Office Buildings in Santiago: What are we doing from the point of view of energy consumption?

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What kind of facade is the most energy efficient for a Mediterranean climate like Santiago? This article presents an energy efficiency analysis in offices built in Santiago between 2005 and 2011. The conclusions are far from what we see today: buildings with mixed facades (walls and windows) are more efficient than glazed facades.

Along with the recovery of democracy, Chile experienced a process of economic trade liberalization in the nineties that included the building material market. Indeed, the construction of a float glass plant by British transnational Pilkington was one of the most important investments (Vásquez, 2006). By that time the domestic production of flat glass was based on vertically drawn glass technology, and the new plant represented a major technological upgrade. In the field of façade design the new companies offered remarkable innovations in the pre-fabrication and assemblage of curtain-walls and seismic-safe designs.

At the beginning of this century, real estate companies incorporated these innovations and began to develop a new market for office buildings; a new infrastructure to meet the country's rapid economic development. From an architectural point of view, this led to a massive introduction of models developed under different climate conditions, with a widespread use of transparent façades in

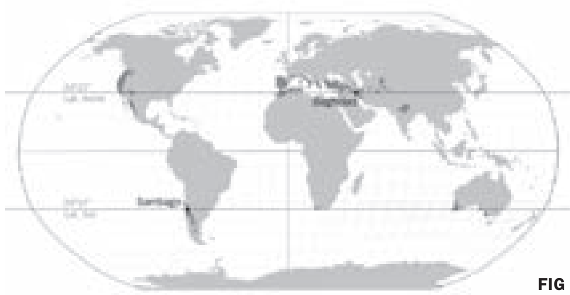


FIG 1

World regions with the same climate classification than Santiago, according to Köppen's.
Fuente / Source: Alejandro Prieto.

FIG 1

spite of the arid climate of Santiago. Thus, the transparent façades seen in recent office buildings imply high energy consumption to maintain minimum interior comfort.

According to Köppen's climate classification, Santiago has a temperate-warm climate with winter rainfall and a long dry season. It is characterized by a high thermal oscillation, reaching a high of 15°C daily and an annual high of 13°C; it also has high levels of solar radiation (Sarmiento, 2008), reaching over 1,000 W/m^2 on a vertical plane in peak winter hours. Figure 1 shows the regions of Earth with the same climate as Santiago: the Iberian Peninsula, Italy, North Africa, and Australia. The prevailing landscape in all of these are areas is rather arid, as opposed to Santiago where the availability of fresh water from the Andes has made it possible to artificially maintain a green landscape (uncharacteristic of its climate) that does not reduce the high levels of radiation the city is exposed to. Therefore, we have a contradictory urban landscape, as water from the mountains allows a green image that does not match the arid climate, while architectural models applied to office buildings are more consistent with the urban image than they are with the climatic reality of the city.

On the other hand, one of the main obstacles for the country's development is its structural dependence on energy imports, mainly gas and coal. The efficient use of the current energy matrix is one of the strategies proposed by the national Energy Agenda (Ministerio de Energía, 2014), a goal that requires accurate knowledge on how much energy is consumed and how it is consumed in order to work on the implementation of suitable strategies for energy efficiency.

This paper is part of a broader research whose main goal is to establish the energy profile of the office buildings built in Santiago with the aim of proposing specific future energy efficiency policies. Today, the lack of scientifically validated information about how these buildings operate and the energy cost associated with their operation prevents the development of accurate strategies to improve their performance.

PRELIMINARY WORKS

Between 2011 and 2012, a first assessment of office buildings in Santiago was conducted. It focused on profiling energy consumption and indoor environment quality of transparent façades buildings representative of those built between 2005 and 2010. Some of the key findings of that evaluation are:

- Energy consumption in these buildings is not correlated with the weather conditions outside, mainly because it does not relate to sunlight or temperature changes.
- There are no criteria for the distribution of internal loads according to, for instance, the orientation or distribution of air conditioning systems. Moreover, there are no criteria for generating appropriate workstations. About 20% of the analyzed working areas are deprived of any visual connection with the outside.
- 43% of interviewed users declared an inability to achieve thermal comfort in summer; among these, 26% said they perceived an excess of cold. Measurements showed that 36% of working hours are uncomfortable and about 30% of that time the lack of comfort is due to over cooling. The same occurs in winter, in similar proportions, but here the cause is overheating.
- Regarding the illumination comfort, about 50% of people who work in areas that have no visual contact with the outside claim to not have comfortable vision; however,

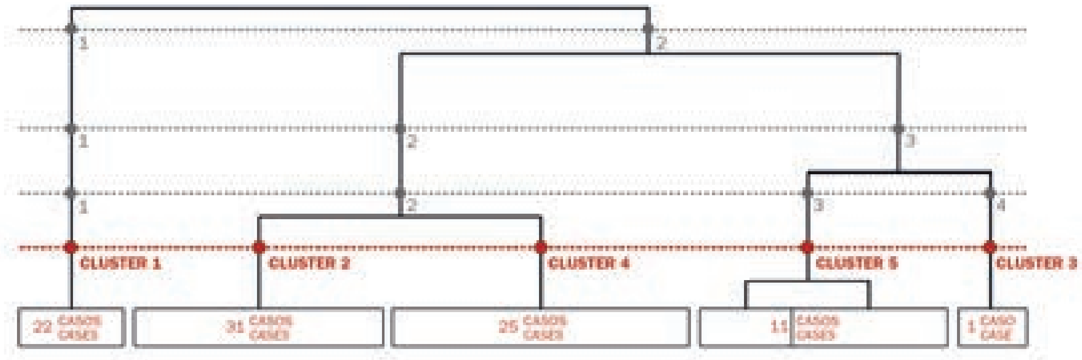


FIG 2
Dendograma
Dendogram

most of the rest of the users stated no problems of this kind. Furthermore, over 80% of users claimed to use artificial light throughout the day. This is because the high glare forces users to have sun protection systems in all directions, thus leading to artificial lighting during the day.

The overall conclusion was that the type of office buildings analyzed works with a very low performance due to issues associated with both its architectural characteristics and to problems in the management of their conditioning systems. This prompted the development of a new study aimed at establishing the performance of all buildings, without discriminating by façade type. This paper is based on the results of the first phase of this new project.

METHODOLOGY

The study consisted of office buildings built in Santiago between 2005 and 2011: a total of 105 cases. Due to problems of availability or quality information available, it was necessary to exclude 14 cases, with a final consolidated database of 91 case studies. The sample reaches a 99% confidence level and margin of error of 3.83%.

The Database (DB) was constructed using two sources: information obtained *in-situ* (interviews and surveys) and cadastral information obtained from the archives of the Municipal Departments of Works.

IN-SITU INFORMATION

The behavior of people who use and manage buildings count among the least studied and most determinant aspects of energy consumption in buildings (Azar & Menassa, 2014). Several studies have attempted to model the behavior of users focusing on certain critical actions in determining the performance of buildings, such as opening and closing windows or controlling sunscreens (Bonte, et al., 2014). However, the influence that facility managers (individuals or companies) have on the performance of buildings has not been studied with the same dedication, especially in the commercial sector.

Building managers or facility management companies provided the information obtained *in-situ*. It consisted of a survey on existing systems and building management criteria, in addition to information on electricity consumption costs for the months of January and July for the last two years. Most of the cases used electricity as fuel, and only a small fraction used a gas boiler for heating. These were, coincidentally, two cases which did not have available billing information, and thus all of the information collected was based on electricity based systems.

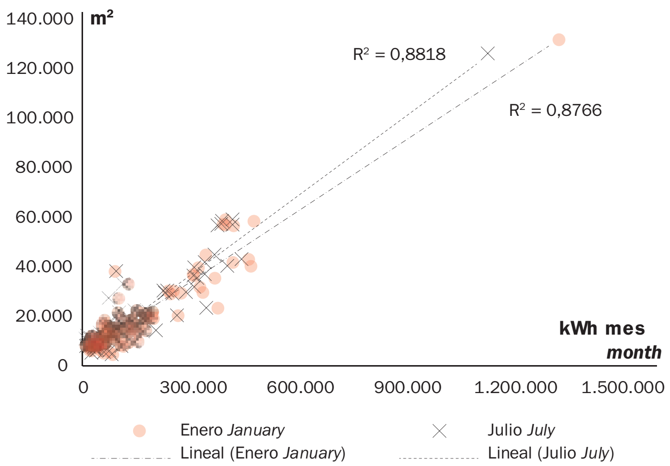


FIG 3

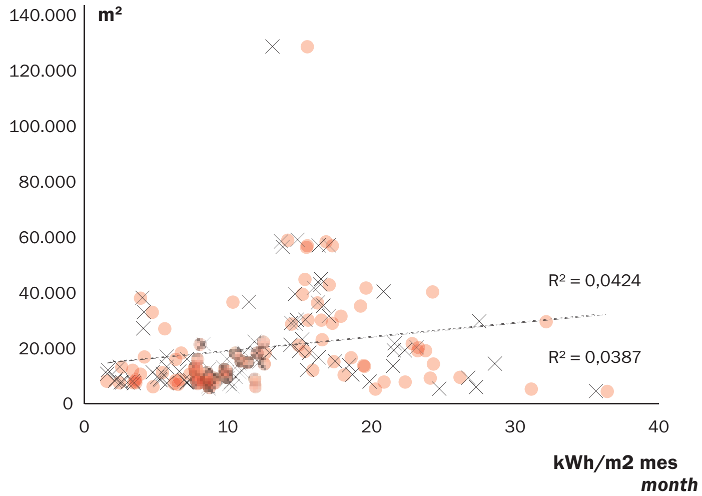


FIG 4

FIG 3

Correlation between built surface above the ground level (m2) and the total energy consumption (kWh/month).

FIG 4

Correlation between built surface above the ground level (m^2) and the relative energy consumption (kWh/m^2 month).

Out of the 91 cases comprised in the DB, 75 (82%) provided cost information and responded to the surveys. Of these, 33 (36.2%) had bills for the whole building, while the remaining 42 only had information for common spaces. This inconsistency was resolved through statistical techniques (multiple regression) to estimate the consumption for the whole building, based on the characteristics of its shape and its envelope, as will be explained below.

INFORMATION OBTAINED FROM THE MUNICIPAL DEPARTMENTS OF WORKS

The shape of the buildings is one of the predictive aspects of energy consumption because it determines the kind of relationships established with variables such as solar radiation and light, wind or its immediate context, all directly related to the heat balance and indoor visual comfort conditions.

Various indexes have been developed to describe the energy potential of architectural form. Shape Factor, for instance, describes the ratio between the surface of the envelope and the interior volume to express the potential of interior-exterior heat exchange; Plan Factor describes the ratio of the plan with it the depth to determine various aspects of visual comfort; Percentage of Openings describes the ratio between the opaque and transparent areas of a facade, thus its ability to transmit heat radiation to the interior; and finally, Shading Coefficient expresses the amount of radiation entering the inside based on the characteristics of the façade (Pacheco, 2012).

With the aim of developing indicators on the shape of the buildings, technical information regarding its architectural design was compiled from the archives of the Municipal Departments of Works. The information obtained was the following: plans, building permits and final as-built approval. With this information all dimensional data of the buildings were collected.

VALIDATION OF THE SAMPLE AND DEFINITION OF BUILDING TYPES

As mentioned above, the most important problem to build the DB was the heterogeneity of the information obtained for energy consumption, considered essential to the objective of the research. Since only 36.2% of cases studied presented billing information, it was necessary to apply statistical techniques to complete the missing data.

Using a multiple linear regression calculated by taking some of the continuous variables in the DB an equation was obtained based on the goodness-of-fit indicators used by

Variable	Observaciones Observations	Observaciones con datos perdidos Observations with missing data	Observaciones sin datos perdidos Observations without missing data	Mínimo Minimum	Máximo Maximum	Media Mean	Desviación estándar Standard deviation
Consumo observado enero (kWh) Observed consumption in January	33	0	33	34.960,0	1.371.159,5	283.329,0	242.668,7
Consumo estimado enero (kWh) Estimated consumption in January	33	0	33	21.202,5	1.303.513,7	283.329,0	237.701,9
Consumo observado julio (kWh) Observed consumption in July	33	0	33	35.280,0	1.145.075,5	264.181,4	209.947,0
Consumo estimado julio (kWh) Estimated consumption in July	33	0	33	18.601,4	1.101.997,6	264.181,4	206.315,5

TABLA / CHART 1

Descriptive statistics of the observed and estimated energy consumption for the months of January and July.

each model, which allowed us to obtain an estimate for the energy consumption of the 91 buildings in the DB.

The resulting equations for estimation of energy consumption in the months of January and July were:

- Estimated Consumption, January = -57001,83 + (13,13 * Building Façade Area) + (31,17 * Openings Area) + (71756,26 * Opaque Sun Protection)
- Estimated Consumption, July = -115865,80 + (24,06 * Openings Area) + (8099,57 * Number of Stories) + (55,07 * Useful Area for a typical floor) + (83477,94 * Opaque Sun Protection)

Furthermore, in order to compare the level of accuracy of the approach used, the samples observed and the distribution of the estimated and observed energy consumption were compared with the cases for which the regression model was constructed.

In terms of descriptive statistics, we can see the overlap of observed and estimated intakes of energy in the sample means, both in January and in July, as well as the differences between the minimum and maximum values for both cases (Chart 1). However, it is not possible to establish from these indicators if the distribution between the samples of observed and estimated energy consumption are similar. This could provide a confirmation regarding the robustness of the regression performed. In a first step, both samples were checked to fit a normal distribution in order to establish the kind of probe that would eventually be implemented. Since in fact the samples returned abnormal, a non-parametric test was applied that verified that the distributions in both samples were the same. This confirmed the results as representative of the proposed regressions for energy consumption in January and July.

Having applied and checked the estimates, it was possible to begin the analysis consisting of formations of buildings in groups from the various variables in the DB, for which the statistical classification method called Cluster Analysis was applied. This method is based on the hypothesis that when certain things are related in a specific way, they can be grouped into a single discrete category or taxonomy. Cluster Analysis is used to generate instance types or groups with a similarity that can be quantified and measured (Vivanco, 1999).

To perform cluster analysis, it is necessary to correct the interdependencies that may exist between the variables and the non-equivalence of the metrics used. In our case, it is necessary because some variables are expressed, for

	Componentes Components	
	1	2
Área total edificio Total built area	0,96	
Área de oficinas Office area	0,96	
Número de pisos Number of floors	0,87	
Área fachada oficina Front office area	0,95	
Área de vanos Openings area	0,96	
Área útil de piso tipo Net area of the standard floor	0,56	
Fachada estructura liviana Light structure facade		0,59
Protección solar opaca Opaque sunscreen		0,82

TABLA / CHART 2

Orthogonal rotation components' matrix. Main components analysis.

Variables contínuas **Continuous Variables**	**Media Robusta** **Robust Mean (Estimator - M. Huber)**				
	Tipología 1 Tipology 1 N=22	Tipología 2 Tipology 2 N=31	Tipología 3* Tipology 3* N=1	Tipología 4 Tipology 4 N=25	Tipología 5 Tipology 5 N=11
Superficie del edificio Total built area	36191,9	10253,1	128663,1	9576,8	16313,4
Superficie de oficinas Office area	20342,0	5897,8	89625,0	5674,3	7639,0
Número de pisos Number of floors	22	11	52	10	12
Superficie fachada oficinas Front office area	11075,2	4076,5	32422,9	3705,1	5003,0
Superficie de vanos Windows area	7804,1	2051,1	29975,0	1516,5	3058,1
Superficie útil del piso tipo Net area of the standard floor	1019,7	611,9	1366,9	633,2	715,8

Variables categóricas **Categorical Variables**	**Mediana y moda** **Median and Mode**				
	Tipología 1 Tipology 1 N=22	Tipología 2 Tipology 2 N=31	Tipología 3* Tipology 3* N=1	Tipología 4 Tipology 4 N=25	Tipología 5 Tipology 5 N=11
Fachada liviana Light structure facade	Si / *Yes*	Si / *Yes*	Si / *Yes*	No	No
Protección solar opaca Opaque sunscreen	No	No	No	No	Si / *Yes*

TABLA / CHART 3

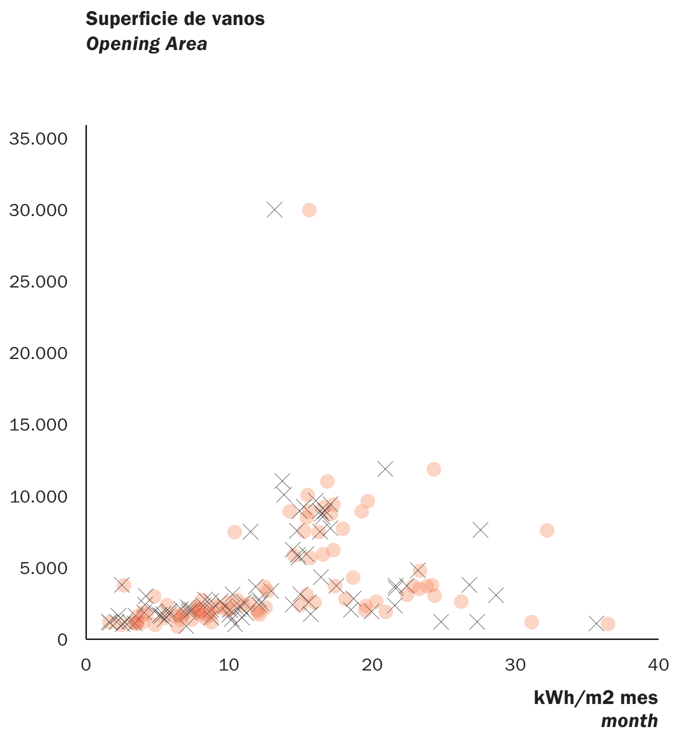
Continuous and categorical variables that conform typologies.
Nota / Note (*):

Given that this is a typology that has only one case, data corresponds to that case.

example, in units of energy (kW) or area (m^2), and others as dichotomous responses (yes-no). This correction was performed by means of a Principal Component Analysis (PCA) with orthogonal rotation. This procedure corresponds to a multivariate statistical analysis technique and is used to reduce the information of a large number of variables modeled as linear combinations. The new variables obtained by this process are called components and summarize the information contained in the original variables.

Regarding the obtained components, the high coherence between component 1 groups size variables and component 2 groups facade system configuration is particularly interesting. This analysis has left out the variable of the estimated energy consumption because the equations resulting from the regressions used to calculate it included virtually the same variables that make up the component PCA which would generate multi-co-linearities in the data.

Based on the components resulting from the PCA, a hierarchical cluster analysis was conducted that followed a tree structure where each stage produces a new branch. Although there is no rule to define the appropriate number of clusters, it is possible to establish a criterion through the interpretation of a dendrogram or graphical representation of the hierarchical cluster analysis that shows the successive stages of the classification. Figure 2 shows the dendrogram



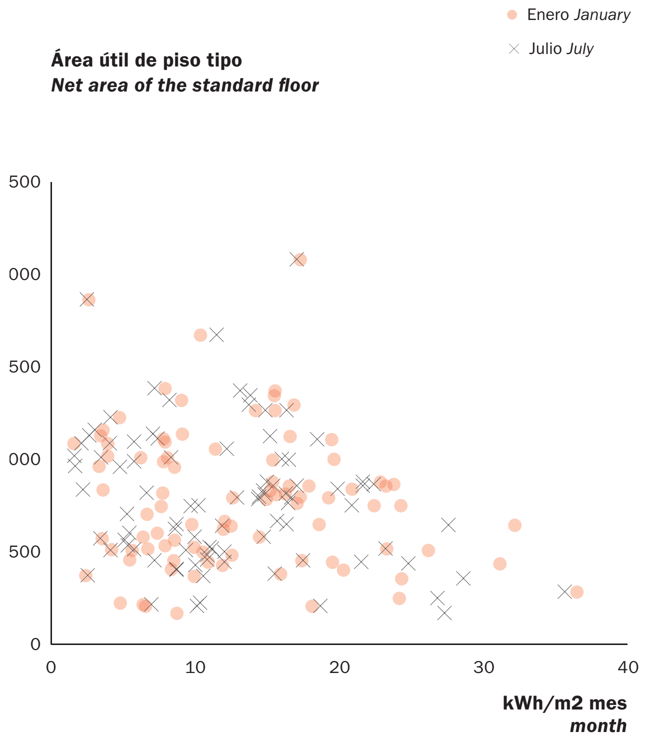


FIG 5

Correlation between openings area and the relative energy consumption (kWh/m2 month).

FIG 6

Correlation between the net surface area of the standard floor (m²) and the relative energy consumption (kWh/m² month).

obtained here, which is cut into five clusters concurrency considering the relative size of the clusters is balanced with the sectioning used.

Chart 2 presents the continuous variables with descriptive indicators showing data dispersion as well as the occurrence of continuous and categorical variables where each is expressed.

RESULTS

To explain the results we will elaborate a description of the complete sample and clusters, explaining which links can be established between the shape of the buildings and their energy consumption. This will allow us to clarify which are the characteristic profiles of each in relation to energy consumption.

DESCRIPTION OF THE COMPLETE SAMPLE

As shown in Figure 3, the correlation of the total area of the buildings with the building energy consumption is very high and reflects a very obvious fact: a building consumes more energy as its size increases. The coefficient of determination (R^2) shows that the regression has a high reliability (close to 1.0); however, when sorting the sample based on relative energy consumption (which corresponds to the total energy consumption divided by the net area expressed in kWh/m² (fig. 4)), the correlation results in a dispersion showing a significant independence between the size of the buildings and the efficiency with which energy is used in them.

In order to verify this we analyzed other dimensional aspects of buildings. The useable floor area expresses the area in which buildings develop vertically, representing the size of the main heat and energy exchanger units of each building with the outside. At the same time, the openings area expresses the net heat and energy exchange capacity between the building and the outside. The graphs of Figures 5 and 6 show the correlation between the two parameters and the relative energy consumption of buildings. In both cases the dispersion is evident. The concentrations suggest that both parameters are not predictors of energy consumption in buildings.

A better predictor is the Window to Wall Ratio (WWR), whose increment explains the increase in relative consumption, according to the graph in Figure 7. This highlights the importance of a climate like Santiago's on façades design. Indeed, the prevailing high solar radiation imposes an important role in energy demands over the building envelopes. This is the why the percentage of openings is one of the main predictors of energy consumption.

To verify these observations, we analyzed the sample DB according to façade system type. Figure 8 shows that the average relative consumption of light façades is the highest. As explained above, this kind of envelope is the one with the highest percentages of openings, because it is built with lightweight structures attached to the main structure of the buildings. At the other extreme, façades based on load-bearing walls show the lowest average relative consumption, because in this case windows are mostly subtractions from a mainly opaque plane. The difference between the two is very eloquent, as the average of the first is almost the double than the latter. On the other hand, these results suggest a highly glazed façade could be cooling the spaces at night –leaking heat through the envelope. This would explain the difference between the relative energy consumption between January and July, which show a difference of 18.6%, compared to only a 6.5% in the case of an envelope with a 24-34% of WWR. It is important to keep in mind these kinds of buildings are typically subject to high internal heat gains from users, artificial lighting and equipment, which are roughly constant across the year.

In summary, the analysis of the complete database shows that the energy consumption of office buildings currently being built in Santiago is directly related to the design of their façades, an issue on which we will go in depth by discussing the information from the clusters.

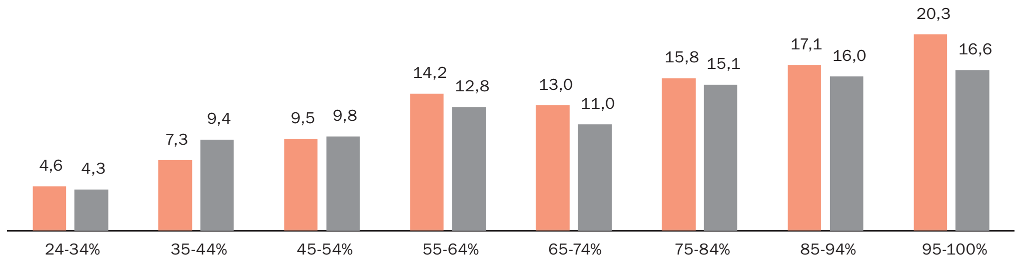
DESCRIPTION OF THE SAMPLE BASED ON CLUSTERS

Figure 9 shows the share of each cluster within the entire sample. A special note is needed for cluster 3 (composed of only one case) which when studied the DB building was the largest in the market and incomparable with the rest, hence its autonomy as a cluster.

The average relative energy consumption per cluster (fig. 10) represents the efficiency in consumption, because it links the size of the buildings with their total energy consumption. Moreover, the total energy consumption per cluster (fig. 11) expresses total energy consumed, i.e. the combined total of all buildings. Observing these graphs it is apparent that there is no consumption pattern, firstly because some of the buildings double the total energy consumption of others, and secondly because the efficiency in consumption is also variable and distributed among different clusters. The high diversity of consumption profiles of the clusters can be understood by cross-linking the three variables described above (efficiency, total consumption, and participation):

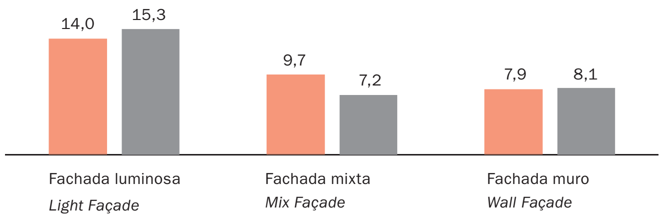
- Type 1 is the highest consumer, but its efficiency is within the average (15.9 to 14.9 kWh/m^2) and it reaches ¼ of the representativeness of the sample (25%).
- Type 2 is the most representative (34%) and its efficiency is among the best (11.9 to 10.5 kWh/m^2).
- Type 3 is a special case, its consumption profile is unique and its efficiency is within the average observed in the sample. Taking into account this is a unique case, its performance can be considered as good.

FIG 7



Average Relative Energy Comsumption (kWh/m²), by Window Wall Ratio (%)

FIG 8



Average relative energy comsumption (kWh/m²), by facade system typology.

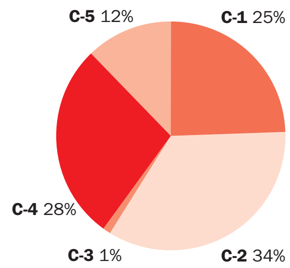
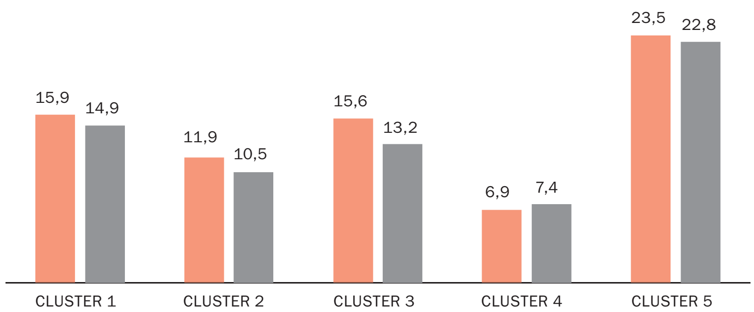


FIG 9

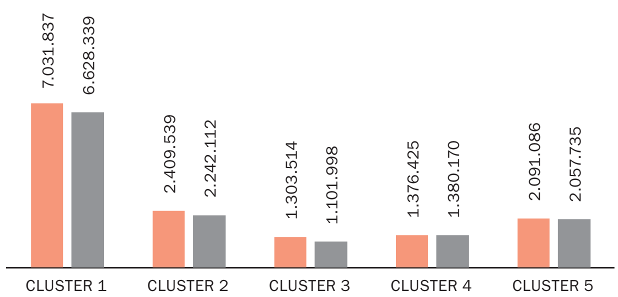
Distribution of typologies in the sample.

FIG 10



Average relative energy consumption by typology (kWh/m²).

FIG 11



Total energy consumption by typology (kWh/month).

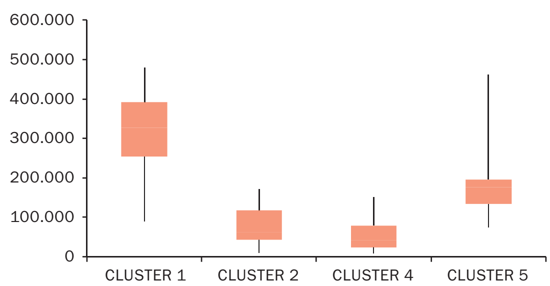
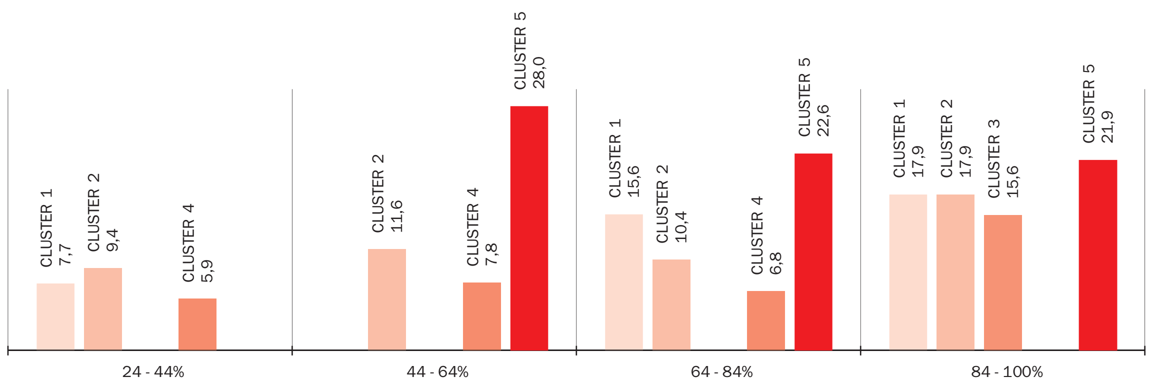


FIG 12

Total energy consumption (kWh/month) by typology. Box diagram.

FIG 13



Types ordered by Window Wall Ratio and average relative energy consumption (kWh/m²).

- Type 4 is the most efficient (6.9 to 7.4 kWh/m²) and has one of the lowest consumptions with a strong presence within the sample (28%), thus emerging as the best performing group.
- Type 5 is not the main consumer from the point of view of total energy consumption and also the least efficient (23.5 to 22.8 kWh/m²), although its representation is very low (12%).

The boxplot, which excludes Type 3 due to its unique character was built based on quartiles of consumption for each cluster and shows that the aforementioned diversity is nuanced (fig. 12). Indeed, it is possible to distinguish two groups from the point of view of the distribution of energy consumption per Type.

The first group includes Types 1 and 5, which have the largest amplitudes of consumption but differ in their central quartiles showing a smaller and more concentrated consumption in Type 5. The Graph also shows that Type 1 is the largest consumer of the sample. The second group consists of Types 2 and 4 and show much lower consumption and very similar profiles to each other. It is also important to consider that the second type group is the most representative of the universe of analysis, with a 62% of the analysis universe.

To explain the profiles of each Type, and the groups of Types, it is necessary to observe how they are distributed based on the façade systems. Some explanations can be derived by looking at the WWR distribution by Type and relative energy consumption (fig. 13).

The first is that cases with higher WWR correspond to those with the highest consumption; however, only one special case appears when observing Cluster 5 as the average relative consumption is inversely proportional to the WWR (fig. 10). Thus, the explanation of the high relative energy consumption in this Cluster appears that they are buildings where neither their size nor the transparency of their façades influence consumption; therefore other reasons need to be found.

Type 1, the main consumer of all Types, is consistent in that the relative consumption of the composed buildings is directly proportional to their WWR. Moreover, it encompasses three groups from the lowest (24-44%) to the two highest (64-100%) each with a consistent relative consumption.

In the group consuming the least, including Types 2 and 4, we observe characteristic features. Cluster 2 is the only one that has a cross-participation in all WWR groups each with consistent relative consumption. Meanwhile, the Type 4, which is the least consuming of all in the DB, is the only one not present in the group with higher WWR.

Type 3 is in the group of higher WWR, but it is more efficient than the averages of the buildings of the other clusters with similar transparencies. This shows that despite a significant total energy consumption, its efficiency for use is within what is to be expected (fig. 11).

Finally, to understand the importance of the façade system when looking for an explanation of the energy consumption of office buildings built in Santiago, we can see how the façade types and WWR per cluster are distributed (fig. 14).

Type 1, the main energy consumer in the sample only includes buildings with lightweight façade systems with average 82% WWR. This is a group of buildings with a consistently high transparency, a characteristic that explains its energy performance.

Type 2, grouping the buildings with less consumption, includes buildings classified in two different types of

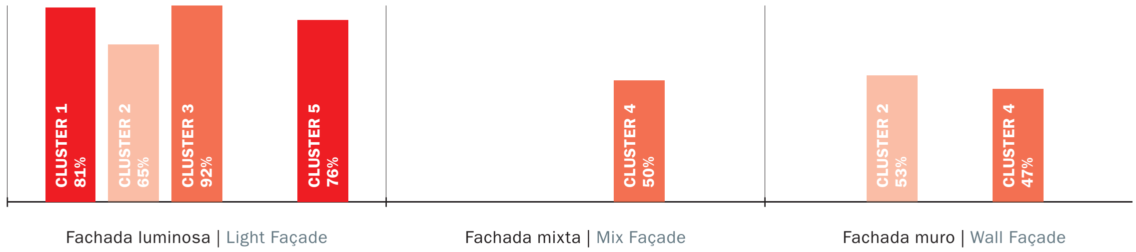


FIG 14

Window Wall Ratio (%) by type of facade and building typology.

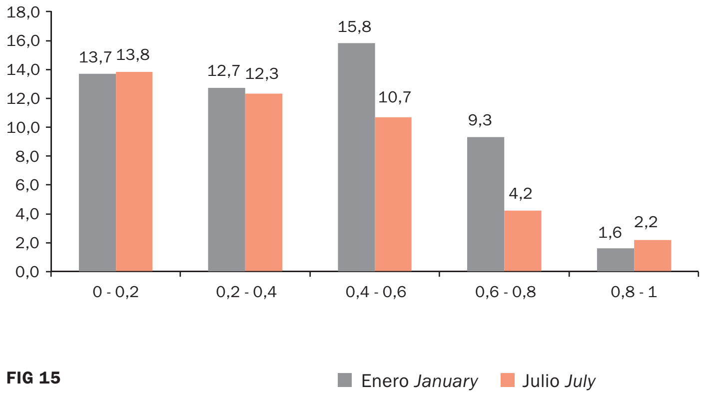


FIG 15

Relation between the buildings' Shape Factor and their relative energy consumption (kWh / m^2).

facades: lightweight façades, with the lowest average WWR (65%) and wall façades with an even lower WWR (53%). A low WWR is an explanation for their good performance in any of the types of façade systems applied.

Type 3 appears as the building with a highest WWR, although it is not comparable with the rest, because it is a single case. Its performance is typical of high transparency.

Type 4 is considered the most efficient of the buildings' entire sample, and façade systems provide an explanation: it contains only buildings with façades based on load-bearing or mixed walls. One singularity is that this Cluster concentrates all mixed façade buildings of the entire sample and is the only one that does not include buildings with lightweight façade systems. Its WWR are among the lowest since it is the only one in any of the façade types around 50%.

Type 5 was considered abnormal due to its strange profiling and poor performance. The average WWR of its buildings reaches 76% with a persistent transparency that explains their low performance. The low share in the sample (12%) (fig. 9) and high total energy consumption (fig. 11) explains that these are truly anomalous cases that would be interesting to understand further.

CONCLUSIONS

An analysis of the office buildings built in Santiago de Chile between 2005 and 2011 has been presented with the aim of profiling them from the point of view of energy consumption. By means of a Type analysis a group of buildings were divided in five clusters based on variables associated to the building façades.

We have shown that the size of buildings does not explain their energy consumption, and in contrast the characteristics of their façades explains it with resounding clarity. This shows the relevance of architectural design in the energy efficiency of office buildings and the inefficiency of a regulation based on the geometry of the plots as the sole parameter defining the general shape of the built volumes. A progress in this field is a matter of public policy, since only through regulations considering building energy efficiency are able to influence this market segment that today lacks any kind of relevant regulation. Using the Shape Factor to promote the construction of middle density urban buildings is an element to be considered. Graph 15 shows what happens with the relationship between the Shape Factor (envelope area / built volume) and energy consumption. It shows a clear relationship especially in July. Despite the fact that it is just a hypothesis and not a conclusive study, it is evident that the formal characteristics play a substantial role in the energy performance of buildings.

Also, the role that facility management companies or building administrations play must be established, as they are determinant of how energy is used. The development of predictive abilities and the implementation of strategies according to climate seasons and the density of occupation could be keys in this regard. For this, it is necessary to study the quality of inner comfort and relate it with energy consumption. This research team is currently conducting these studies, and we expect to obtain concluding results.

Among the resulting clusters, those with the worst energy performance are those with high WWR (>75%) utilizing light façade systems; on the contrary, those with the best performance are those with a low WWR (<55%) and walls or mixed-wall façade systems. It is important to understand this correctly. It is easy to believe that the problem is transparency; however, the question is different; what we see is a great ignorance on how to work with the building envelope. All the analyses we have conducted to consider the use of sun protection led us to discard it due to inconsistency in relation to its presence, its materials, and its application in relation to solar trajectories. This is relevant because it demonstrates that the architecture of these buildings lacks a correct or accurate formulation to deal with transparent façades.

The worst interpretation of the results would be to conclude that only massive, wall based envelopes should be used in Santiago. Quite the contrary, we believe it is necessary to learn how to use transparency to manage sun radiation and thus use it as a passive contribution to the building systems. Here is a huge challenge that must be addressed and developed.

In any case, the results obtained are consistent with the climatic characteristics of the city of Santiago, characterized by high solar radiation during most of the year. **ARQ**

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