Statistical Analysis of Architectural Features Effects on Indoor Environmental Conditions in a Plus Energy House Prototype

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ABSTRACT: Data from an experimental investigation, carried out during the summertime (from the end of July to mid-September, 2016), have been statistically analyzed, with the purpose of proposing a post-instalment-evaluation technique by assessing the effects that some architectural features have on the indoor environmental conditions in a prototype of Plus Energy House in southwest France. The proposed correlation analysis is tested first, to evaluate its reliability for distinguishing strong from weak correlations. Since the proposed analysis appears to be acceptable, it was used then for studying the relationship between outdoor and indoor environments. Results from the correlation analysis strongly suggest that the impact of direct solar radiation on the indoor environment is well attenuated by the double-glazed windows with blinds implemented in the house.
KEYWORDS: Statistical correlation analysis, assessment of architectural features, post-installment-evaluation.

1. INTRODUCTION

The cravings of bioclimatic architecture for the sustainable design of buildings focuses mainly on indoor environment quality under any climatic conditions, by encouraging the endeavor of improvement in buildings' upstream dynamic simulation and downstream empirical observations. Such empirical observations assess the post-installment-evaluation of the effects that architectural features have on indoor environmental conditions.

In this context, data from an experimental investigation dedicated to studying the interaction between the natural ventilation and thermal behavior of a Plus Energy House (PEH) prototype, are analyzed, using a correlation analysis approach, to highlight the effects that its architectural features have on the indoor environment thermal behavior. Such features are mainly: double-glazed windows, window blinds, natural ventilation openings, and envelope.

Since such an approach is not conventional for the assessment of architectural features; no similar investigations reported in the literature have been encountered. However, there are other methods of evaluation [1-2]. In the end, it is intended to characterize the architectural features designed for this PEH prototype, mainly regarding: (*a*) the reduction of indoor radiative heat gains from external sources, (*b*) the influence of wind effects in the indoor air movement.

2. EXPERIMENTAL PLATFORM AND METHODOLOGY

After participating in the Solar Decathlon Europe 2012 competition, the PEH prototype used in this experimental study had, afterward, became an experimental platform for research purposes located in Bordeaux, southwest France.

The building's envelope, enclosing a 211 m^3 air volume and a 46 m^2 floor surface area, can be briefly described as an external structure of maritime pine, with 32 cm of thermal insulation and outdoor cabinets at the east and west facades (1.4 $W.m^{-2}.K^{-1}$ each), and 32 cm of thermal insulation at the North façade (1.2 $W.m^{-2}.K^{-1}$), ceiling, and floor. South and north façades include natural ventilation openings (bottom hung window type) representing the 9.58% and 7.51% of each façade, respectively; apart from this, the south façade is fully glazed corresponding to the 90.42% of the total surface (with a total heat transfer coefficient of 1.6 $W.m^{-2}.K^{-1}$).

Moreover, this platform was designed to promote a charge-discharge sensible energy strategy to control the indoor air temperature rising and reduce artificial acclimatization usage, in the summertime.

2.1 Experimental protocol

The experimental approach adopted was to instrument the indoor space of the platform, consisting mainly of the following measurements: (*i*) air and surface temperatures (T), (*ii*) airspeed (V), and (*iii*) convection (φ_C) and radiation (φ_R) heat fluxes. These parameters were measured at the ceiling and floor surfaces (Fig. 1 and 2). The indoor air temperature (T_{in}) was measured at 1.70 m height; the outdoor air temperature was also measured by our means (T_{out}); their locations are shown in figure 1 and 2. Other outdoor environmental conditions (direct solar radiation and wind speed) were acquired from a meteorological station at 10 m height and a distance of 1.5 km from the platform's location.

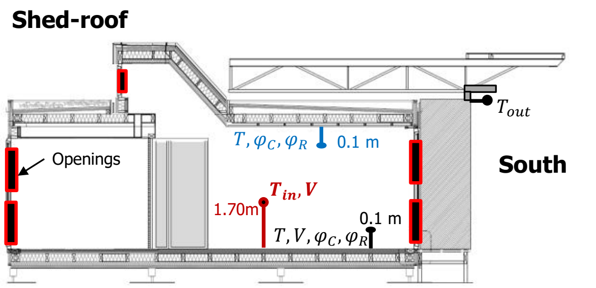

Figure 1: West-side view of the experimental platform with sensors distribution.

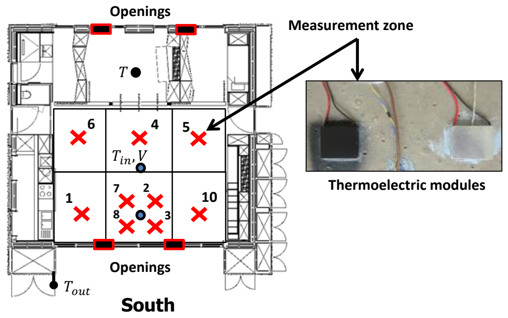

Figure 2: Top view of the experimental platform and sensors distribution.

A measurement campaign was carried out from July 27th to September 12th, 2016 (except from July 30th to August 11th). During this campaign, the natural ventilation openings were configured as to promote a night stack ventilation strategy; programmed to open only when the outdoor air temperature falls lower than the indoor air temperature, which happened mostly at night. The platform was unoccupied, and the window blinds were kept down during the entire campaign.

Three physical variables implemented later in this study are: (*i*) the mean radiant temperature, (*ii*) the total incident radiation heat flux, and (*iii*) the convective heat flux on the floor surface. These variables were obtained by data processing, implementing analytical models developed in previous studies [3-4].

2.2 Statistical approach

2.2.1 Data collection and sample rate

During the measurement campaign (34 days in the summertime), data were collected from the indoor environment (including the outdoor temperature) at a sample rate of an observation every minute, equivalent to 1440 observations per day. From the outdoor environment, data were collected at a sample rate of an observation every ten minutes, equivalent to 144 observations per day. Here, a reduction for the indoor environment data was performed to be consistent with the outdoor environment sample rate: only 144 observations per day will be used for the indoor environment data.

2.2.2 Correlation analysis

A correlation analysis based on the Pearson correlation coefficient R was implemented to evaluate how strong the relationship between indoor and outdoor measurements is and to better understand the coupling between the heat transfer and airflow effects in the platform. The value of R indicates a perfect linear relationship between two concerned physical quantities when R is equal to one ($R=1$), a no linear relationship when R is equal to zero ($R=0$), which might mean a curvilinear relationship, which is not detected by R , and a perfect but inverse linear relationship when R is equal to negative one ($R=-1$) [5].

As the implementation of a correlation analysis of such physical problem via only the correlation coefficient R may lead to subjective conclusions, the significance of R is further analyzed using other approaches concerning its interpretation. To do this, we have implemented the following three approaches as presented in [5]:

- The verification of the null and alternative hypothesis state via the p-value (we will assume 0.95 as confidence level).
- The explained variability of the data via the squared value of R .
- The visual trend that verifies the linear or curvilinear relationship via scatter plots.

Regarding the first approach, the null hypothesis states, as default, that there is no significant correlation between the two variables studied (a p-value greater than or equal to 0.05). Once the p-value of the supposed correlated data is determined, if its value lays under 0.05, it is said that the null hypothesis is rejected and the alternative hypothesis holds: there is a significant correlation in between the two variables studied.

Regarding the second approach, as stated in [5], the squared value of R indicates the percentage of the variability that can be explained by the knowledge of the correlated variables. Regarding the third approach, the visualization of the two correlated variables will verify their relationship subjected by R . In the case where R values near zero are encountered (indicating no linear relationship exists), the visual trend can help us to determine whether to accept the "no correlation" implied by the value of R or to consider the determination of another correlation coefficient that allows evaluating the strengths in the trend encountered.

Finally, regarding the last part of the previous paragraph, the Spearman's coefficient (or Spearman rank-order correlation coefficient) will be determined, since it allows evaluating monotonic relationships. In such relationships, the variables tend to change together, but not necessarily at a constant rate.

It is worth mentioning that it is possible to meet a situation where Pearson's coefficient is negative while Spearman's coefficient is positive or vice versa, which might lead to infer that this is an inconsistency. However, with a logical understanding of the difference between these two coefficients, such "inconsistencies" are justified [6].

In addition to correlation plots, to present the results with Spearman's coefficient, we use correlation matrices using the software **R**, as they allow us to group the three approaches mentioned earlier.

2.2.3 Distinguishing strong from weak correlations

Here, we establish a threshold for the value of R that could help us to distinguish, as unbiased as possible, strong from weak correlations. This threshold is chosen based on the statistical interpretation of R^2, described in §2.2.2.

As a value of R^2 greater than 0.51 indicates that the 51% of the variability of variable A is explained by a variable B, we extend this to the following: the variable B can explain the variability of variable A at least 51% of the times, which represents the majority. Thus, the threshold value for R results in 0.71 (the squared root of 0.51).

Then, a correlation will be classified as strong if the R value is greater than 0.71 and as weak if the R value is lower or equal to 0.71. Similar threshold or critical values were proposed by Cohen in 1988, as encountered in [7].

2.2.4 Day/night-time criteria for data sorting

As the aspects we wish to analyze here are the impacts of external sources on the indoor environment and the impact of the night natural ventilation strategy implemented, the experimental data collected will be analyzed separately in the daytime and the night-time. To do this, we have sorted the data using the following criteria:

- Night-time: Solar radiation = 0 & indoor-outdoor temperature difference > 0.
- Daytime: Solar radiation ≠ 0 & indoor-outdoor temperature difference < 0.

Here, we have included the condition of the temperature difference, because of the configuration proposed for the natural ventilation openings (§2.1).

3. RESULTS AND DISCUSSION

3.1 Classification of the correlations as strong or weak

The results from the meteorological station have shown that the majority of days presented cloudy and windy daytime and clear and no-windy night-time. Nevertheless, first, we decided to apply the statistical approach to days with similar meteorological conditions: sunny and windy daytime and no-windy night-time (August 15th, 16th, 22nd, and 23rd); the corresponding total sample size is 576: four days with 144 observations.

The correlation analysis results, based on the Pearson's coefficient, are presented in figures 3 and 4, for no-windy night-time (sample size of 196), and sunny and windy daytime (sample size of 271), respectively, using the criteria presented in §2.2.4. The missing 109 observations laid outside the day/night-time criteria established.

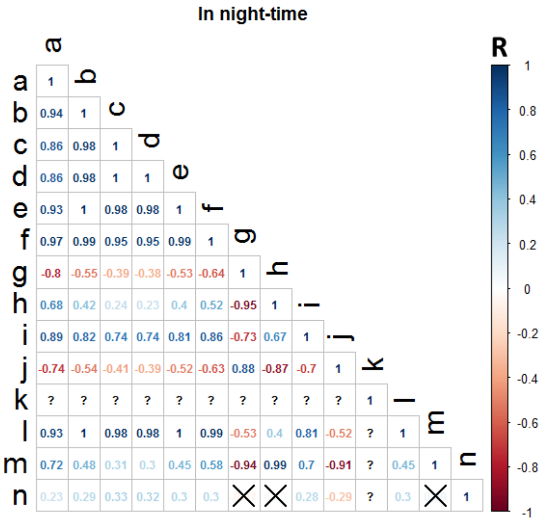

Figure 3: Correlation plot based on the Pearson coefficient for experimental results from no-windy night-time: the sample size resulted in 196.

The variables presented in figure 3 and 4 are: temperature of the (a) outdoor air, (b) indoor air, (c) floor surface, (d) ceiling surface, (e) averaged of surrounding surfaces and (f) air near floor surface. Also, the temperature difference between (g) the indoor and outdoor air, and (h) the air near the floor and the floor surface. The airspeed at (i) the location where the indoor air temperature was measured and (j) near the floor. Additionally, the following heat fluxes: (k) outdoor, direct solar radiation, (l) incident radiation on the floor surface, and (m) convection. And finally, (n) the external wind speed.

To read these graphs, we can assign to each segment (frames containing numbers) a pair of variables: (vertical-axis variable, "stairs"-axis variable). For example, in figure 4, the Pearson's coefficient between indoor and outdoor air temperatures is the cross value between letter "b" in the vertical axis the letter "a" in the "stairs" axis, namely R = 0.64. Additionally, segments presenting an "X" indicates no significant statistical correlation, since the computed p-values resulted in being greater than 0.05.

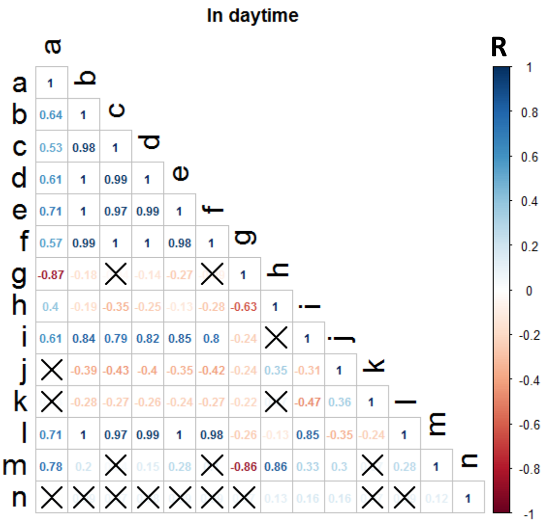

Figure 4: Correlation plot based on the Pearson coefficient for experimental results from windy and sunny daytime: the sample size resulted in 271.

Before going further, in order to evaluate if the proposed correlation analysis can be considered as acceptable or not, it is applied to correlate variables that normally, in agreement with the physical laws, should present strong correlations coefficients. For instance, consider the convective heat flux (m) and the temperature difference between the air near the floor surface and the floor surface (h). Since these variables are known to be directly related, as stated by Fourier's law of convection, a strong R value should be expected; this can be observed in segment (m,h) in figures 3 and 4, which R values are 0.99 and 0.86. These values indicate that the correlation between m and h are both strong (R > 0.71) and positively correlated, as expected.

The difference in the previous R values for each period (daytime and night-time), can be explained by the fact that convective heat flux values are stronger when the openings are opened than when they are closed. Another fair and obvious example can be the solar radiation heat flux (k) during night-time. Since this variable is normally zero during this period, no correlation whatsoever should be encountered between this and other variables; this can be observed in figure 3, of which every R value related to the variable k resulted in a question mark (?) (in other words: "NA").

Moreover, another fair example, not as obvious as those presented before, is that all the temperatures from the indoor environment (b,c,d,e,f) should present strong correlations between one-another all the time. This can be observed in both figures 3 and 4, as expected. From the aforementioned, the statistical method proposed here, *a priori*, seems to be a reliable method to evaluate the strengths of correlated variables.

3.2 Correlation between the outdoor and indoor environments

The variables from the outdoor environment selected for the correlation analysis are: the air temperature (a), the direct solar radiation (k), and the wind speed (n). To evaluate the influence that these three variables have on the indoor environment, we choose the following variables for the indoor environment: the air temperature (b), the floor surface temperature (c), the total incident radiation on the floor surface (l), and the airspeed (i) and (j). In this way, we can evaluate, specifically, the contribution of the direct solar radiation to the thermal behavior of the floor surface temperature, and also the contribution of the wind speed to the air movement inside the platform.

First, from the variables mentioned here before we depurate by focusing on the R values greater than 0.71, and the "X" presented in both figures 3 and 4. Every segment is presenting an R value lower or equal to 0.71 and an "X," is eliminated from the analysis. This allows us to obtain the relevant variables and to consider the third approach mentioned in §2.2.2, using correlation matrices with the Spearman's coefficient (refer to Figs. 5 and 6).

The correlation matrices include the following:

- The graphs of each pair of correlated variables, as well as their magnitudes (visual trends).
- The distribution of each corresponding sample (represented by histograms).
- The statistical significance due to the p-value with red asterisks; where three asterisks (***) indicate that the p-value is very close to zero, two asterisks (**) that are very close to 0.001, and one asterisk (*) that is very close to 0.01. A point (·) indicates that the p-value is very close to 0.1, and nothing () indicates that is very close to 1.

The interest in using Spearman's coefficient is for comparison purposes as the Pearson's coefficient are already presented before. This type of graph (refer to Figs. 5 and 6) can be read in the same way as figures 3 and 4, but here the correlation coefficients of two correlated variables are presented above the diagonal with histograms; under this diagonal are the scatter plots of those variables showing their trend.

3.2.1 Wind speed and indoor air movements

In figures 5 and 6, for the wind speed (variable n), it is clear that there is no strong correlation presented between variable n and those representing the air movement in the indoor environment (i and j). This is fairly expected for the night-time periods (refer to Fig. 5) since they presented no-windy conditions. In daytime (refer to Fig. 6), the weak correlations encountered between variables n, i and j, might be explained by the fact that the openings remained closed; as a consequence, the air infiltrations are minimal.

It is worth mentioning that in cases of no-windy night-time periods, thermal buoyancy dominates the ventilation airflow in the platform.

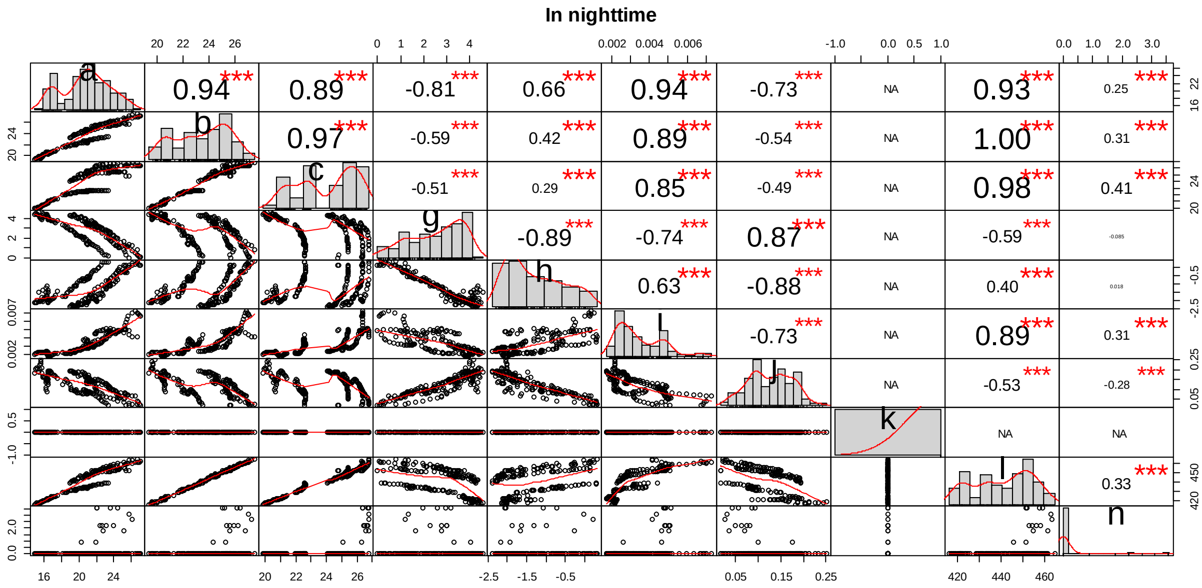

Figure 5: Correlation results for no-windy night-time with Spearman's coefficient: sample size of 196.

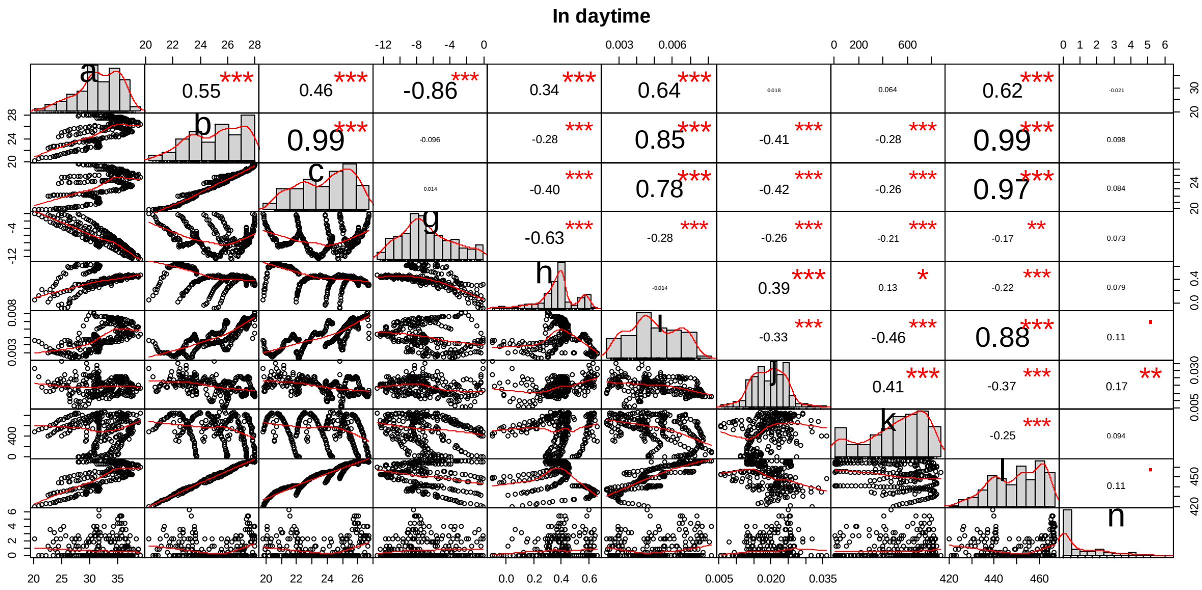

Figure 6: Correlation results for sunny and windy daytime with Spearman's coefficient: sample size of 271.

Therefore, it can be inferred that the air movements in the indoor environment may be strongly correlated with a specific temperature difference. In this matter, figure 5 shows that there are strong correlations between the air movements (i and j), and the temperature differences: g and h. Between the segments (g,i), (g,j) and (h,j), which are the strongest ones, higher R values were encountered when using Spearman's coefficient (refer to Fig. 5), than when using Pearson's (refer to Fig. 3). This indicates that the relationship between these correlated variables is rather curvilinear than linear. In fact, based on the physical laws of natural convection and thermal buoyancy, relating the temperature difference and the resulting airspeed, a 1/2 power law trend is expected to be encountered. This trend can be observed in figure 5 segments (h,j), (g,i), and (g,j). Moreover, similar correlation coefficient values and trends were encountered when using data from periods of windy nighttime (sample size of 187 observations). This indicates that wind effects do not play an essential role in the air movement near the concrete slab surface nor near the center of the platform.

3.2.2 Outdoor solar radiation and the indoor radiative environment

Results from correlation analysis showed that the direct solar radiation heat flux does not play an essential role in the indoor radiative environment, whether using the Pearson's coefficient (refer to Fig. 4, segment (l,k): R = 0.24) or Spearman's (refer to Fig. 6, segment (l,k): R = -0.25). In fact, the solar radiation heat flux (k) is not strongly correlated with any other variable, when considering the R threshold criterion proposed. This *a priori* means that the implemented double-glazed windows with blinds, reduce the incoming solar radiation heat flux, which lead to suspect that the indoor radiative environment is driven by internal long wavelength (LWL) radiation. This implies that the floor surface is heated by the surrounding surfaces, i.e., the glazed-façade, ceiling, and other vertical walls.

However, the fact that no strong correlations have been encountered for the variable k can also be explained by the position of the Sun in the summertime and the solar eave facing south, on the ceiling. Since the Sun position is higher, the solar eave prevents the sunrays from reaching the glazed-façade, and thus, the indoor floor surface. Also, a consequence of the orientation of the platform, the windows at the north façade won't be heated by direct solar radiation.

It is worth mentioning that this analysis was first applied to data from only one day (sample size of 144), and greater correlation coefficient values have been encountered when a larger sample size was used.

3.3 Correlation analysis when using data with mixed meteorological conditions

So far, we have analyzed data from days with similar meteorological conditions. In addition to this, we decided to apply the correlation analysis to days with mixed meteorological conditions, to observe if the correlation results hold: July 28th and 29th, and August 15th, 16th, 19th, 20th, 22nd, and 23rd.

In general, all the R values were encountered to be lower than those found in the analysis presented before. This lead to conclude that if the variability of a variable A wants to be statistically studied regarding a variable B, data from experiments with similar meteorological conditions should be used, rather than mixing data from experiments under different conditions together, as expected.

5. CONCLUSION AND PERSPECTIVES

Results from an experimental research project dedicated to studying the interaction between natural ventilation and thermal behavior in buildings have been analyzed by a statistical approach, reporting the effects of some architectural features on the indoor environmental conditions.

The correlation analysis, using experimental data, strongly suggests that direct solar radiation is well attenuated by the solar protections (doubled glazed with blinds and solar eaves). Thus, the LWL radiation dominates the indoor radiative heat exchanges. Also, the correlation analysis strongly indicates that buoyancy forces (and not winds effects) dominate the indoor air movement, whether the openings are kept open or not, whether the night-time is windy or not.

This kind of correlation analysis might emerge as a suitable post-installment-aid tool (after *in situ* implementation) to evaluate the effectiveness of architectural features on indoor environmental conditions.

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