DEFINITION OF OCCUPANT BEHAVIOUR PATTERNS WITH RESPECT TO VENTILATION BY MEANS OF MULTIVARIATE STATISTICAL TECHNIQUES

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ABSTRACT

It has been demonstrated that there is a strong relationship between occupant behaviour and the thermal performance of dwellings. At the same time, some aspects of this behaviour, especially with respect to natural ventilation, constitute some of the most important sources of uncertainty in the field of building energy simulation. A survey about perception of thermal comfort and occupant behaviour was carried out in Santiago de Chile during December 2009 and January 2010 in a pilot case study corresponding to an apartment building. This paper proposes a methodology based on the systematic application of multivariate statistical techniques which were applied to the collected data of the survey. The results of the analyses show that daytime ventilation is not strongly correlated to the perception of thermal comfort, probably because it is mainly oriented to hygienic purposes. On the contrary, nigh ventilation appears as a very significant predictor for the same dependent variable. The final objective of these models corresponds to the definition of occupant behaviour profiles which can be used as hard data to make calculations of thermal behaviour of dwellings more accurate and reliable. At the light of the results of the energy building simulations, night ventilation presents a high potential as passive cooling technique, considering also the climatic conditions of Santiago de Chile.

KEYWORDS

Summer thermal comfort, occupant behaviour patterns, energy building simulation

1. INTRODUCTION

It has been demonstrated that there is a strong relationship between occupant behaviour and thermal performance of dwellings. Indeed, according to Macdonald et al. (1999), some variables related to occupant behaviour constitute some of the main sources of uncertainty in the field of energy building simulation [1]. In that sense, depending on the variability of aspects such as scheduled internal gains or natural ventilation (by means of manually operable windows), a wide range of variation in the energy consumption of dwellings may be expected. This also can be observed through various studies, where large differences in the thermal behaviour of similar buildings have been observed, which suggests that occupant behaviour exerts a strong influence [2].

Uncertainty and sensibility analyses frequently deal with this situation, since they can generate a great range of forecast values based on the distribution of the input variables. For example, in the case of the physical properties of building materials, this variability has been studied and may be obtained from references as Clarke et al. (1999) or Lomas & Bowman (1987) [3] [4]. However, Hyun et al. (2008) explain that the widely varying occupant influences - especially related to operable windows - have not been directly measured or investigated [5].

At the same time, most of the building energy simulation programs are deterministic, rather than probabilistic and consequently their results frequently are not expressed in probabilistic terms. Additionally, a considerable difference between the standard values of ventilation used for simulations (based on average occupant behaviour) and the ventilation patterns in real occupied dwellings may be expected. Therefore, if the aim is to represent a wide range of cases based on a more real approach (instead of a singular and/or standard case study), it is necessary to characterize the occupant behaviour in terms of patterns to be used as input data in energy building simulations.

Due to the link between occupant behaviour and energy consumption, it is important to define it from the interaction with the control mechanisms of windows during both day and night, and also establishing the reasons for that specific behaviour, as is recommended by IEA (1988) [6]. Andersen et al. (2009) indicate that most of the energy building simulation programs provide possibilities of regulation of control systems (such as opening/closing windows), but there are no guidelines for how the simulated environment should be managed by the software [7]. Similarly, Yu et al. (2011) explain that it is difficult to completely identify the influences of occupant behaviour through simulation due to users' behaviour diversity and complexity; current simulation tools can only imitate patterns in a rigid way [8]. Accordingly, the definition of a set of behaviour patterns – based on the quantification of real inhabitants' behaviour – would significantly improve the validity of the outcomes of the simulations.

Consequently, this study tries to establish occupant behaviour patterns for apartments from the real estate market of Santiago de Chile based on field data and also determining their impact on the summer thermal comfort. According to this, four main research questions were formulated:

(1) Do patterns of occupant behaviour exist with respect to perception of thermal comfort and ventilation (by means of windows opening)?

(2) Do different occupant behaviour patterns lead to significant differences in the thermal comfort of the apartments in summer?

(3) Which are the most important physical variables (e.g. wind conditions, difference between indoor and outdoor temperatures) in terms of their influence with respect to the ventilation rate in each one of the occupant behaviour patterns?

2. METHODOLOGY

2.1 Research data

Due to the importance of the occupant behaviour and ventilation on the thermal behaviour of apartments it is necessary to collect data about these aspects based on real sources. Nonetheless, due to the lack of references in the national state of art of Chile, a survey to obtain this information is required.

The pilot case study corresponds to the *Edificio Don José*, located in the Santiago borough, city of Santiago. This is an apartment building, constructed in 1993-1994, with 22 floors and 8 apartments per floor. The building is situated in an urban environment, near to the city centre. The survey was applied to 91 randomly selected apartments in two summer months (December 2009 and January 2010). The sample size corresponds, consequently, to 91 cases over a population of 166 apartments. The margin of error and the confidence level are 6% and 90%, respectively. It is important to remember that the scope of the survey is related to the indoor environment and occupant behaviour in apartments of Santiago de Chile based on a pilot case study. Due to this, the survey frame was considered as appropriate. A most ambitious experience may be proposed as further research. In that case, the population of the survey can be extended to various apartment buildings in Santiago de Chile.

2.2 Approach

The seminal articles of van Raaij & Verhallen – published in the 1980s – distinguish two different occupant behaviours as determinant of energy house in the home. According to them, purchase and maintenance–related and usage–related energy behaviour can be identified [9].

In this study, occupant behaviour was defined in the sense of the usage–related behaviour involved the day–to–day energy–conscious behaviour of use of ventilation (by means of windows opening) and passive/active strategies for thermal conditioning (such as external solar protection to avoid overheating or the use of heating systems in winter). It is important to notice that in most households, energy behaviour generally does not constitute a separate type of behaviour but is contingent on other behaviour associated with, for example, household work, childcare, in–home entertainment and sleeping [9]. This situation is highly consistent with the findings of this study, especially with respect to daytime ventilation, as it will be explained latterly.

Fig. 1 presents the methodology of this study, which is based on the systematic application of multivariate statistical techniques to the collected data of the survey. As a first step, the definition of behaviour variables was carried out (Fig. 1a) with the aim of obtaining factors of behaviour by means of a factor analysis (Fig. 1b). Principal component analysis – a kind of factor analysis according to the procedure to extract factors – can be used for exploratory purposes, in order to know the relations structure on a specific set of variables.

Afterwards, a discrete choice model was implemented to determine the level of incidence of the factors of behaviour on the overall predicted thermal comfort (Fig. 1c). If these independent variables have enough explanatory capacity, they will be able to predict the behaviour of the dependent variable (perception of thermal comfort) in the analyzed apartments.

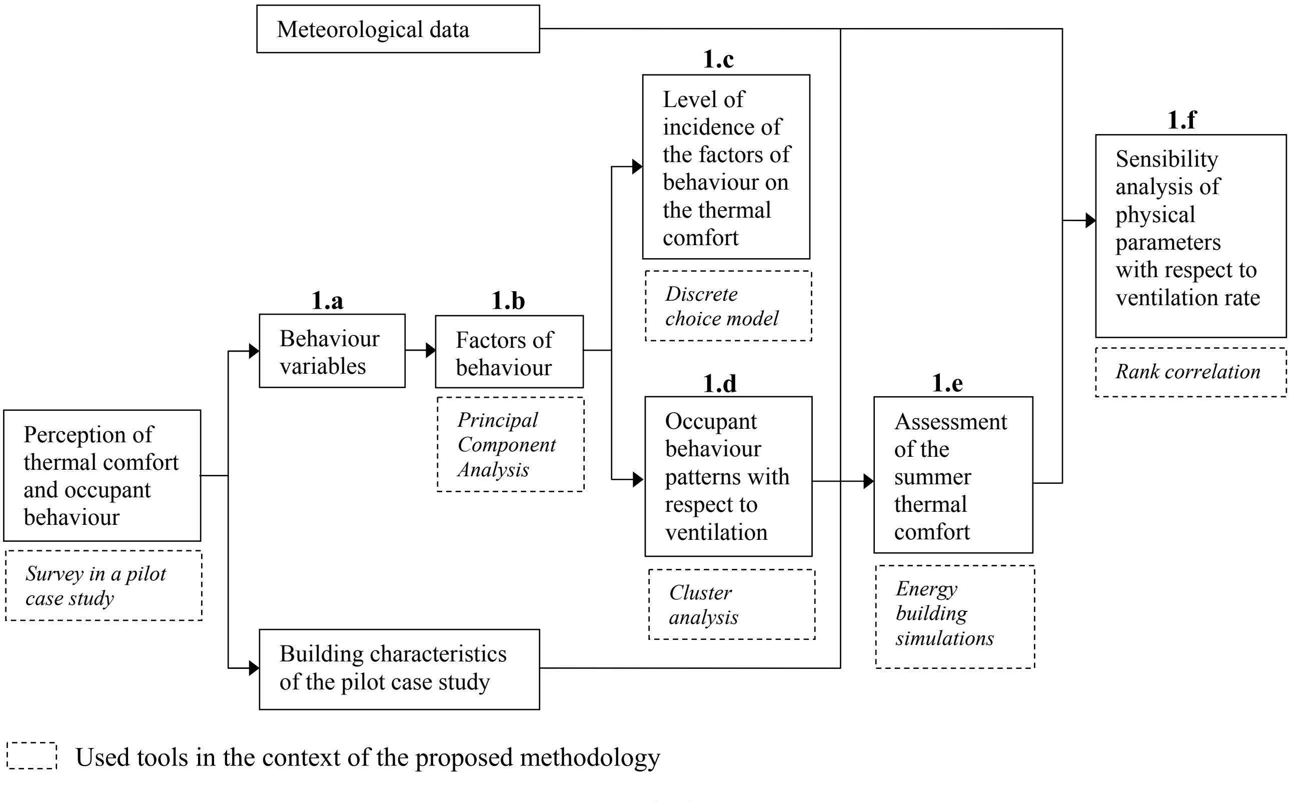


Figure 1. Methodology

In the fourth step the occupant behaviour patterns with respect to natural ventilation were established by means of a cluster analysis (Fig. 1d). Indeed, four different profiles were identified (P1, P2, P3 and P4) which were defined as *cool*, *conscious–moderate*, *comfort* and *conscious–warm* respectively. With this information, energy building simulations were performed using the TAS software [10], with the aim of assessing the summer thermal comfort in the studied cases (Fig. 1e).

Finally, by means of a sensibility analysis, the influence of physical variables (e.g. wind conditions, difference between indoor and outdoor temperatures) with regard to the obtained ventilation rate in each one of the occupant behaviour patterns was established (Fig. 1f).

3. RESULTS

3.1 Definition of factors of behaviour by means of a Principal Component Analysis

Principal Component Analysis was used to identify factor underlying occupant behaviour, since this technique allows the detection of subjacent dimensions that, in this context, can be understood as drivers of behaviour.

Table 1 presents the seven variables that were considered to carry out this analysis. These questions were selected in order to represent the different aspects related to the perception of thermal comfort, natural ventilation and strategies and systems that affect the thermal behaviour of apartments. Additionally, the obtained ratio of 12.5 between the number of observations (N=88) and the number of variables can be considered as appropriate [11].

Table 2 shows the rotated component loadings, which give information about the strength of the relationships between the variables and the obtained components. These loadings are expressed in terms of correlation coefficients (with values between 0 and 1). According to the Kaiser's criterion (Eigen values >1), four components were extracted, which account for the 73.2% of variance.

Subject	Survey questions	Behaviour variables
Perception of thermal comfort	Q6	Thermal sensation in winter*
	Q10	Thermal sensation in summer*
Ventilation	Q16	Daytime ventilation in winter
	Q20	Daytime ventilation in summer
	Q24	Use of night ventilation in summer
Strategies and systems	Q13	Presence of external solar protection
	Q27	Use of heating systems in winter

* To define the categories of these questions, the 7 point subjective scale of EN15251 [12] was considered

Table 1. Definition of behaviour variables for the Principal Component Analysis

Behaviour variables	Components				Communalities
	C1	C2	C3	C4	
Q6		0.85			0.76
Q10			0.65		0.52
Q13				0.90	0.82
Q16	0.76				0.75
Q20	0.86				0.81
Q24			0.84		0.74
Q27		-0.71			0.72

Rotation method: Varimax with Kaiser normalization

Note: component loadings <0.6 are suppressed according to the sample criterion established by Hair et al. [11]

Table 2. Component loadings and communalities based on the Principal Component Analysis (N=88)

In consequence, the four defined components of the rotated matrix with their proportions of explained variance are:

C1: *Daytime ventilation*, both in winter and summer [21.3%]

C2: *Perception of favourable thermal comfort in winter and avoiding the use of heating appliances*. Both situations can be related to a good thermal behaviour since occupants declare they generally do not feel cold during winter and at the same time they minimize the use of heating [18.7%]

C3: *Perception of unfavourable thermal comfort in summer and use of night ventilation*. This situation can be represented for occupants that describe their apartments in summer as “warm” or “hot” and consequently, open windows during night time [17.4%]

C4: *Presence of solar protection* [15.8%]

Fig. 2 presents perceptual maps per orientation, based on the factor scores obtained by means of the Principal Component Analysis. In this case, perceptual maps are the graphical expression of the associations between two components that compose the solution and where their observations are clustered by a specific criterion.

Fig. 2 (left) shows the perceptual map of C3 vs. C4 (horizontal and vertical axis, respectively). According to this, both north and south orientations were characterised as comfortable in summer and they do not present solar protection, which can be considered as expected. Indeed, in Santiago de Chile (33°28’S; 70°78’W), direct solar radiation can be easily controlled in the north orientation by means of an overhang (which can be provided, for example, by an upper balcony) and there is no need of any kind of solar protection for southern facades. On the contrary, western orientations (W, NW and SW) may present and unfavourable thermal behaviour in summer, since they were characterized as “not comfortable”. At the same time – and probably due to this – these orientations concentrate the presence of solar protection, which can also be considered as expected.

Fig. 2 (right) presents the perceptual maps of C3 vs. C1, which means that the perception of summer thermal comfort is compared to daytime ventilation. However, it is not possible to identify a correlation pattern between them. For example, there is not a direct relationship between orientations that declare comfortable indoor conditions in summer and a specific behaviour with respect to ventilation (ventilate or not ventilate). This situation can be understood from the idea that daytime ventilation of C1 may be mainly oriented to a hygienic purpose (instead of cooling). However, to test this hypothesis is necessary other kind of multivariate analysis technique which be able to predict the perception of thermal comfort.

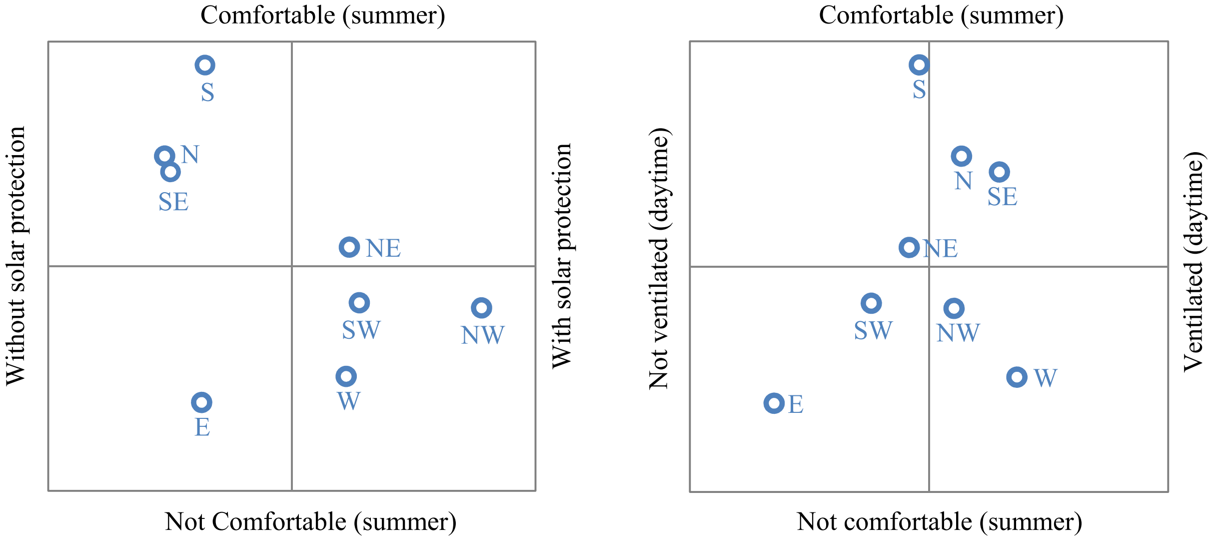


Figure 2. Perceptual maps of C3 vs. C4 (left) and C3 vs. C1 (right) per orientation

3.2 Incidence of the factors of behaviour on the overall thermal comfort by means of a discrete choice model

The logistic regression analysis is a mathematical model with the aim of predicting the behaviour of a dependent variable as function of one or more independent variables. The objective of this model is to predict the probability of occurrence of an event with a dependent variable that assumes the value of 1 when the event occurs and zero in the absence of the event. The prediction is made from a group of independent variables with explanatory capability with respect to the dependent variable

With the aim of predicting the level of incidence of the variables that determines the perception of thermal comfort, one question of the survey (Q41) was expressed as: "Do you feel comfortable in your apartment in terms of thermal comfort?" The two possible answers were "yes" or "no", which convert this variable in dichotomical. Therefore, the probability of occurrence of the answer "yes" (*Y=1*) in the question 41, can be expressed through the following logistic regression:

$$\boldsymbol{P}_{\left(\boldsymbol{Q41}=\frac{\mathbf{1}}{C_{i,i=1\ldots4}}\right)} = \frac{\mathbf{1}}{\mathbf{1}+e^{-(a+b_1C_1+b_2C_2+b_3C_3+b_4C_4)}} \qquad (1)$$

where C_1, C_2, C_3 and C_4 are the factor scores that were obtained through the Principal Component Analysis, b_1, b_2, b_3 and b_4 are the coefficients for these variables, *a* is a coefficient of the model and *e* is the base of natural logarithms.

Table 3 presents the obtained coefficients for the logistic regression model proposed for the Q41 of the survey. According to the obtained solution, b_1 is a not significant coefficient. This means that component C_1 is not significant to predict the probability of occurrence of Q41. This situation can be understood from the previously mentioned hypothesis that daytime ventilation is mainly oriented to a hygienic purpose, instead of cooling.

Another important aspect regarding the obtained coefficients of Table 3 is the sign of b_3. As can be observed, this is negative, which means that while the value of C_3 is higher, the probability that Q41 can be answered as "yes" is lower. In other words, if the thermal sensation of the occupants during summer is hot, there are more possibilities that the people feel uncomfortable in their apartments from a wider sense.

Considering the obtained coefficients, the logistic regression applied can be expressed as:

$$\boldsymbol{P}_{(\boldsymbol{Q41})} = \frac{\mathbf{1}}{\mathbf{1}+e^{-(1.97+0.30\,C_1+0.62\,C_2-0.90\,C_3+0.97\,C_4)}} \qquad (2)$$

In the equation (2), it can be observed that the most important aspects related to the overall perception of thermal comfort in the apartment (Q41) are solar protection (C_4) and perception of summer thermal comfort and night ventilation (C_3). These weightings can be considered as expected since the survey was taken during summer. Indeed, it is not surprising that with the presence of solar protection, a not excessive indoor temperature and night ventilation most of the people considered their apartment as comfortable.

	Coefficients	Standard error	Z value	p-value
a	1.97	0.48	4.09	4.38E-07***
b_1	0.30	0.30	1.01	0.313
b_2	0.62	0.35	1.77	0.076*
b_3	-0.90	0.45	-2.00	0.046**
b_4	0.97	0.49	1.99	0.046**

Significant variables for: *** $p<0.01$; ** $p<0.05$; * $p<0.1$

Goodness-of-fit: The number of cases correctly predicted was 76 (86.4%). Also, the McFadden's R^2 was 0.293 above the minimum value of 0.28 (for a proportion of 80/20 in the answers of the dependent variable) [13]

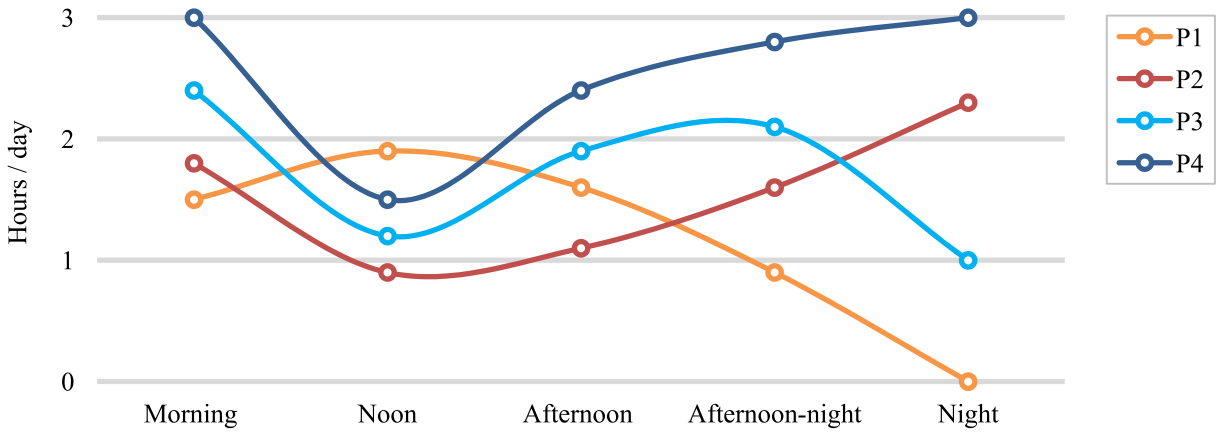
Table 3. Obtained coefficients from the multivariate logistic regression

3.3 Definition of occupant behaviour patterns by means of a cluster analysis

The seminal study carried out by Punj & Stewart (1983) established that cluster analysis is a statistical method for classification. According tho them, the essence of classification is that certain things of as related in a certain way. Indeed, the objective of this can be defined as the identification of a group of entities that share certain common characteristics [14]. According to Vivanco (1999), the use par excellence of cluster analysis is the generation of typologies. A typology is a group of cases that present a strong similarity [15]. In this context, cluster analysis appears as an appropriate tool to identify occupant behaviour patterns from the collected data of the survey. Van Raaij & Verhallen (1983) attempt to apply clustering procedures to both original variables and factor scores obtained by means of a Principal Component Analysis [9]. However, natural groupings were not found probably due to the inclusion of numerous types of occupant behaviour, where energy behaviour represents in practice just one aspect of them.

For the purposes of this research, the hierarchical technique was chosen as clustering method. This classifies by stages through a process that follows the structure of a tree and where each stage of the process generates a new branch. In this context, the selection of the factor scores of the Principal Component Analysis as variables for the procedure is justified since it allows correcting the interdependencies. Also, the non-equivalence of metrics between the original variables suggests the use of this procedure.

In the range of solutions proposed for the model, the alternative of 4 clusters was selected as the most representative, since their groups are consistent and well defined. Therefore, four profiles (P1, P2, P3 and P4) were characterized as function of all the originally considered behaviour variables. Fig. 3 presents the quantitative characterization of these behaviour profiles in terms of the number of hours of ventilation per day (excluding the period between 24:00 and 08:00) in summer. As can be observed, P2, P3 and P4 present a similar behaviour (in terms of the shape of their curves) with respect to the different times of the day, excepting for the period between 21:00-24:00. On the contrary, P1 presents a very particular behaviour, since the highest level of ventilation occurs at noon (the hottest period time of a summer day in Santiago). This situation is consistent with the qualitative characterization of the behaviour profiles in terms of thermal sensation in summer vs. summer daytime and night ventilation that is presented in the Fig. 4. According to this, the four profiles were described as *warm* (P1), *conscious-moderate* (P2), *comfort* (P3) and *conscious-cool* (P4).



Note: 3-hours periods are defined as morning (9:00-12:00), noon (12:00-15:00), afternoon (15:00-18:00), afternoon-night (18:00-21:00) and night (21:00-24:00)

Figure 3. Quantitative characterization of the behaviour profiles in terms of number of ventilation hours (by means of manually operable windows) per day in summer (mean values)

P1 can be identified as *warm* due to the thermal sensation in summer is perceived as "neutral" and also they do not use night ventilation (probably they think that do not need to ventilate during nigh-time). This is also consistent with the reasons for opening windows in summer that they declare since a high percentage of cases are associated with hygienic purposes (and not for cooling) (Fig. 5). On the contrary, P4 is related to the concept of *conscious-cool* because its category for thermal sensation is "hot" and both ventilation regimes (daytime and nigh-time) are identified as high. This situation suggests that night ventilation may be motivated for cooling reasons, which can also be observed from the reasons for ventilating of Fig. 5. Similarly, P2 was identified as *conscious-moderate* because the thermal sensation in summer is perceived also as "hot", but the level of night ventilation is lower than in the case of *conscious-cool* (P4). However, its level of summer daytime ventilation is low, which represents a key aspect concerning the summer thermal comfort that this behaviour profile can latterly obtain. Finally, in an intermediate level, P3 was defined as *comfort* since to the thermal sensation in summer is perceived as "warm" (not too hot) and probably due to this, its level of night ventilation is medium.

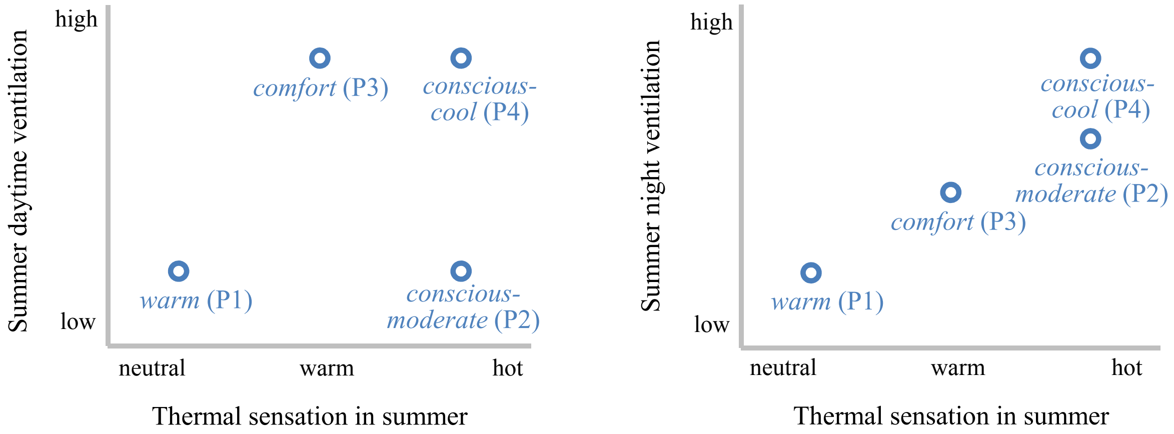
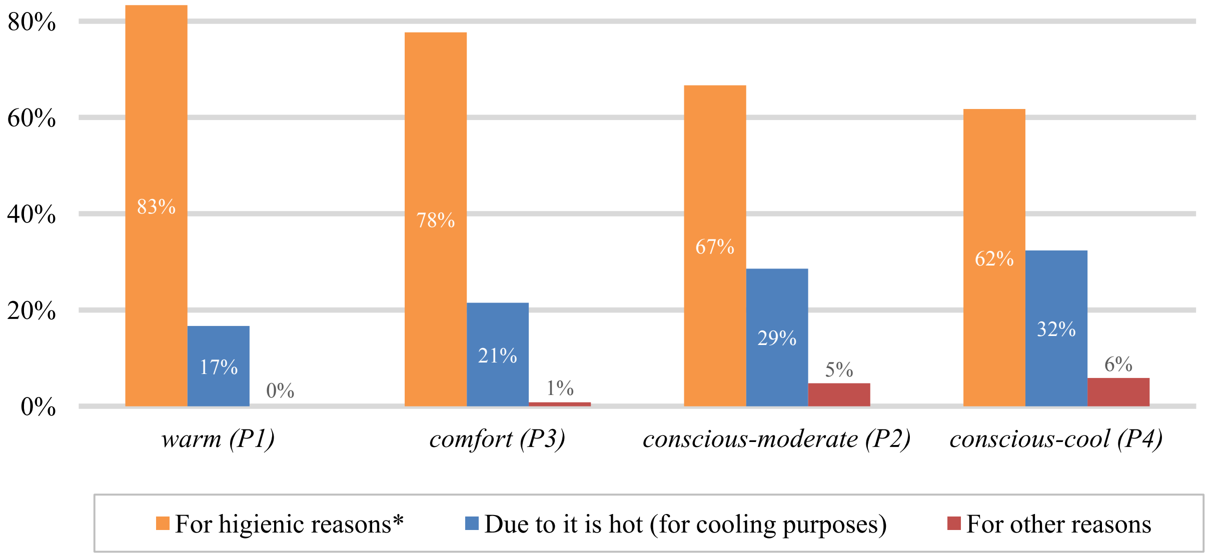


Figure 4. Qualitative characterization of the behaviour profiles in terms of thermal sensation in summer vs. summer daytime ventilation (left) and summer night ventilation (right) (median values)



Note (*): Corresponding to the answers of the survey: "for entering fresh air" and "while the rooms are cleaned"

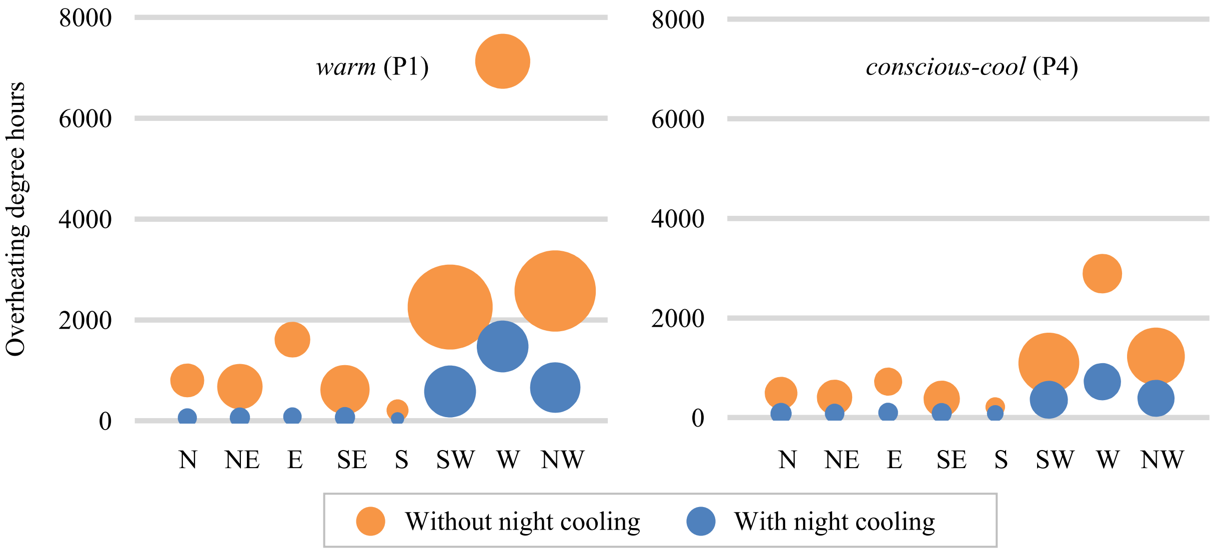
Figure 5. Column chart of results for the question Q22 (percent with regard to the total number of mentions): "Which are the reasons for opening windows in your apartment in summer?" by behaviour profiles

3.4 Assessment of the summer thermal comfort applying the behaviour profiles

After the definition of occupant behaviour patterns in terms of profiles, energy building simulations were carried out. These numeric simulations were performed using TAS software [10], applying the obtained behaviour profiles as input data (in terms of window opening regimes). The four profiles were applied to a floor layout of the pilot case study, using also the collected data of the survey to define internal gains of the different apartments (between 105 and 115 Wh/m²/day, including occupation, lighting and equipments). Hourly meteorological data for the year 1989 in Santiago de Chile were taken from ASHRAE (2001) [16], which were also compared and validated with respect to the monthly values of the NCh 1079 national standard (based on a period of 30 years of meteorological observations) [17] .

The aim of these numeric simulations is to find a relationship between occupant behaviour patterns, ventilation rates and thermal behaviour. The proposed profiles, at the moment, just represent an intention of ventilation (since they are defined as function of windows opening), but they need to be characterized in terms of their impact on the thermal comfort of the apartments. Fig. 6 presents the number of summer overheating degree hours according to the adaptive model of EN 15251 [12] for *warm* (P1) and *conscious-cool* (P4) profiles per orientation. These results are highly consistent with regard to the perception of summer thermal comfort per orientation in the perceptual maps of the Fig. 2.

According to this graph, it is possible to observe the favourable impact of the night ventilation strategy for reducing overheating. However, this thermal behaviour (when night cooling is applied) probably is also influenced by windows operation during daytime, as can be observed by the simulation outputs (in terms of overheating degree hours) of the different occupant behaviour patterns. Anyway, these results can also be explained considering the climatic characteristics of Santiago (because of the difference between outdoor and indoor temperatures that it is possible to reach during night-time). It is important to notice that the recommended climate conditions for the application of night cooling according to the literature (e.g. a range between 30-36°C as maximum allowable daytime temperatures and 8°C as minimum diurnal temperature swings [18] [19]) can be perfectly applied to the Mediterranean climate of Santiago de Chile as it has been observed in previous studies.



Note: The centre point of each bubble is the extent of overeating measured in degree hours (mean value for the different spaces). The area of the bubble represents the standard deviation for the distribution of values including the same rooms.

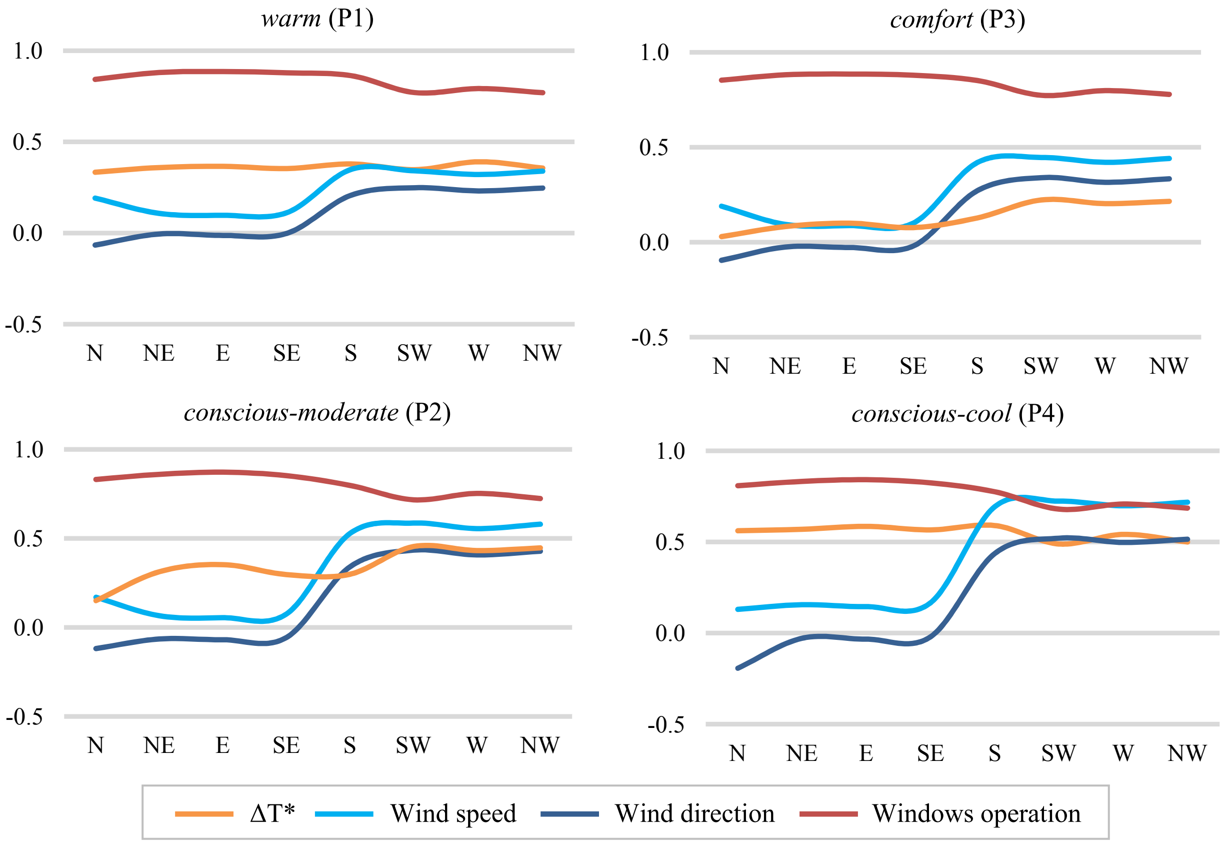
Figure 6. Bubble plots for overheating degree hours in summer according to the adaptive comfort model of the EN15251 [12] for *warm* (left) and *conscious-cool* (right) profiles per orientation

4. DISCUSSION

4.1 Sensibility analysis of physical parameters with respect to ventilation rate

The previously observed behaviour may respond that the idea that different ventilation regimes (in terms of windows opening) generate different air change rates, which also may be influenced by external variables such as wind conditions. This situation suggests that windows operation may be correlated with ventilation rates, which could be determined by means of a sensibility analysis. The sensibility analysis assesses the contribution of the inputs parameters (in this case corresponding to physical variables) to the total uncertainty in analysis outcomes (here defined as the ventilation rate).

Fig. 7 shows the rank correlation coefficients of different physical parameters with respect to the air change rate (in terms of h^{-1}) for the different occupant behaviour profiles in the main bedroom per orientation. All the parameters (windows operation, difference between indoor and outdoor temperatures, wind direction and wind speed) appear as significant variables with respect to the ventilation rate ($p<0.05$), which modify their relative level of importance as function of the higher exposition to opened windows, as can be observed through the comparison between the different profiles. If we consider also the notorious difference between the overheating degree hours in summer by profiles (as it was presented in Fig. 6), the time at when windows are opened/closed represents a key aspect with respect to both air change rate and summer thermal comfort. Additionally, wind direction and wind speeds show important differences in each profile with regard to orientation, presenting considerable higher correlation coefficients in the wind–oriented facades (S, SW, W and NW).



Note (*): ΔT = Difference between indoor and outdoor temperatures [°C]

Figure 7. Rank correlation coefficients for different physical parameters for *warm* (left) and *conscious-cool* (right) profiles with respect to air change rate [h^{-1}] in the main bedroom per orientation

5. CONCLUSIONS

The explanatory analysis carried out through the Principal Component Analysis and the multivariate logistic regression established the relative importance of the different variables that determine the perception of thermal comfort of an apartment in Santiago de Chile. Through these multivariate statistical techniques, the role of ventilation in the thermal sensation of the occupants was identified, associating daytime ventilation with hygienic purposes, while night ventilation appeared directly related to passive cooling.

These observations are useful to understand the perception of occupants about the different aspects related to the thermal comfort of apartments in Santiago de Chile, especially during summer. However, if one of the declared objectives of the survey is to provide information for energy building simulations based on a more real approach, it is absolutely necessary to generate hard data from the collected information. As it was explained, the definition of ventilation regimes is one of the main sources of uncertainly in an energy building simulation, mainly due to its dependence on the inhabitant's behaviour (by means of windows opening). Nonetheless, if these ventilation regimes are defined based on hard data collected directly from the inhabitants, the results of the simulation are more representative and reliable and in consequence, uncertainty decreases. This process was carried out by means of a cluster analysis, obtaining four different behaviour profiles (P1, P2, P3 and P4). These occupant behaviour patterns were characterized as function of all the originally considered variables. According to this, the four profiles were identified as *warm*, *conscious-moderate*, *comfort* and *conscious-cool*, respectively. At the same time, it was observed as these different occupant behaviour patterns lead to significant differences with respect to the summer overheating degree hours, obtained by means of energy building simulations.

The sensibility analysis carried out with the obtained results of these numeric simulations indicate that the difference between outdoor and indoor temperatures, wind direction and wind speed appear as sensitive physical variables with respect to the ventilation rate. Also, these variables increase their relative level of importance regarding ventilation profiles as function of the higher exposition to opened windows. In that sense, the time at when windows are opened / closed represents a key aspect with respect to both air change rate and summer thermal comfort.

At the light of these results, night ventilation presents a high potential as passive cooling technique, considering also the climatic conditions of Santiago (because of the difference between outdoor and indoor temperatures that it is possible to reach during night-time). However, this thermal behaviour (when night cooling is applied) probably is also influenced by windows operation during daytime, as can be observed by the simulation outputs (in terms of overheating degree hours) of the different occupant behaviour patterns.

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