold Months" (CM), and the third was called "Very Cold Months" (VCM).

2.5. Schedule variations and profile generation

To make the heating profiles, the variations were established in the schedule records by Zone for the following four cases:

- CM weekend record
- CM weekday record
- VCM weekend record
- VCM weekday record

An algorithm was formulated for this process, that allowed defining the periods where increases in emissions revealed a greater use of heating. This algorithm considered heating to be present when emissions of a given hour were higher than 60% of the annual maximum value, or when the studied hour had an increase in the emissions concentration compared to the previous hour. 60% was set considering that, on there being a percentage above 50%, its use is representative of most of the homes that use wood-burners. The detail is presented below:

- Heating On (On): $Eph\text{-}1 \leq Eph$ o $Eph \geq 60\%$ of the annual maximum record
- Heating Off (Off): $Eph\text{-}1 > Eph$ Si Eph less than 60% of the maximum record

Where:

Eph: Average emissions percentage of zones with PDA for the evaluated hour.

Eph-1: Average emissions percentage of zones with PDA for the previous hour.

The 60% condition of the annual maximum record was used because it was seen that there were hours where the *Eph* was slightly below *Eph-1* without seeing a sudden fall in $PM_{2.5}$ emissions. This implied that there had been a dilution of the contamination caused by weather phenomena or a small reduction in the use of heating systems. However, the high contamination rates, above 50% of the annual maximum value for the hour being studied, meant that the wood-based heating systems continued to be used in more than half the dwellings, and, therefore, that the heating was on, continued to be representative of the city's homes.

Table 2
Comparisons evaluated in the sensitivity analysis.

Profile developed	Profiles compared
Week (CM) Week (VCM) Weekend (CM) Weekend (VCM)	Zone 1, zone 2, zone 3, zone 4, zone 5, zone 6, zone 7, zone 8, zone 9, zone 10, ECSV, occupation

2.6. Occupation profile

The study developed an occupational profile to compare with the operational profiles. For this, surveys were carried out in 40 houses to determine their relationship with the proposed profiles and their behavior. The studied dwellings came from previous research, whose goal was to develop adaptive comfort models for social housing in central-southern Chile [18]. In the study, data was collected through surveys made to a sample, whose main feature was having been benefitted by a type of state subsidy. Among the typologies, 6 single-family dwellings and 6 semi-detached dwellings were considered, along with another 25 single-family dwellings, and 3 apartments located in condominiums.

The occupation was established using surveys where residents were asked questions associated with the use of the dwellings. The consultation was split into weekdays and weekends. In both cases, data was collected for all 24 h of the day. A total of 121 people were surveyed, 57 men and 64 women, whose ages ranged between 14 and 84. With the information collected, the average hourly occupation percentage of the dwellings was obtained for the study sample. This was compared graphically with the heating use profiles obtained for weekdays and weekends. Appendix B includes the survey's questions and answers.

This occupancy profile was used to contrast the similarity between the occupancy of the dwellings and the operational use of the heating systems.

2.7. Sensitivity analysis

The comparison of the operational options of the developed heating profiles was carried out using a sensitivity analysis. More specifically, since average operational profiles were made for each of the 10 zones (as indicated in subsection 2.5), the average profiles were compared with the profiles for each zone. Likewise, the average profiles were compared with the profile used by the ECSV as well as with the occupancy profiles of the dwellings (as indicated in section 2.6.). Table 2 summarizes the sensitivity analyses performed.

The analysis used the kappa coefficient, sensitivity, and specificity. The kappa coefficient (K) is used to evaluate the concordance or reproducibility of measurement instruments whose result is categorical (2 or more categories). It represents the proportion of agreements observed beyond chance with respect to the maximum possible agreement (Eq. (1)). A K of 0 is associated with poor agreement strength, from 0.21 is considered acceptable, and above 0.81 almost perfect (Landis & Koch, 1977). With the evaluation of K, it was possible to verify the concordance of the profiles developed. This analysis was performed for each month of the year.

$$K = \frac{P_0 - P_e}{1 - P_e} \tag{1}$$

Where P_0 is the proportion of observed agreements (Eq. (2)) and P_e is the proportion of expected agreements (Eq. (3)).

$$P_0 = \frac{ON_{Profile-Developedprofile} + OFF_{Profile-Developedprofile}}{N} \tag{2}$$

$$P_e = \frac{ON_{Profile} \bullet ON_{Developedprofile} + OFF_{Profile} \bullet OFF_{Developedprofile}}{N^2} \tag{3}$$

Where $ON_{Profile-Developedprofile}$ is the number of matching hours in the 2 profiles when the system is activated; $OFF_{Profile-Developedprofile}$ is the number of matching hours in the 2 profiles when the system is off; $ON_{Profile}$ is the total number of hours the system is on in the original profile; $OFF_{Profile}$ is the total number of hours the system is off in the original profile; $ON_{Developedprofile}$ is the total number of hours the system is on in the developed profile; $\bullet OFF_{Developedprofile}$ is the total number of hours the system is off in the developed profile.

In addition, the analysis evaluated sensitivity and specificity. The sensitivity is the probability that the 2 profiles coincide in the activation of the heating systems. The sensitivity varies from 0 to 1 (0 to 100%). The higher the numerical value, the greater the agreement in the activation of the heating systems; and (ii) the specificity is the probability that the 2 profiles coincide in the hours that the system is disabled. The specificity varies from 0 to 1 (0 to 100%). The higher the numerical value, the more agreement there is in the hours that the system is not in operation.

3. Results and discussion

3.1. Emissions

The average monthly emissions spread (see Fig. 2 and Fig. 3) in all the studied areas tended to increase from March, extending to October in some cases. This matches the drop in temperature from the fall (March to June, see Table 7), becoming more prominent as winter approached (June to September). Both zone 9 and 10 had a higher emissions average, and also had a longer period (March to October), compared to the rest of the studied zones. Meanwhile, the zone with the lowest emissions average was zone 5. The difference increases in colder months and asymmetric distribution of the concentrations are seen in those months. On the other hand, the months between November and February had a distribution close to normalcy on not using wood-based heating linked to higher outdoor temperatures.

In general, the average hourly emissions spread (see Fig. 4 and Fig. 5) shows a slight increase from 3 to 4 pm, increasing considerably from 6 pm and even to 8 pm and 9 pm, depending on the zone and period evaluated (weekday or weekend). After this time, the values decrease but remain high until around 11 pm, when a clear drop is seen. Finally, from 6 am, and until 9 to 10 in the morning, there is an increase once more in the emissions. Although the minimum and maximum values differ greatly throughout daytime hours, it is seen that the first quartile maintains a lower variation. The spread of the data is mainly seen in zones 8, 9, and 10, and a positive asymmetry of the data is seen in a large part of the hours and zones evaluated.

Fig. 6 shows that there is a positive correlation between the number of emissions and the mean outdoor temperatures, both on weekdays and weekends, which indicates that the intensity of wood-based heating used in the study zones is quite similar in both periods. However, it is shown to be slightly higher on weekdays. Therefore, it can be established that both calendars are practically alike, except on weekdays of CM months, as it is estimated that heating is used more in the mornings.

3.2. Background contamination

To reduce bias when establishing heating calendars, an estimation of the environmental contamination associated with different factors such as traffic, industrial processes, and the use of wood stoves, among others, was determined. If the summer months (January, February, March, and December) of Figs. 2 and 3 are observed, the outdoor contamination values remain practically constant compared to the rest of the months, identifying that the environmental contamination in those months

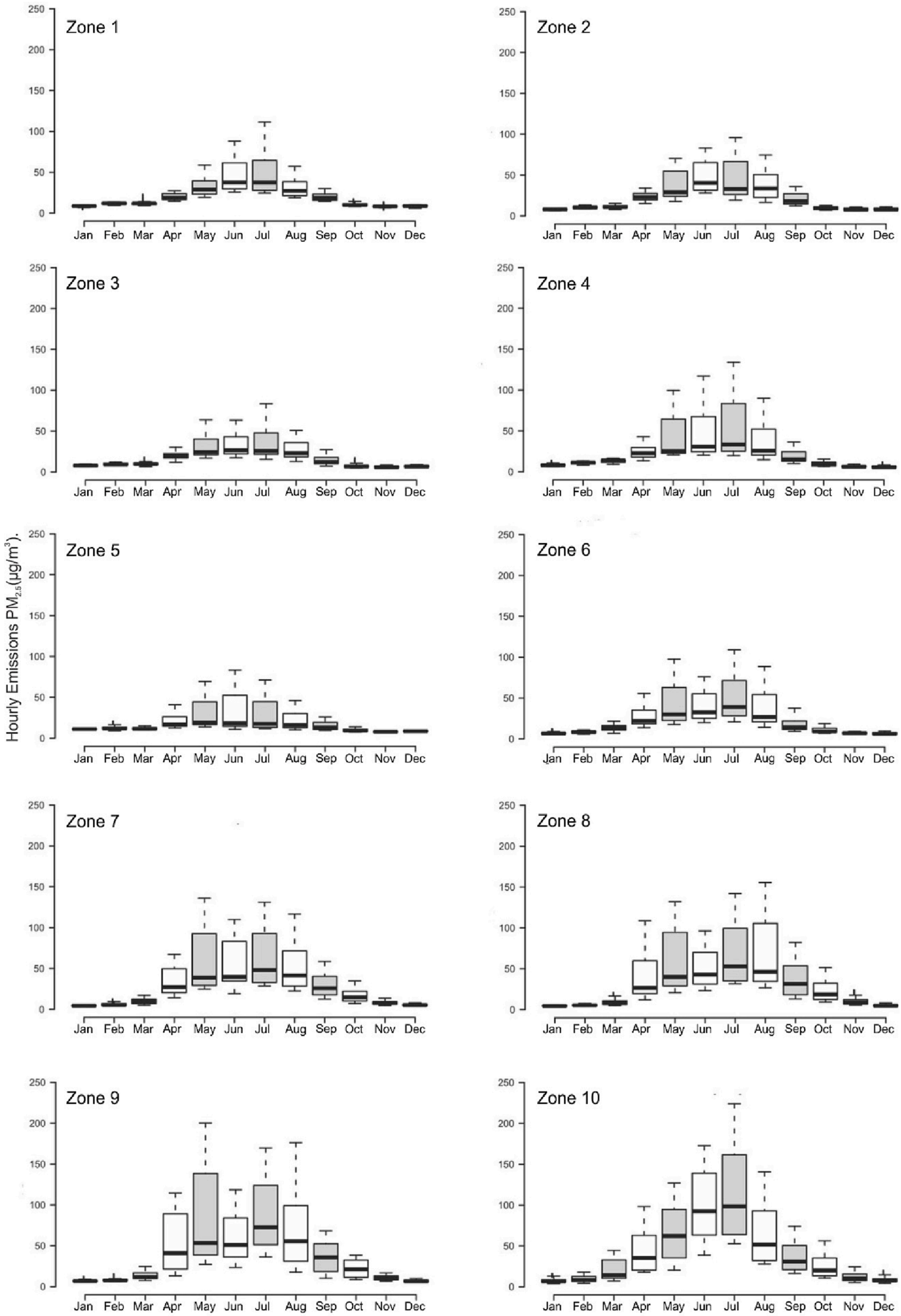

Fig. 2. Boxplot of average hourly emissions for weekdays per month in the 2018–2020 period ($PM_{2.5}$ μg/m^3).

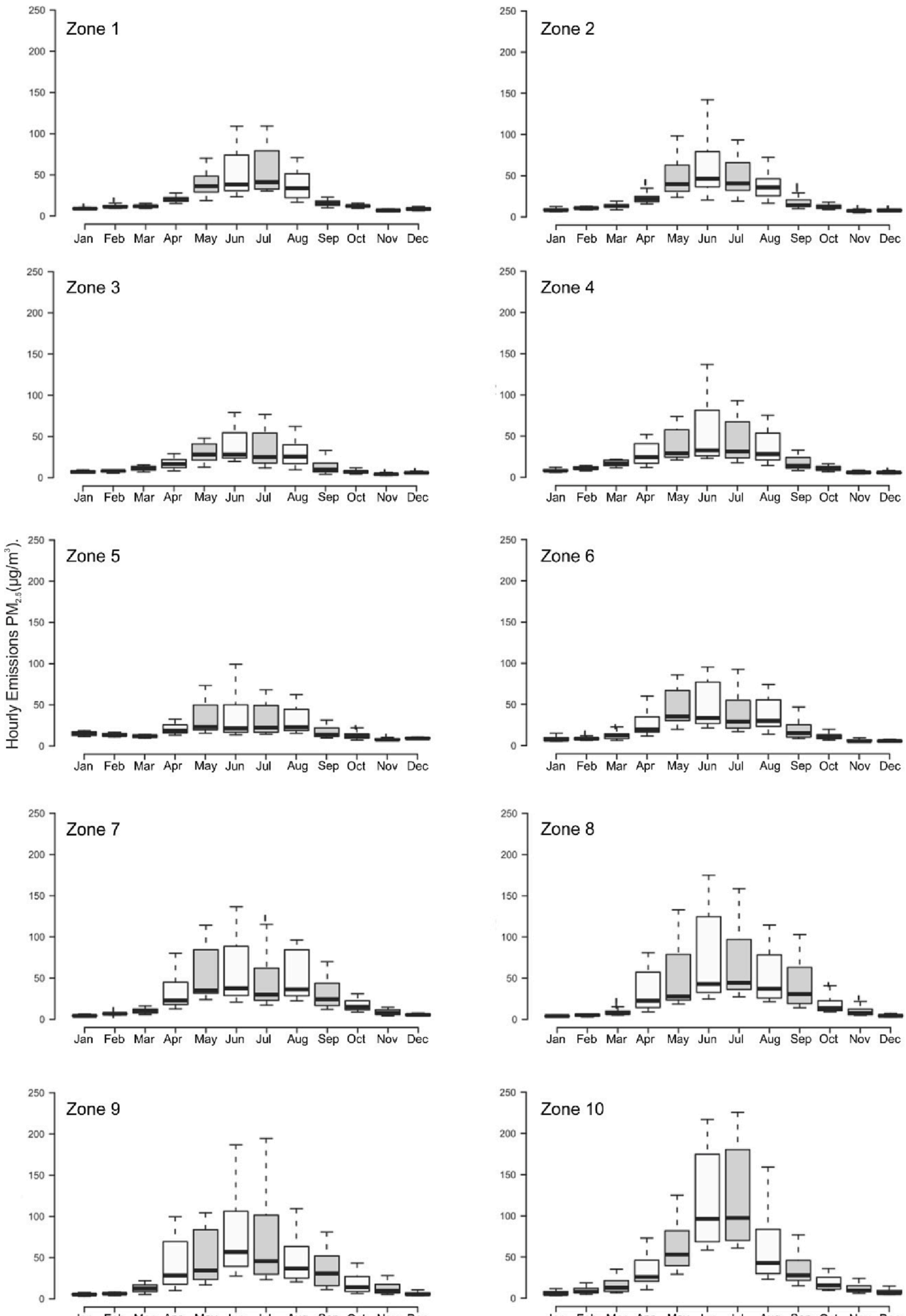

Fig. 3. Boxplot of average hourly emissions of 2018–2020 for weekends per month ($PM_{2.5}$ μg/m^3).

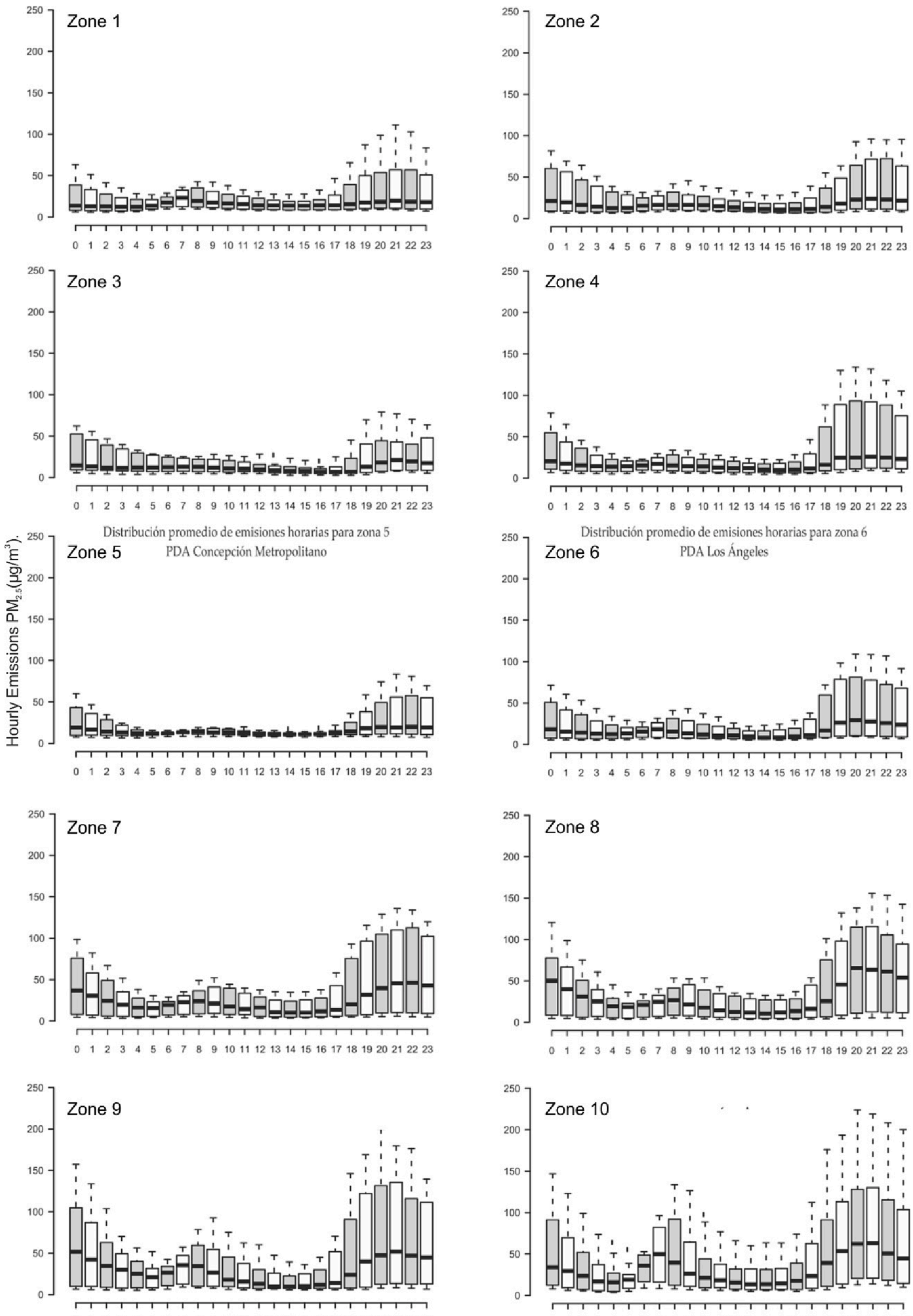

Fig. 4. Boxplot of average hourly emissions of 2018–2020 for weekdays per hour ($PM_{2.5}$ μg/m^3).

mainly came from processes other than heating-related wood burning. Likewise, if Figs. 4 and 5 are seen, the upper limit of quartile 1 in terms of the time of the day, both for weekdays and weekends, in the different zones analyzed, presents little oscillation in the 24-hour period. In Table 3, it is possible to see that said value for weekdays ranges between 4.5 and 20.8 μg/m^3 for the different zones, with an hourly variance between 1.0 and 10.5, and a standard deviation per hour between 1.0 and 3.2, said values oscillating in the zones between 0.6 and 21.7 (Variance), and between 0.8 and 4.7 (Deviation). Regarding weekends (See Table 4), the upper limit of the first quartile oscillates between 3.9 and 21.4 μg/m^3, sensitively similar to weekdays, with an hourly variance between 1.9 and 12.5 and a standard deviation per hour between 1.4 and 3.5, said values ranging for the zones between 0.8 and 21.7 (Variance) and between 0.9 and 4.7 (Deviation). This allowed

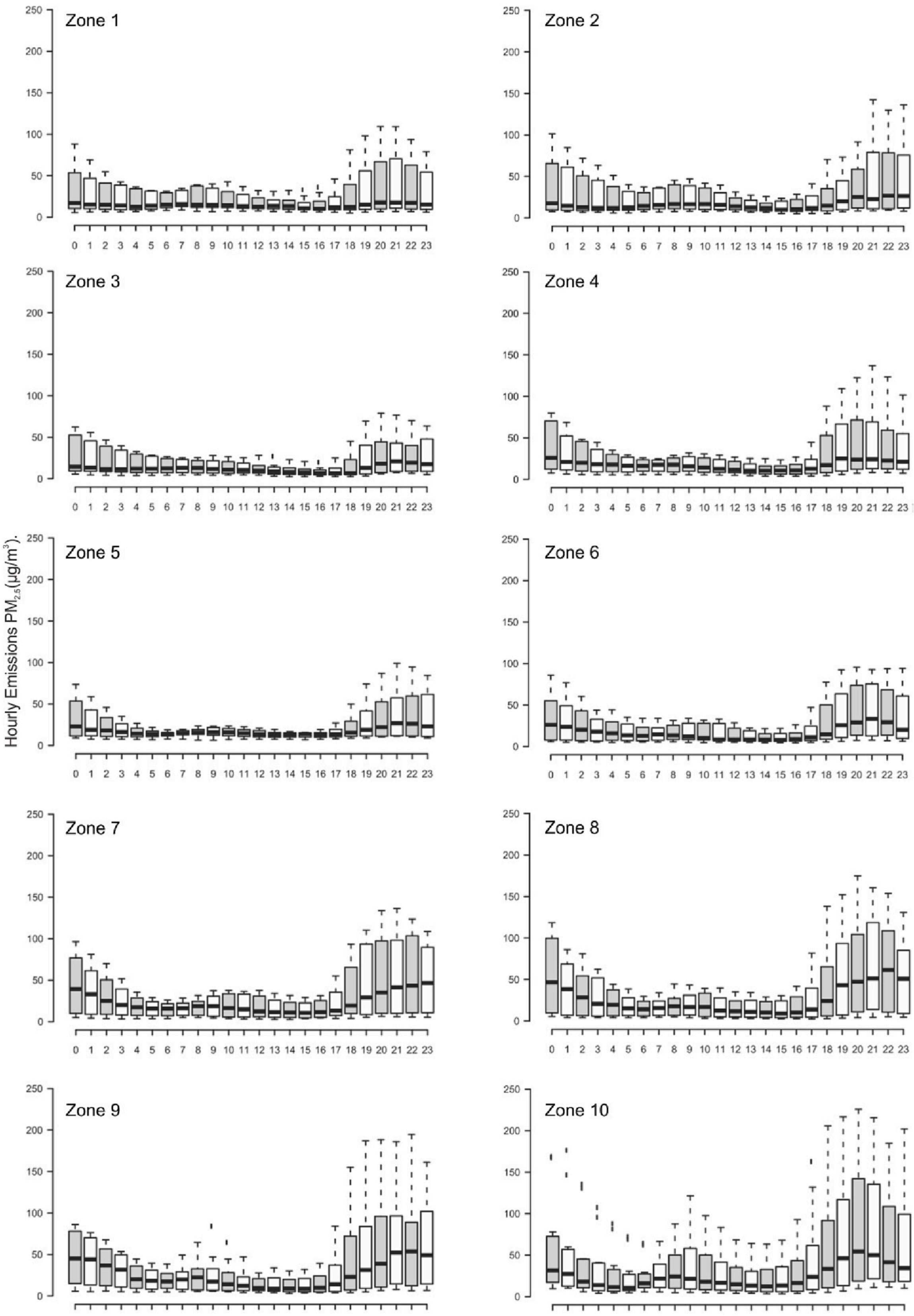

Fig. 5. Boxplot of average hourly emissions of 2018–2020 for weekends by hour ($PM_{2.5}$ μg/m^3).

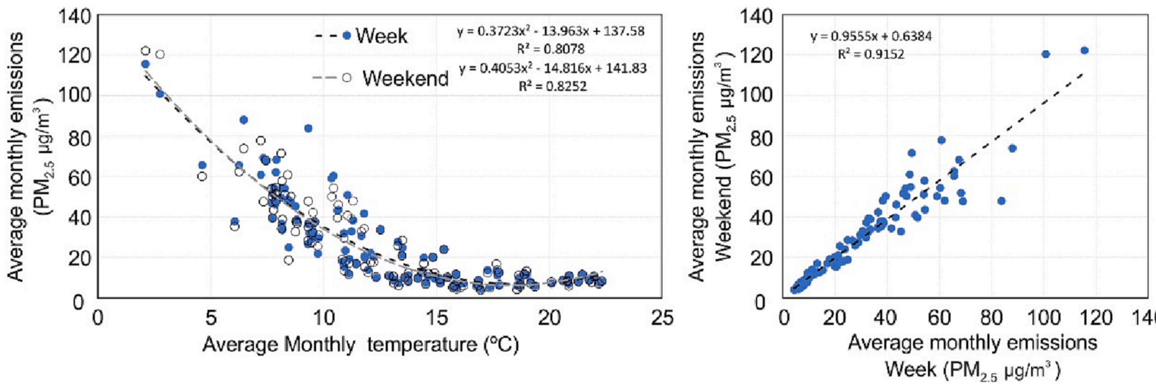

Fig. 6. Correlation between monthly mean outdoor temperatures and emissions, and monthly week and weekend mean emissions.

Table 3
Values of the upper limit of the first quartile for weekday hourly emissions by Zone (μg/m^3).

Time	Weekday hourly emissions by Zone (μg/m^3)									
	Zones									
	1	2	3	4	5	6	7	8	9	10
0:00	8.2	8.0	9.5	10.8	9.4	7.6	8.0	8.5	9.8	12.5
1:00	7.8	7.5	9.2	9.5	9.7	7.9	7.0	8.1	9.7	9.3
2:00	7.8	6.9	8.8	8.2	9.5	6.7	6.0	6.1	8.8	7.2
3:00	7.5	6.6	8.9	8.0	9.3	6.8	5.6	7.1	7.7	5.6
4:00	7.9	6.3	9.2	7.6	9.2	7.1	5.3	5.4	8.2	4.8
5:00	9.7	6.4	9.3	7.8	9.6	7.5	5.8	5.1	8.1	8.4
6:00	12.0	7.8	10.1	9.8	10.6	8.6	7.2	6.2	10.8	16.7
7:00	12.6	9.0	11.1	9.6	11.6	8.6	8.0	7.1	12.6	16.1
8:00	11.9	8.0	11.2	8.7	11.0	8.0	8.7	8.3	10.0	12.3
9:00	11.3	8.1	10.8	8.0	11.0	7.6	9.0	7.9	9.8	10.8
10:00	10.2	8.1	10.1	7.8	10.0	7.3	7.9	6.6	9.5	9.2
11:00	9.5	8.2	10.3	7.2	9.5	7.3	7.8	6.0	7.9	9.3
12:00	9.3	7.5	9.9	7.1	9.1	7.0	5.5	5.6	7.1	7.6
13:00	9.1	6.7	8.8	6.8	9.1	6.3	5.1	4.5	7.5	7.0
14:00	8.6	6.4	8.5	6.8	9.3	6.3	4.7	4.6	7.5	6.9
15:00	8.8	6.5	8.3	6.4	9.4	6.3	4.8	4.7	7.1	7.3
16:00	8.9	6.2	8.0	6.4	9.5	6.8	5.1	4.9	7.5	7.1
17:00	8.9	6.0	9.0	6.9	10.3	7.9	5.9	5.9	7.6	8.5
18:00	9.4	6.2	8.7	8.8	10.5	8.5	6.5	6.6	7.8	10.9
19:00	10.2	8.0	9.8	10.0	10.3	10.0	7.8	8.3	9.0	13.8
20:00	10.5	8.8	11.8	11.2	11.2	10.6	9.7	10.8	12.4	20.5
21:00	10.4	10.0	11.0	12.1	11.4	10.3	10.4	12.4	13.4	20.8
22:00	9.9	10.0	11.0	12.0	11.1	9.5	10.0	12.1	12.5	18.2
23:00	9.6	9.4	11.8	11.3	10.4	9.0	9.0	11.7	12.9	14.5

establishing that said values are not greatly affected by the harshness of the weather, remaining within stable ranges throughout the year, and observing that they are very similar to the records of summer months where there are no heating needs (See Figs. 2 and 3). Hence, it was estimated that the upper limit of the first quartile of hourly data could be assumed as the contamination associated with processes other than wood-related heating.

3.3. *Monthly heating profiles*

Once the values considered as background contamination are discounted, the average percentage of monthly hourly $PM_{2.5}$ emissions was determined (See Tables 5 and 6). Based on this, the data show that, despite discounting the background contamination, some zones maintain small concentrations during certain times of the summer months. In general, these records are found in times with the highest temperatures of the day, which could imply that these are the hours when wood-burning stoves are used [13]. Among the zones studied, the highest concentrations in summer are produced in Concepción (Zone 5), on including an industrial hub. However, the values are close to the rest of the zones. In Tables 5 and 6, it is possible to see that the emissions increase as winter approaches, and fall when closing in on spring. In this sense, the months where the average hourly emissions were less than 2% of the annual maximum were classified by zone, establishing that in January, February, November, and December, there was no wood-based heating as the outdoor temperatures were above 15 °C in most of the zones (See Table 7). In the case of March, this is an atypical month, as despite having outdoor monthly average temperatures above 15 °C, the drop in temperature from the hottest season can mean that heating is used even though the temperatures are quite similar to November, where clearly it is not used [19]. Likewise, it can be seen in Tables 5 and 6 that the months of September and October are where most of the zones have an average monthly hourly emissions percentage, compared to the annual maximum, of between 2% and 15% (medium intensity), and the monthly average temperatures for most of the zones is between 10 °C and 15 °C. Because of this, March, September, and October have been considered Cold Months. In the case of April, just as what happens with March, despite having monthly average temperatures between 10 °C and 15 °C, and just as in October, the use of wood-based heating is estimated to be used more intensively due to the drop in temperatures from the hottest season, even though their monthly mean temperatures are quite similar. Finally, the months where a more intensive use of

Table 4
Values of the upper limit of the first quartile for weekend hourly emissions by Zone (μg/m^3).

Time	Weekend hourly emissions by Zone (μg/m^3)									
	Zones									
	1	2	3	4	5	6	7	8	9	10
0:00	10.4	9.2	9.5	12.2	11.3	7.9	9.9	9.9	15.1	17.1
1:00	10.3	8.9	9.2	11.3	11.4	7.8	8.8	6.9	13.4	12.4
2:00	9.6	8.4	8.8	9.8	10.8	7.1	8.8	6.3	12.3	10.5
3:00	9	8	8.9	9	10.6	6.6	8	5.9	10.9	7.2
4:00	9.1	7.5	9.2	9.2	10.4	7.6	7.5	6.1	9.1	6.4
5:00	9.7	7	9.3	8.7	10.6	7.3	7	6.4	8.3	7.2
6:00	11.4	7.1	10.1	9.7	11.2	6.8	6.9	6	9.1	10.7
7:00	12.7	7.5	11.1	9.5	12.9	7.6	7.5	6.7	7.9	10.9
8:00	11.8	6.8	11.2	8.8	13.3	8.3	7.7	6.8	7.1	9.9
9:00	11.7	6.8	10.8	9.7	12.2	8.2	6.5	7.1	6.9	9.2
10:00	11.5	6.4	10.1	8.4	11.6	8	5.5	5.3	6.4	8.2
11:00	10.6	6.8	10.3	8.4	10.8	7.5	5.5	5	6.6	7.8
12:00	10.2	6.7	9.9	7.9	10.3	6.9	5.8	4.8	6.4	7.4
13:00	10	5.6	8.8	7.1	9.9	6.7	5.2	4.5	5.9	6.3
14:00	9.5	5.3	8.5	6.7	10.1	6.1	5	4.3	5.2	5.8
15:00	9.4	5	8.3	6.5	10.2	6.2	4.5	3.9	5	5.9
16:00	9.1	4.7	8	6.3	9.8	6.6	5.1	4.4	4.9	6.5
17:00	9.1	4.7	9	6.9	10.3	7.2	7.3	4.6	5.4	8.3
18:00	8.9	5.3	8.7	8.1	11	8.6	9.6	6	7.1	10.5
19:00	9.5	6	9.8	9.8	11.3	10.7	8.5	7.1	9	13.2
20:00	9.9	7.4	11.8	12	11.1	13.5	10	11	10.9	18.6
21:00	10.6	8.7	11	12.8	11.7	12.6	9.9	13.8	14.6	21.4
22:00	9.7	8.9	11	12.5	11.3	13.6	10.8	10.7	12.3	17.9
23:00	9.5	8.7	11.8	12	10.7	9.7	10.8	8.8	14.5	18.4

Table 5
Average monthly hourly $PM_{2.5}$ emissions percentage compared to the annual maximum for weekdays by zone.

Zone	Average monthly hourly $PM_{2.5}$ emissions percentage											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Zone 1	0.00	1.60	1.60	10.10	28.40	40.70	43.40	26.50	5.30	2.00	0.00	0.10
Zone 2	0.00	0.70	2.80	10.90	29.20	39.00	30.80	21.20	6.10	2.00	0.00	0.10
Zone 3	0.40	1.30	6.10	14.20	31.70	44.60	38.30	29.90	8.10	0.50	0.00	0.10
Zone 4	0.00	1.40	6.20	15.60	24.50	36.00	27.60	22.40	6.50	1.20	0.00	0.00
Zone 5	3.90	2.50	1.10	12.90	28.30	27.60	21.20	18.80	4.20	1.10	0.00	0.00
Zone 6	0.50	0.80	5.10	20.80	44.80	49.60	37.10	35.10	12.90	3.40	0.00	0.00
Zone 7	0.00	0.30	2.20	20.80	37.00	39.80	32.00	34.30	18.60	7.50	1.00	0.00
Zone 8	0.00	0.00	1.60	16.80	26.50	39.50	37.50	27.50	21.70	7.10	2.10	0.00
Zone 9	0.00	0.00	2.10	17.50	21.40	37.80	35.60	21.20	14.30	4.80	1.90	0.00
Zone 10	0.00	0.10	2.30	10.70	25.00	52.90	53.80	23.90	11.90	3.90	0.50	0.00
Average	0.48	0.87	3.11	15.03	29.68	40.75	35.73	26.08	10.96	3.35	0.55	0.03
Zones between 2% and 15%	1	1	7	4	0	0	0	0	8	7	1	0
Zones > 15%	0	0	0	6	10	10	10	10	2	0	0	0
Classification			CM	VCM	VCM	VCM	VCM	VCM	CM	CM		

Table 6
Average monthly hourly $PM_{2.5}$ emissions percentage compared to the annual maximum for weekends by zone.

Zone	Average monthly hourly $PM_{2.5}$ emissions percentage (%)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Zone 1	0.00	2.20	2.50	10.30	23.10	36.20	39.10	22.30	10.20	0.90	0.00	0.00
Zone 2	0.00	1.70	2.70	17.30	34.40	46.50	45.00	33.20	13.40	0.70	0.00	0.00
Zone 3	0.30	2.50	3.00	16.50	32.60	34.90	38.90	25.50	8.50	0.60	0.00	0.10
Zone 4	0.00	1.80	3.70	13.10	28.10	31.20	37.30	24.40	8.60	0.70	0.00	0.00
Zone 5	1.70	3.20	2.50	15.50	28.60	31.30	26.40	16.30	7.30	0.70	0.00	0.00
Zone 6	0.00	0.60	5.80	20.10	36.20	32.00	44.50	30.90	10.20	2.80	0.00	0.00
Zone 7	0.00	0.10	2.10	21.10	42.50	37.70	43.80	37.40	18.00	8.00	1.00	0.00
Zone 8	0.00	0.00	1.50	24.00	36.20	29.50	42.10	42.60	20.40	11.20	1.90	0.00
Zone 9	0.00	0.00	2.00	22.00	39.70	27.40	41.90	31.80	14.40	6.80	0.90	0.00
Zone 10	0.00	0.00	4.70	16.80	26.80	44.10	51.40	26.80	13.20	6.80	0.50	0.00
Average	0.20	1.21	3.05	17.67	32.82	35.08	41.04	29.12	12.42	3.92	0.43	0.01
Zones between 2% and 15%	0	3	8	2	0	0	0	0	8	6	1	0
Zones > 15%	0	0	0	8	10	10	10	10	2	0	0	0
Classification			CM	VCM	VCM	VCM	VCM	VCM	CM	CM		

Table 7
Monthly mean temperatures by zone (°C).

Zone	Monthly mean temperatures (°C)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Zone 1	21.8	21.5	18.9	14.8	11.3	7.9	7.9	9.4	11.8	14.6	18.7	20.8
Zone 2	22.3	22.0	19.0	15.3	11.3	8.4	8.6	9.6	12.2	14.9	19.2	21.3
Zone 3	22.2	21.9	18.7	14.5	10.9	8.2	8.2	9.3	12.0	14.5	18.6	20.9
Zone 4	20.8	20.9	17.7	13.5	10.6	7.7	7.8	8.8	11.2	13.1	16.8	19.4
Zone 5	17.7	17.8	15.9	13.5	11.7	9.5	9.5	9.8	10.9	12.3	15.2	16.9
Zone 6	20.1	20.6	17.3	13.3	10.7	7.8	7.7	8.8	10.8	12.9	16.2	18.7
Zone 7	17.0	17.8	15.5	12.5	10.5	8.2	7.9	8.3	9.8	11.5	13.8	15.7
Zone 8	17.0	17.4	15.2	11.8	10.4	8.1	7.5	7.9	9.5	11.0	13.6	15.9
Zone 9	16.1	16.9	14.4	11.1	9.3	7.2	6.5	7.3	9.3	12.1	13.8	15.8
Zone 10	13.3	14.2	11.8	8.8	6.3	2.8	2.1	4.6	6.1	8.5	11.1	13.1
Average	18.8	19.1	16.4	12.9	10.3	7.6	7.4	8.4	10.4	12.5	15.7	17.9

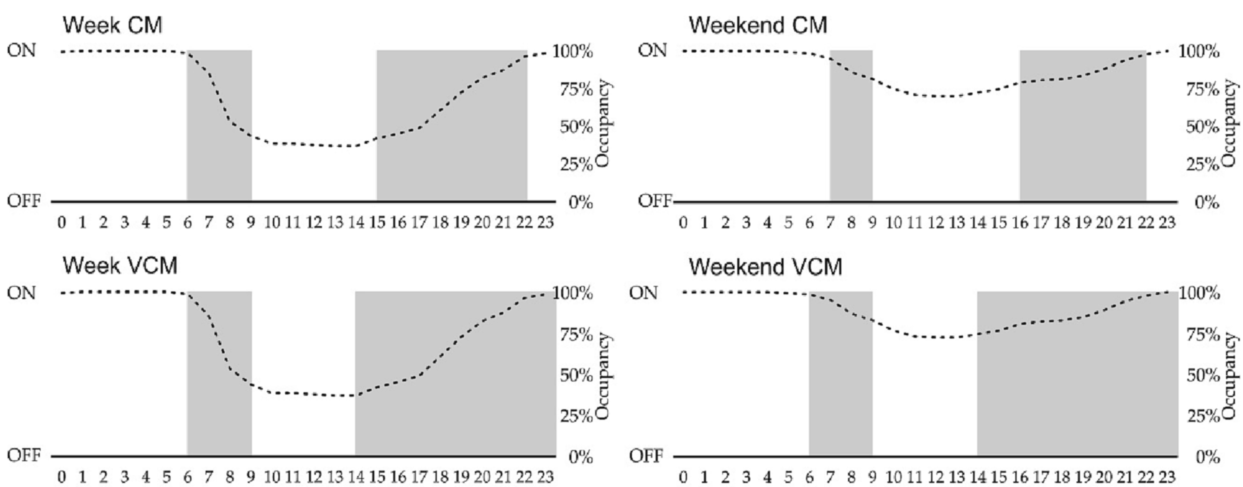

Fig. 7. Proposed hourly heating profiles and occupation profile.

heating is considered, and thus, a colder thermal sensation is assumed, are the months of May, June, July, and August, where for all the zones, the average monthly hourly emissions percentage compared to the annual maximum exceeds 15%.

Hence, the results obtained indicate that the highest emissions concentrations match the coldest months of the year, and the geographic location of each zone evaluated, showing that the environmental contamination associated with PM is mainly linked to the use of wood for heating [13]. In months with higher temperatures, a drastic reduction in emissions was observed, mainly in the monitoring stations.

3.4. Hourly heating profiles

Appendix A summarizes the hourly heating profiles for the CM and VCM heating periods in each zone studied. These were obtained from the algorithm laid out in section 2.5, using the emissions records. The four proposed profiles were defined using these, considering the statistical mode of the hourly data for weekdays and weekends.

Fig. 7 shows the proposed heating profiles. Moreover, Fig. 7 represents the relationship between the proposed profiles and the typical occupation of a sample of 40 dwellings in Zone 5 of Metropolitan Concepción. From these, it is seen that there are two heating periods during the day. The first is at the start of the day between, 6 am and 9 am on weekdays, from 7 am at weekends for CM months, and from 6 am for VCM. The second period mainly starts from 3 pm and lasts until 10 pm in the CM on weekdays, is between 4 pm and 10 pm on weekends, and is between 2 pm and 12 am for the VCM, both on weekdays and weekends.

One of the key aspects was to determine the concordance of the heating profiles developed for the operational profiles of each zone, as well as the ECSV profile. For this, Figs. 8 and 9 show the values obtained in the sensitivity analysis performed for kappa, sensitivity, and specificity. The results show how the developed profile has a high degree of concordance with the profiles of each area. In this sense, the kappa coefficient obtained values that oscillated between 0.45 and 0.91 on weekdays and between 0.33 and 0.83 on weekends. Therefore, the concordance values were acceptable and with values close to 1 in most of the comparisons. A lower concordance was only detected in zone 2 during the weekends. This may be due to the thresholds established to determine the operational modes based on the concentration of $PM_{2.5}$. Despite this, the concordance is within acceptable levels and serves to endorse the similarity of the profiles developed. Likewise, it can be verified that the sensitivity and specificity analysis does not show a clear trend in the differences detected between the profiles developed and the profiles of each area. Thus, the differences are due to both the activation and deactivation times of the heating system. This aspect does show a very notable difference when comparing the profiles developed with the profile used by the ECSV (systems activated 24 h a day). As can be seen, the kappa values in these comparisons were equal to 0. The fundamental difference was due to the hours in which the profiles developed did not use the heating systems. In this sense, the specificity was always null in all the comparisons with the profiles developed. These results reflect the limitations associated with the standard ECSV profile. A use throughout the day is not consistent with the behavior patterns of users. Thus, the use of the ECSV profile leads to obtaining unrepresentative results when compared to real operating conditions (i.e., the ECSV profile would usually obtain energy consumption values higher than the real ones).

Finally, it was decided to evaluate the similarity between the operational profiles developed and the occupational profile obtained

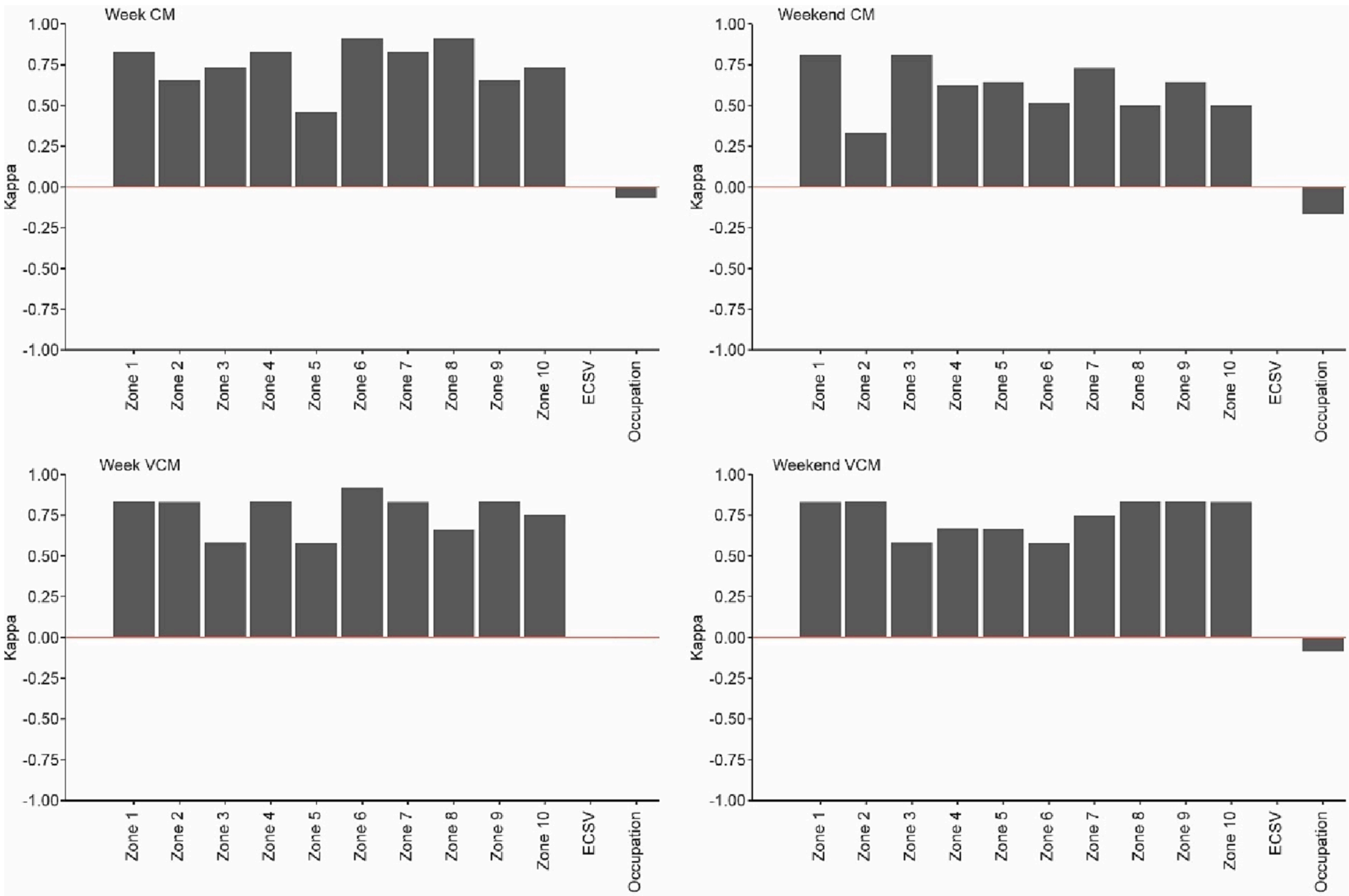

Fig. 8. Values obtained from the kappa coefficient.

through the surveys. This was done to determine if occupancy can be used to establish activation of the heating system. For this, it was considered that the system was activated when the occupancy percentage values were equal to or higher than the average value of the day. This would make it possible to eliminate those hours of the day in which the homes would be with low occupancy. Figs. 8 and 9 also show the values obtained in the sensitivity analysis. As can be seen, kappa obtained values equal to or less than 0, demonstrating the low concordance between the 2 profiles. Likewise, it was possible to appreciate how the sensitivity values obtained were less than 0.4. Therefore, the occupancy hours do not reflect an activation of the heating systems. Related to this, early morning hours (at 100% occupancy) do not have the systems activated. Thus, the occupancy profile is not useful for knowing when the systems are activated. In the case of the periods with the systems deactivated, a greater range of values is found for the specificity (between 0.41 and 0.58). This means that in hours when the interior spaces have low occupancy, the systems are also deactivated. Although there is agreement between the 2 approaches, the results also show that the low occupancy rate does not allow delimiting all the hours in which the system is deactivated (as indicated for the early morning hours). Thus, the results reflect that the operational profiles are not dependent on the occupation profiles.

3.5. Hourly heating profile developed vs existing approaches

Regarding the profiles developed, the data showed that most of the population in the evaluated zones has an intermittent use of heating, both on weekdays and weekends. Following the validation made, the intermittence is consistent with the occupation profiles in dwellings, where the start times for morning activities and the return times in the afternoon are seen as the periods where there are changes in the heating use (on and off). The monthly distribution allows seeing that, in the hotter months (Nov-Feb), there are almost imperceptible differences among the $PM_{2.5}$ records. This allows deducing that the influence of $PM_{2.5}$ emitting sources, other than heating systems, such as transport, industry, or commerce, is relatively low considering the total when wood-based heating is being used.

The proposed profiles outlined important differences with the criteria currently in use in the energy simulation processes of the Sustainable Building Standards for Housing and the Energy Rating of Housing, which establish a 24-h use profile for heating [16]. Moreover, the schedule profiles used in the simulation are overestimating, by 11 h, the use of heating for VCM months, and by between 14 and 16 h in CM months. This shows, just as in other research, an important gap in the schedules used for heating [20–22].

From the revision of other studies, several publications were found that address methods to improve the accuracy of results associated with determining energy demand. Most of them link occupation profiles with heating periods to establish building performance. However, this type of analysis tends to be for commercial buildings, schools, and offices, due to the direct connection between the occupation periods and the energy requirements of equipment and systems [22,23]. The determination of heating schedules has been studied in dwellings but based on other methodologies. For example, Shipworth et al. (2010) [20] carried out a study where the heating patterns were obtained by analyzing the data of surveys made to English homes. Their results also considered temperature measurement using sensors. Based on this, an average heating schedule of 8.2 h was estimated on weekdays, and 8.4 h on weekends. Meanwhile, Kane et al. (2015) [21], went into greater depth on environmental temperature data from 2009 to 2010. Their results showed

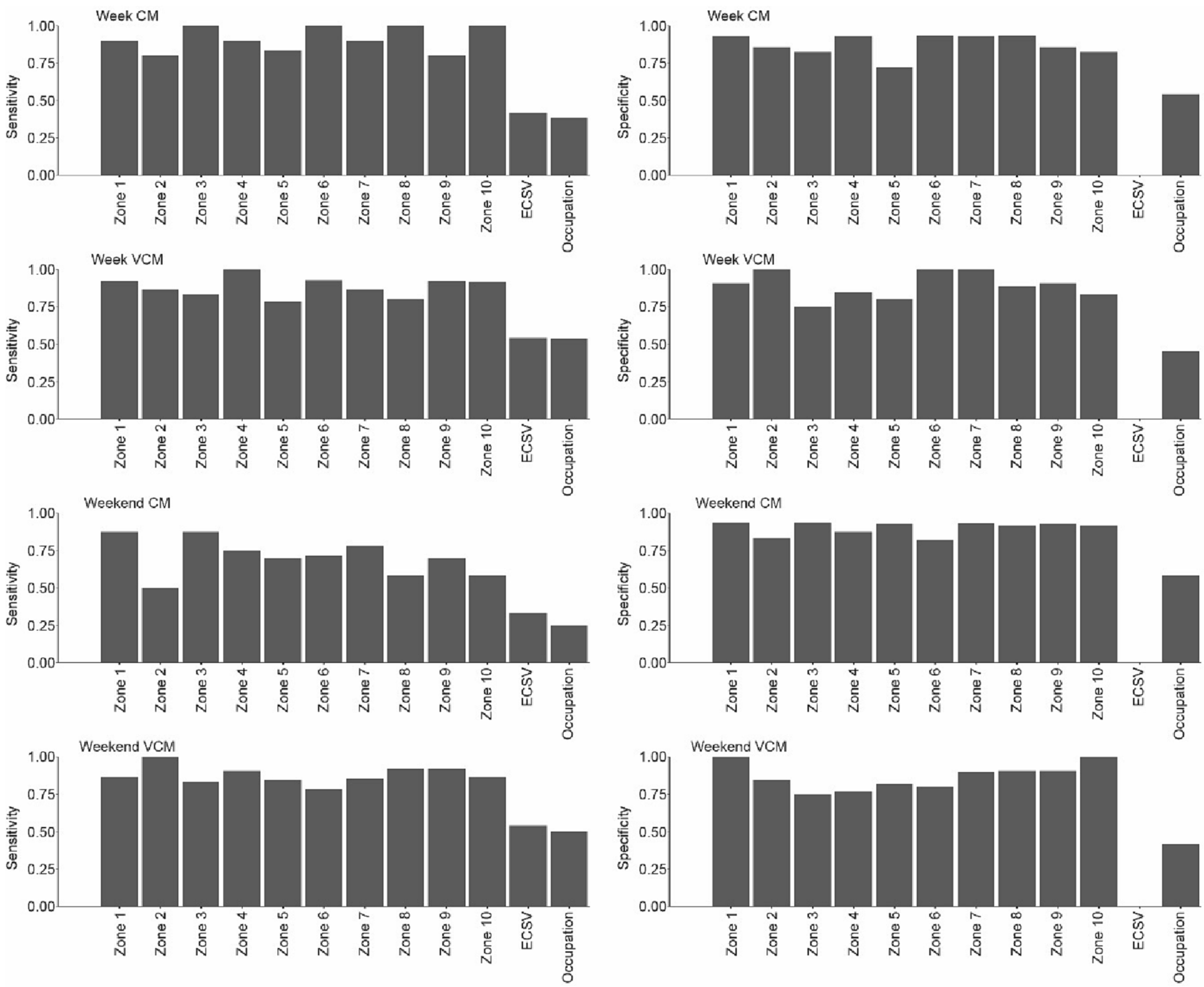

Fig. 9. Values obtained from the sensitivity and specificity coefficients.

that in 51% of the dwellings, a double heating pattern (morning – afternoon/evening) was observed, whereas 31% showed a unique pattern. Their days did not show clear differences between weekday and weekend patterns, but it was seen that the individual pattern was more common in dwellings with retired occupants or those who did not work. On the other hand, their data indicated that the double pattern had the median of their data between 6 am and 9 am in the morning, and 3 pm and 10 pm in the afternoon/evening. Meanwhile, a unique pattern was identified between 7 am and 11 pm. The works of the aforementioned authors are part of a series of studies made in the United Kingdom in recent years. In general, it can be seen that the results of these studies are quite similar to those obtained in this research, where the increase and decrease of emissions led to profiles with two heating schedules (morning and afternoon/evening), and with several daily hours ranging between 8 and 13 h. This result coincides with what is laid out by Hammer et al. (2019) [22], recording that heating in the United Kingdom commonly works intermittently, keeping it off during sleep hours, and when people are not at home.

On the other hand, the number of hours where heating is considered shows that, although there are some differences, these are quite minor. While the profile derived from the analysis of the different zones of Central-Southern Chile varies between 8 and 13 h, considering the analyzed period, the data of the studies in the United Kingdom show a variation that ranges from 8.2 to 15 h. This is more realistic, in comparison to the criteria of the ECSV and the CEV that consider 24 h a day, a condition that is difficult to comply with if it is considered that at least 50% of the country's population is within the lowest socio-economic segments [24]. This aspect is related to the concept of energy poverty. In this regard, in developed countries, the study has been focused on equality and those that are less developed in terms of access [25].

The effects of energy poverty in the policies, aimed at reducing emissions in the central-southern part of the country, have been studied in Chile. The results show that the effectiveness of the measures can be reduced by 25% using this concept [26]. One of the reasons why this has been associated with obtaining lower savings than foreseen is based, to a great extent, on the savings estimations made from a theoretical point of view, excluding with this, the effect of the occupants. This phenomenon has been seen in other locations as well. In Germany, for retrofits to be cataloged as economically viable requires a theoretical saving of 80%. However, the real measurements show that the potential saving is just 33% [27].

Bearing this in mind, it is very likely to find homes with some degree of energy poverty [28], with said possibility increasing in central-southern Chile [29]. This is relevant given that both the ECSV and the CEV establish savings percentages that may be affected, just as has been indicated by Galvin & Sunikka-Blank [7], as poor households, in

Table A1
Hourly heating use profiles by zone, for weekdays.

Time	Zones																				Statistical mode	
	1		2		3		4		5		6		7		8		9		10			
	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	**CM**	**VCM**
0:00	Off	Off	On	On	Off	Off	Off	Off	Off	Off	Off	Off	Off	On	Off	On	On	On	Off	Off	**Off**	**Off**
1:00	Off	Off	Off	On	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
2:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
3:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
4:00	On	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
5:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
6:00	On	On	On	On	Off	On	On	On	Off	Off	On	On	On	On	On	On	On	On	On	On	**On**	**On**
7:00	On	On	On	On	Off	On	On	On	Off	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
8:00	On	On	On	On	On	Off	Off	On	On	On	On	On	Off	On	Off	Off	Off	On	Off	Off	**On**	**On**
9:00	Off	Off	Off	Off	Off	On	Off	Off	Off	On	Off	Off	Off	Off	Off	On	Off	Off	Off	Off	**Off**	**Off**
10:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	On	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
11:00	Off	Off	Off	Off	Off	On	Off	Off	Off	Off	Off	Off	Off	On	Off	Off	Off	Off	Off	Off	**Off**	**Off**
12:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	On	Off	Off	Off	Off	**Off**	**Off**
13:00	Off	On	Off	Off	Off	Off	Off	Off	Off	On	Off	On	Off	Off	Off	Off	Off	Off	Off	On	**Off**	**Off**
14:00	Off	On	Off	On	Off	Off	Off	Off	Off	Off	Off	On	Off	On	Off	On	Off	Off	Off	Off	**Off**	**On**
15:00	Off	On	Off	On	Off	On	On	On	Off	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
16:00	On	On	On	On	On	On	On	On	Off	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
17:00	On	On	Off	On	On	On	On	On	Off	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
18:00	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
19:00	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
20:00	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	Off	On	**On**	**On**
21:00	On	On	On	On	On	On	On	On	On	On	Off	On	On	On	On	On	Off	On	Off	On	**On**	**On**
22:00	Off	On	Off	On	Off	On	On	On	On	On	Off	On	On	On	Off	On	On	On	Off	On	**Off**	**On**
23:00	Off	Off	On	On	Off	Off	Off	Off	Off	On	Off	On	Off	On	Off	On	Off	On	Off	On	**Off**	**On**

Table A2
Hourly heating use profiles by zone, for weekends.

Time	Zones																				Statistical mode	
	1		2		3		4		5		6		7		8		9		10			
	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	CM	VCM	**CM**	**VCM**
0:00	Off	Off	Off	Off	Off	On	Off	Off	Off	Off	Off	On	Off	Off	Off	Off	Off	Off	Off	On	**Off**	**Off**
1:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	On	Off	Off	On	Off	Off	Off	On	On	**Off**	**Off**
2:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
3:00	On	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
4:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
5:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	**Off**	**Off**
6:00	Off	On	On	Off	Off	Off	On	Off	Off	Off	On	Off	Off	On	Off	On	Off	On	On	On	**Off**	**On**
7:00	On	On	On	On	Off	On	Off	On	On	On	Off	Off	On	On	On	On	On	On	On	On	**On**	**On**
8:00	On	On	On	On	On	On	On	On	On	On	Off	On	Off	On	Off	Off	On	On	On	On	**On**	**On**
9:00	Off	On	On	Off	Off	Off	Off	Off	On	On	Off	Off	On	On	On	Off	Off	Off	Off	Off	**Off**	**Off**
10:00	Off	Off	On	Off	On	Off	Off	Off	On	On	Off	On	On	Off	On	On	Off	Off	Off	Off	**Off**	**Off**
11:00	Off	Off	Off	Off	Off	On	Off	Off	Off	Off	On	Off	Off	On	Off	Off	Off	Off	Off	Off	**Off**	**Off**
12:00	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	On	Off	Off	**Off**	**Off**
13:00	Off	On	On	Off	Off	Off	Off	On	Off	Off	Off	Off	Off	Off	On	Off	Off	Off	On	Off	**Off**	**Off**
14:00	Off	On	Off	Off	Off	Off	Off	Off	Off	Off	Off	On	Off	Off	Off	On	On	On	On	On	**Off**	**On**
15:00	Off	On	On	On	Off	Off	Off	On	Off	On	Off	On	Off	On	On	On	Off	On	On	On	**Off**	**On**
16:00	On	On	Off	On	On	On	On	On	Off	On	Off	On	On	On	On	On	On	On	On	On	**On**	**On**
17:00	On	On	Off	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
18:00	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
19:00	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
20:00	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	On	**On**	**On**
21:00	Off	On	On	On	On	On	Off	On	On	On	On	On	On	On	On	On	Off	On	Off	On	**On**	**On**
22:00	Off	On	Off	On	Off	On	On	On	On	On	Off	On	Off	On	Off	On	On	On	Off	On	**Off**	**On**
23:00	Off	On	On	On	Off	On	Off	Off	Off	On	Off	On	Off	On	Off	On	On	Off	Off	On	**Off**	**On**

general, do not consume the energy required to reach thermal comfort. Something similar has been established in Chile, where users state having thermal comfort temperatures close to 14 °C [29].

4. Conclusions

This research sought to establish typical heating use profiles of central-zone Chile. For this, the $PM_{2.5}$ emissions were studied in zones with elevated atmospheric contamination levels. Based on the results of the study, the following conclusions were obtained:

1. The analysis showed that the highest concentrations take place in the coldest months of the year (with mean values of up to 53% with respect to the annual maximum), which is why the contribution of other particulate matter-generating sources such as industry, commerce, and transportation, would end up being marginal within the overall analysis. For the same reason, it is clear that the increase in concentrations comes mainly from residential heating. In this sense, in the summer months (not heating) the average increases with respect to the annual maximum are less than 5%. This justifies the importance of establishing heating profiles associated with the population under study.
2. The heating period in the different zones extended for between 6 and 8 months, a period where increases in the intensity of use for the months closest to winter were seen.
3. Regarding the proposed profiles, it was seen that the concentrations experience increases in two periods of the day. The first is in the mornings, for around two hours, after which a clear drop was observed, which matches the least occupied period for the dwellings. The second is in the afternoons, from about 3 pm, with a slight increase until 6 pm and a peak between 6 pm and 10 pm in cold months, and until 12 am in very cold months. The results also showed that heating is not conditioned in all periods of the day due to the occupation. Proof of this is that, during the night (12 am – 6 am), despite having a maximum occupation, the emissions are reduced considerably. This aspect should be considered in simulation and evaluation processes, as just considering the occupation and comfort temperature implies that people have enough resources to keep their dwellings comfortable at all times. This condition is not reflected in the studied population, since the emissions are mainly concentrated in just two periods of the day. The distribution of the emissions implies that there is a relevant population group facing energy poverty due to the intensive use of wood as an energy source, which is important to consider, especially when the effectiveness of measures associated with energy improvements for dwellings is being studied.

The findings of this research provide information to establish more realistic criteria for the effect that energy improvement projects can produce for dwellings, especially when detailed information about occupant behavior is not known when it comes to heating their homes.

Finally, it has to be highlighted that the top-down methodology used in this study, and validated through the bottom-up data, can be replicated in those countries where there are environmental monitoring stations, and a tradition of using wood as a fuel, being also able to obtain heating use patterns that are representatives of the housing built, to reduce the performance gap of the energy heating systems, the simulations, or the processes of energy certification. Finally, it is necessary to mention some limitations. The study considered quite a lot of information collated from external sources. The data on concentrations came from SINCA records, so it was not possible to know the procedure behind this or the information associated with equipment calibration. However, in the first stage of the research, the records were reviewed to discard variables that could alter the representativity of the data, while in general the averages of more than one monitoring station were considered, which helps to reduce the impact of any environmental alterations resulting from other causes. Another limitation is associated with the number of zones evaluated. Although data were collected from all the zones with PDAs, not all of them had a monitoring station, a situation that mainly occurred in the communes of the country's central zones. Finally, another aspect to mention is that the validation was made with data from communes with just a single PDA (Zone 5 – Concepción), as only these had surveys of dwellings. In this sense, the occupation records measured in the week do not differ greatly from the hourly occupation profile described in the CEV, but do so at the weekends, since the CEV provides just one profile. These are aspects that could be addressed in future research, by surveying the occupation in other zones that would allow discussing the need of generating differentiated occupation profiles for weekdays and weekends.

Declaration of Competing 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.

Data availability

The authors do not have permission to share data.

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Appendix A

Table A1 and Table A2

Appendix B

Personal Information Survey

Fondecyt Project N°3160806

FONDECYT Fondo Nacional de Desarrollo Científico y Tecnológico

Participant N°:

Name: ____________________

Address: ____________________

Gender ☐ Male ☐ Female **Approximate weight** __________ **Age:** __________

Mark with an X, the times you usually use your home

Week		Time											
Monday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
	Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
Tuesday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
	Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
Wednesday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
	Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
Thursday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
	Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
Friday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
	Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
Saturday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
	Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
Sunday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
	Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00

Degree of importance and satisfaction of the attributes of your home	Degree of importance					Degree of satisfaction				
	VI	PI	R	PU	NI	VS	PS	R	PU	VU
1. Constructive quality	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. Energy consumption of the dwelling	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Energy performance of the dwelling	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Thermal comfort of the dwelling	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. Environmental quality	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Degree of importance for you
VI Very important
PI Pretty important
R Regular
PU Pretty unimportant
NI Not important at all

Degree of satisfaction obtained
VS Very satisfied
PS Pretty satisfied
R Regular
PU Pretty unsatisfied
VU Very unsatisfied

How many times have you had respiratory illnesses in the last year? (Cold or other)

☐ None ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 or more

How much money ($CLP) have you spent on doctors and medicine due to said illnesses? (Cold or other)

☐ Nothing ☐ <10,000 ☐ 10,000-20,000 ☐ 20,000-30,000 ☐ 30,000-40,000 ☐ >50,000

Do you think that if your home had a better energy standard you would spend less money on medicine?

☐ Does not know ☐ Yes ☐ No

Participation in the research is voluntary, previously informed, and without economic or contractual relationship with the researchers. This consent may be reviewed with other people before signing it. Two identical copies of the "Letter of Consent" document have been signed, one remaining in the possession of the participant.

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