Definition of occupant behaviour patterns with respect to ventilation:

An approach to the summer thermal comfort of apartments from the real estate market in Santiago de Chile

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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 simulations. 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 behaviour profiles which can be used as hard data to make calculations of energy performance of dwellings more accurate and reliable.

Keywords: summer thermal comfort, occupant behaviour profiles, building energy 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 simulations [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.

Uncertainty and sensitivity 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) [2]. However, Hyun et al (2008) explain that the widely varying occupant influences - especially related to operable windows - have not been directly measured or investigated [3].

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 and the ventilation patterns in real occupied dwellings may be expected. Therefore, if the aim is to represent a wide range of cases (instead of a singular case study), it is necessary to characterize the occupant behaviour in terms of profiles 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 the IEA (1988) [4]. 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. Consequently, the definition of a set of standard behaviour patterns –based on the quantification of real inhabitants' behaviour- would significantly improve the validity of the outcomes of the simulations [5].

In this context, the obtained behaviour patterns represent a first approach in the process to obtain a more real thermal behaviour, since this information needs to be combined with meteorological data by means of building performance simulations. The aim of these numerical simulations is to find a relationship between occupant behaviour patterns, ventilation rates and summer thermal comfort.

The final objective of these models corresponds to the definition of behaviour scenarios which can be used as hard data to make calculations of energy performance of dwellings more accurate and reliable.

2. METHODOLOGY

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, 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 several apartment buildings in Santiago de Chile.

2.1. Statistical Methods

Factorial analysis is a multivariate analysis technique that it is used to reduce the dimensions of a large set of observed variables. The new obtained variables received the name of factors, defined as a lineal combination of variables. Also, the method allows the detection of subjacent dimensions that belongs to a correlation matrix. According to the procedure for extracting factors, it is possible to distinguish the “Factor Analysis” and the “Principal Component Analysis (PCA). Since the objective of this study is to obtain a reduction of a large set of information contained in certain questions of the survey and perform further analysis with this information, the procedure of PCA was selected.

Table 1 presents all the variables that were considered to carry out the PCA. 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.

3. RESULTS

Table 2 presents the rotated component loadings, which give information about the strength of the relationships between the variables and components. These loadings are expressed in terms of correlation coefficients (with values between 0 and 1). According to the Kaiser’s criterion (Eigen values >1.0), 4 components were extracted, which account for the 73.2% of variance. At the same time, according to Hair et al. (2005), communalities below 0.5 should be probably dismissed, as they do not have enough explanation for their variances [6]. In the table, it can be observed that all variables present communalities that can explain at least the half of their own variance and therefore should be considered in the model.

In order to improve the interpretation of the model, a procedure to rotate the factorial axis of the solution was applied. The objective of the VARIMAX technique is to maximize the components variance. For this solution, coefficient values above 0.60 were considered as significant. As the significance of a factorial loading depends on the size of the sample, this reference value was taken for a sample of 85 observations. The sign of the coefficients indicates if they are positively or negatively correlated with respect to their corresponding component.

In consequence, the four defined components of the rotated matrix can be interpreted as:

C1: Daytime ventilation, both in winter and summer (Q16 & Q20), which are positively correlated

C2: Perception of favourable thermal comfort in winter (Q6) and avoiding the use of heating appliances (since it is negatively correlated) (Q27). 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. This phenomenon can be explained through the specific environmental conditions of their apartments (e.g. favourable orientation) or due to particular reasons.

C3: Perception of unfavourable thermal comfort in summer (Q10) and use of night ventilation (Q24), which are positively correlated. This situation can be represented for occupants that describe their apartments in summer as “warm” or “hot” and due to this, open windows during night time.

C4: Presence of solar protection (Q13), which is positively correlated

Table 2: Rotated component matrix by means of VARIMAX

Variables	Components				Communalities
	C1	C2	C3	C4	
Q6	0.02	0.85	-0.02	0.19	0.76
Q10	-0.22	0.15	0.65	0.13	0.52
Q13	0.01	0.00	0.11	0.90	0.82
Q16	0.76	0.20	-0.26	0.24	0.75
Q20	0.86	-0.16	0.14	-0.16	0.81
Q24	0.14	-0.06	0.84	-0.03	0.74
Q27	0.05	-0.71	-0.14	0.44	0.72

Significant variables per each component

Table 1: Considered variables for the Principal Component Analysis (PCA)

Subject	Question	Variable
Perception of thermal comfort	Q6	Thermal sensation in the apartment during winter
	Q10	Thermal sensation in the apartment during 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

"Factor scores" are a sub-product of the PCA application. Also, they represent a useful result in order to carry out other multivariate analysis techniques. Figure 1 presents perceptual maps per orientation, based on the factor scores obtained previously by means of the PCA. 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.

Figure 1 shows the perceptual map of C2 vs. C3 in terms of "comfortable" and "not comfortable" for both winter and summer, respectively. According to this, north orientation was characterised as comfortable in both seasons, while south oriented apartments are associated with a favourable and unfavourable thermal behaviour in summer and winter, respectively. For both orientations, these results can be considered as expected.

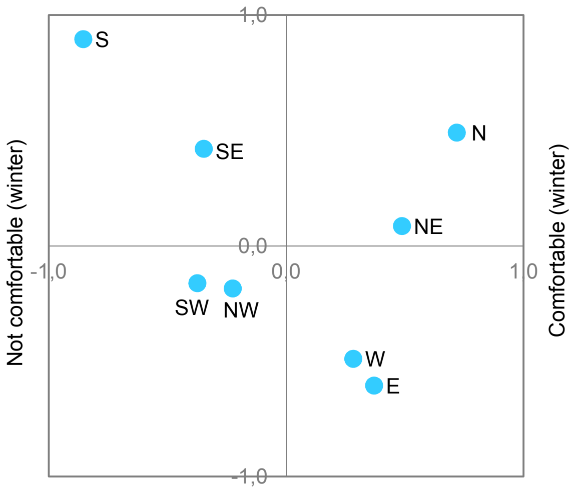

Figure 1: Perceptual map of C2 vs. C3 (horizontal and vertical axis, respectively

4. DISCUSSION

4.1. Application of a discrete choice model to identify relationships between variables

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

The model that predicts the dependent dichotomic variable *Y* from multivariate independent variables X_k in probabilistic terms corresponds to:

$$\boldsymbol{P}_{(Y=\frac{1}{X_k})} = \frac{1}{1+e^{-(a+b_1x_1+\dots+b_kx_k)}}$$

where *e* is the base of natural logarithms and being an irrational number, their first digits are 2.71828.

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 function:

$$\boldsymbol{P}_{(Q41=\frac{1}{C_{i,i=1\dots4}})} = \frac{1}{1+e^{-(a+b_1C_1+b_2C_2+b_3C_3+b_4C_4)}}$$

where C_1, C_2, C_3 and C_4 are the factor scores that were obtained through the PCA, b_1, b_2, b_3 and b_4 are the coefficients for these variables and *a* is a coefficient of the model. According to Hair et al. (2005), it is recommendable to consider factor scores for configuring a logistic regression model where the sample is the same and the independent variables are orthogonal [6].

Table 3 presents the obtained coefficients for the logistic regression model proposed for the Q41 of the survey. These coefficients were obtained by means of the maximum verisimilitude procedure using statistical software.

According to the obtained solution, coefficient b_1 is not significantly different from 0, from a statistical point of view. This means that component C_1 is not significant to predict the probability of occurrence of Q41. This situation can be understood from the idea that daytime ventilation of C1 (which includes both winter and summer) is mainly oriented to a hygienic purpose, instead of cooling. This observation is highly consistent with the study by Andersen et al. (2009), which proposes that the thermal sensation of the occupants is not a statistically significant predictor of the windows opening behaviour [5]. The reason for this may be explained by the idea that if a window is opened because the occupants feel too warm, it will probably stay open until they start to feel cold. Because of this, occupants with open windows may have a thermal sensation anywhere between warm and cold [5].

Another important aspect regarding the obtained coefficients of Table 3 is the sign of b_3. As can be observed, this sign 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

Table 3: Obtained coefficients from the multivariate logistic regression

	Coefficients	Standard error	Z value	Pr (>|z|)
a	1.97	0.48	4.09	4.38E-05
b_1	0.30	0.30	1.01	3.13E-01
b_2	0.62	0.35	1.77	7.68E-02
b_3	-0.90	0.45	-2.00	4.59E-02
b_4	0.97	0.49	1.99	4.64E-02

Not significantly different from zero

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

$$P_{(Q41)} = \frac{1}{1+e^{-(1.97+0.30\,C_1+0.62\,C_2-0.90\,C_3+0.97\,C_4)}}$$

In this equation, it can be observed that the most important aspects related to the overall perception of thermal comfort in the apartment (Q41) are the presence of solar protection (C_4), the perception of summer thermal comfort and night ventilation (both contained in C_3). Newly, these weightings can be considered as expected since the survey was taken during summer. In that sense, 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 (Y=1, considering that the survey was carried out in summer).

4.2. Definition of ventilation scenarios 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. Indeed, the objective of this can be defined as the identification of a group of entities that share certain common characteristics [7].

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 PCA as variables for the procedure is justified since it allows to correct the interdependencies. Also, the nonequivalence of metrics between the original variables of the survey 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 for both winter and summer from the number of hours of ventilation per day.

Figure 1 presents the number of ventilation hours per day in summer. As can be observed, P2, P3 and P4 present a similar behaviour with respect to the different times of the day. On the contrary, P1 presents a very particular behaviour, since the highest level of ventilation occurs at noon. Occupants associated with this profile probably are not aware of the thermal implications of their behavioural habits related to ventilation, since windows are opened in the hottest time of a summer day in Santiago. Then, when temperature decreases most of the windows are closed.

This situation is consistent with the declared reasons for opening or closing windows in summer collected by means of the survey. Figure 3 presents the results for two questions (Q22 & Q23) of the survey with respect to these issues. It can be observed that the occupants that belong to P1 may not use natural ventilation as passive cooling technique, since windows operation is mainly limited to close them. On the contrary, 75% of the people of P4 open the windows of their apartments due to the overheating, which indicates a particular concern with respect to thermal comfort.

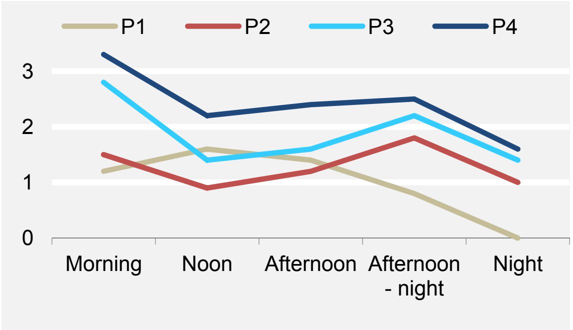

Figure 2: Number of ventilation hours per day in summer

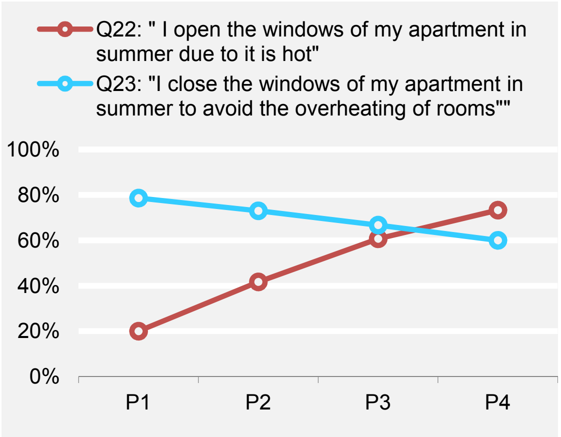

Figure 3: Results for two questions of the survey with respect to the reasons for opening and closing windows in summer per profiles

These ventilation profiles, proposed from the collected data of the survey represented the first step to obtain hard data which might be directly applied to thermal simulations. After that, building performance simulations were done using TAS software [8]. The four profiles were applied to a floor layout of the same building selected for the survey, using also the collected information 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) [9], which were also compared and validated with respect to the monthly values of the NCh 1079-2008 national standard (based on a period of 30 years of meteorological observations).

The aim of these numerical 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, but they need to be characterized in terms of their impact on the thermal comfort of the apartments. Figure 4 presents the overheating degree hours per orientation according to the adaptive model of EN 15251 [10] for P1 and P4 profiles. These results are consistent with regard to the perception of summer thermal comfort of the Figure 1 and show that when night ventilation is being applied, P4 appears as a more efficient regime to reduce overheating. This suggests that the thermal performance of night ventilation also depends on the windows operation during daytime.

Figure 5 presents curves of temperature and air change rate in two summer days for the main bedroom of the western apartment for also P1 and P4 profiles. Indoor temperatures in both profiles show the favourable impact of the night ventilation strategy to reduce the risk of overheating. This also can also be explained considering the climatic conditions of Santiago de Chile (due to the difference between outdoor and indoor temperatures that it is possible to reach during night-time).

At the same time, the obtained ventilation rates differ substantively between both profiles, as consequence of their windows operation regimes. This situation suggests that windows operation may be correlated with the ventilation rate, which could be determined by means of an uncertainty and sensitivity analysis. Figure 6 shows the Pearson's correlation coefficient of different parameters with respect to the air change rate in the main bedroom per orientation. All the variables (windows operation, ΔT: difference between indoor and outdoor temperature, wind direction and wind speed) appear as sensitive variables with respect to the ventilation rate, which modify their relative level of importance as function of the higher exposition to opened windows (as can be observed through the comparison between P1 and P4). Wind direction and wind speeds also show important differences in each profile with respect to orientation, presenting considerable higher correlations in the exposed orientations (S, SW, W and NW).

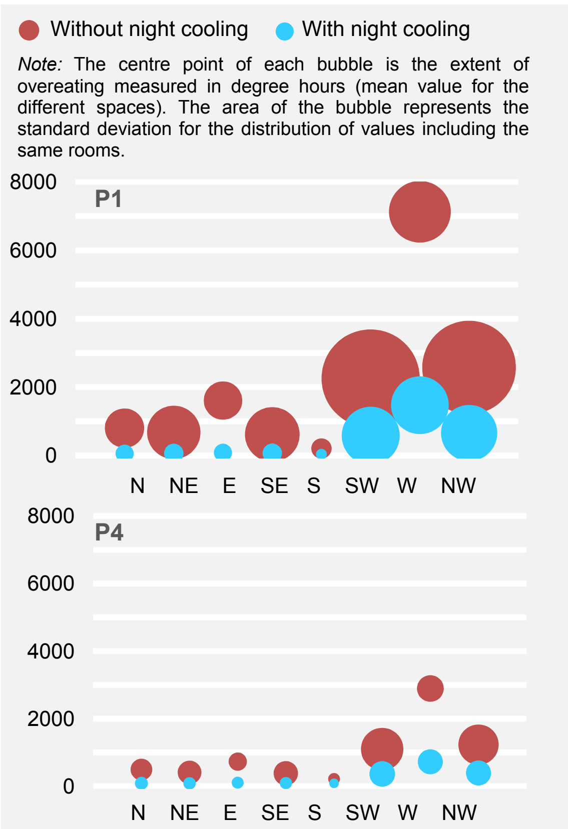

Figure 4: Bubble plots for overheating degree hours according to the adaptive comfort model of the EN 15251 [10] for P1 and P4 profiles under different conditions

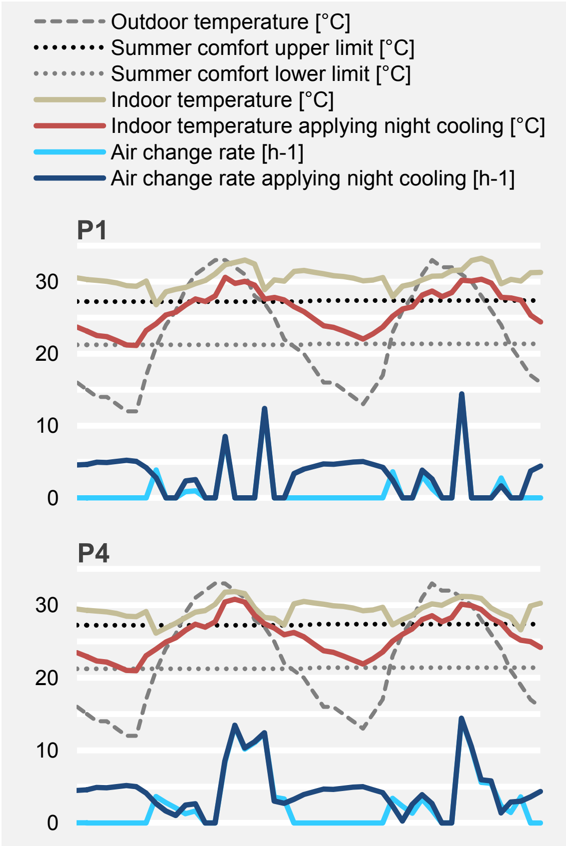

Figure 5: Curves of temperature [°C] and air change rate [h^{-1}] in two summer days for the main bedroom of the W apartment for both P1 and P4. Upper and lower limits of adaptive summer comfort calculated from EN 15251 [10]

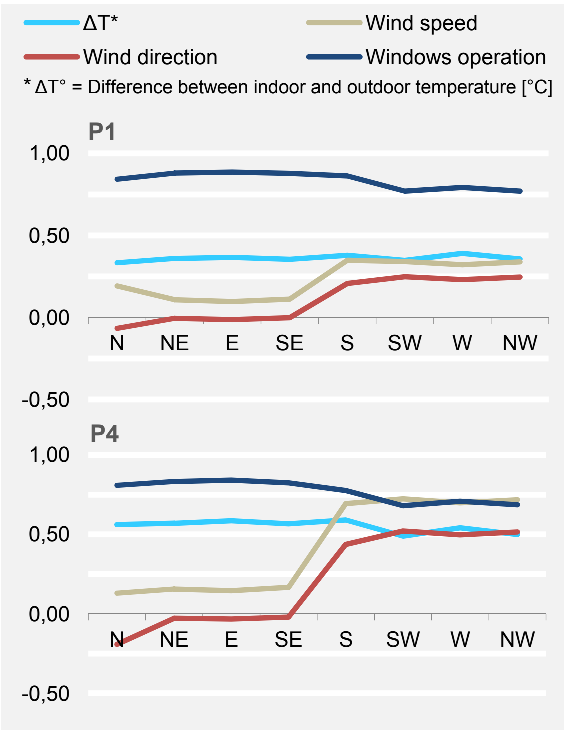

Figure 6: Pearson correlation coefficient for different parameters from P1 and P4 profiles with respect to air change rate [h-1] in the main bedroom per orientation

Finally, Figure 7 shows that orientation has the higher correlation with respect to the obtained overheating degree hours in comparison to other design parameters. Facade area/conditioned area ratio, glazing ratio and layout are the second, third and fourth variables, respectively, in order of sensitivity. However, when night cooling is considered in the assessment, the relative importance of these parameters can significantly change, which should be considered by designers.

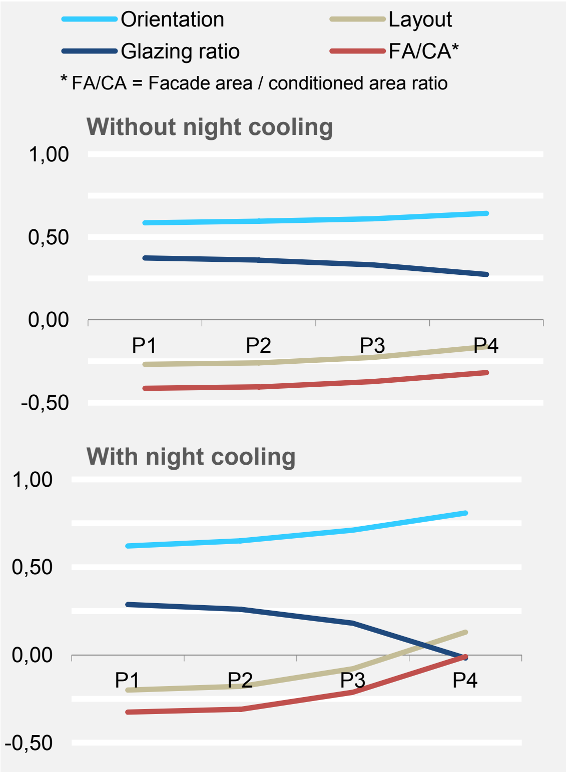

Figure 7: Pearson correlation coefficient for different design parameters under different conditions of night ventilation with respect to the mean value of overheating degree hours

5. CONCLUSIONS

The explanatory analysis carried out through the PCA and the 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 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 very useful to understand the perception of occupants about the different aspects related to the thermal comfort of apartments in Santiago de Chile. Nonetheless, if one of the declared objectives of the survey is to provide information for energy building simulations, it is absolutely necessary to obtain hard data from the collected information. This was carried out by means of a cluster analysis. As 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). However, if these ventilation regimes are defined based on a more real approach, the results of the simulation are more representative and reliable and in consequence, uncertainty decreases.

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