Multidimensional performance analysis of office buildings with highly glazed facades. How do they perform in a Mediterranean climate?

Jordi Pascual[1*], Maria Casanovas[1], Damien Tavan[1], Daniel Perez[2], Emilio Mitre[3], Beatriz Tena[4]

[1] Sistemes Avançats d'Energia Solar Tèrmica (AIGUASOL), C/Roger de Llúria, 29, 3er-2a, 08009 Barcelona, Spain. Phone: +34 93 342 47 55, Fax: +34 93 342 45 56

[2] Centre Internacional de Mètodes Numèrics (CIMNE), Edificio C1, Campus Norte UPC C/ Gran Capitán S/N 08034 Barcelona, Spain. Phone: +34 93 205 7016, Fax.+34 93 401 6517

[3] ALIA Arquitectura Energía y Medio Ambiente, Paseo Zorrilla 98, 7º-b, 47006 Valladolid, Spain. Phone: +34 98 322 13 30

[4] Consorci Zona Franca Barcelona, Av. Parc Logístic, 2-10 - Pol. Ind. Zona Franca, 08040 Barcelona, Spain. Phone: +34 93 263 81 11, Fax. +34 93 263 81 59

[*] Corresponding Author, jordi.pascual@aiguasol.coop

Abstract

A multidimensional performance analysis of office buildings with highly glazed facades has been made in order to analyse the energy and economic performance of those buildings in a Mediterranean climate. A total of 1260 different cases covering a broad range of transparent office facade typologies were simulated in the climate of Barcelona. 6 different commonly used glazed façade designs were compared to a more traditional opaque façade solution used as a reference. Other variables to define the case studies were the glazing solution, the orientation, the shading from surrounding environment as well as the shading from fixed and movable elements mounted on the building itself. A series of building management optimization strategies were also studied. The analyses were made by using both thermal and daylighting simulation tools. Results were then analyzed from both an energy use and economic point of view using a simple, custom-made graphical representation to help quickly identify the problems inherent to each study case. One of the major findings of our study is that, in the Mediterranean climate, transparent buildings will always have a worse overall economic performance than opaque buildings due to the increased investment cost required for transparent designs to reach, only in the best cases, the same energy performance levels as opaque designs.

1. Introduction

Office building designs with highly glazed facades used to be a rarity in the Mediterranean climate, mainly because buildings with large glazed areas usually do not behave very well in warm and sunny climates. But in the recent years highly glazed facade designs have been increasingly adopted in southern European countries, without any clear justification of the comparative benefits of such designs in the Mediterranean climate. Highly glazed facades are usually justified, from an energy perspective, by arguing that the contribution of natural light is supposed to increase occupants' visual and lighting comfort while reducing the need for artificial lighting. While this can eventually be true in climates with low solar resources (i.e., where there is a need to make the most of the available daylight), this is unfortunately far from being true in the Mediterranean climate, where the problem usually resides in the difficulty to control the glare produced as a result of an excess of incoming solar resource. As a result, the lack of knowledge and data around the real performance of glazed facades in the Mediterranean climate generally leads to inadequate facade designs. This, in turn, leads to an excessive energy use due mainly to the high cooling demand of such building designs [1].

Hence, the main objective of the study presented here is to increase knowledge around the design, operation and overall energy and economic performance of transparent office building facades in the Mediterranean climate. The study will especially focus on the HVAC and lighting needs since they represent the greatest share of the total energy use during buildings' operation, which itself represents up to 75% of the energy used by the building over its entire life cycle [2]. Results of the study should lead to the development of an extensive energy performance database for glazed office building facades that could help designer and developers take data-driven decisions regarding facade designs during early stages of the design process.

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2. Methodology

In order to perform such an extensive analysis on building facades performance, a comprehensive set of study cases covering the widest possible range of situations had to be defined and simulated from both a thermal and daylighting point of view. A total of 1260 cases (referred to as scenario 0) were initially analysed covering a wide range of facade typologies and constructive solutions. The same methodology is also used for the optimization scenarios explained in section 4.

2.1. Monitorization

At first, a set of 6 existing transparent office buildings located in Barcelona (Spain) were selected according to their constructive solutions, were then audited and finally monitored both quantitatively (sensors and billing) and qualitatively (interviews and user surveys). On one hand, the obtained data made it possible to identify real-life comfort and energy use issues for those buildings that we would then extrapolate to a larger selection of transparent building designs. Considering the purpose of our project, it didn't make sense to monitor the buildings entirely, neither from a theoretical point of view, nor from a practical one (i.e., too complicated and expensive). Hence, representative zones were selected for each building, with different orientations, and the condition that at least one monitored zone would be unoccupied and unconditioned in order to properly evaluate the building's passive behaviour. On the other hand the collected performance data was also used to calibrate the numerical simulation models used for the case study [3].

2.2. Definition of base cases for scenario 0

The simulation models for all studied cases are based on a single-zone model. The zone geometry, identical for both thermal and lighting analyses, was defined so that significant variations in terms of daylighting levels could be observed across the space, and incident solar radiation be accounted for correctly. The zone is considered to be adjacent to other zones with the same comfort conditions, that is, all walls are adiabatic except for the envelope element that makes up the facade. This is to allow for a parametric analysis without the data being influenced by extraneous factors such as insulation type and thickness between inhabited and uninhabited areas. For the same reason, the zone is considered as being located in the middle floor of the building. The occupation profiles and equipment schedules will be those defined by Spanish building directive (CTE) [4].

The base cases were defined as a function of the façade typology and the constructive solution used. 6 types of transparent facades, 6 glass solutions, 5 shading strategies, 6 orientations, and 1 climatic zone (Barcelona, Spain) were analysed. A reference building with an opaque façade (i.e., façade with 40 % of glazed area), named Type 0, was also defined to be used as a base case. Glazed façade solutions were classified in six distinct basic typologies in an effort to normalize the very broad range of constructive solutions generally found in transparent office building designs.

Table 1. Simulated facade typologies.

Type 1 (T1)	Type 2 (T2)	Type 3 (T3)	Type 4 (T4)	Type 5 (T5)	Type 6 (T6)
Window	Continuous Glazing	Double Skin (Nat. Vent.)	Double Skin (Mech. Vent.)	Optimized single-skin	Double Skin (Mech. Vent. + recirculation)

In order to simplify the model, the thermal behaviour of double skin facades was simulated considering the air gap between the two skins to be an extra thermal zone ventilated by a variable or fixed rate of air changes (depending on the façade type). In the Type 3 façade typology (double skin, naturally ventilated), ventilation of the double skin façade relies on the natural convective effect. The rate of air changes in the air gap between the two skins is increased when the interior temperature of the façade is greater than the exterior temperature. In the Type 4 façade typology (double skin, mechanically ventilated), the façade incorporates a mechanical ventilation system that can enhance air flow depending on external conditions. This allows for a better ventilation of the façade, hence a better overall performance. The Type 6 façade typology (double skin, mechanically ventilated with air recirculation) refers to a typology similar to that of Type 4, but with the addition of a system that recirculates the air flow passing through the double skin in the gap existing in the false ceiling. To do so, the ceiling space was also defined as an extra thermal zone, adjacent to the target thermal zone. Obviously there are other models (not analyzed here) for alternative ways the re-use this pre-heated air, for example as input to the air handling units.

On the other hand, the glazing type was also considered. Thanks to the great development of glazing solutions in the last years, the range of available solutions for building facades is nowadays extremely large. Hence, in order to simplify what would otherwise be a difficult to undertake task, the study was limited to only the most representative glazing solutions. As a result, our study relies on the following selection of glazing solutions:

Table 2. Simulated glazing Solutions

Solution	Glazing	Frame	U [W/m^2.K]	g	T_v(%)
GS1: **Clear**	4-6-4	Low-quality	3.4	0.76	69%
GS2: **Low-e**	4-12-4 (low-e)	Aluminium + thermal break	1.4	0.53	74%
GS3: **Reflective (low)**	6-12-6	Aluminium + thermal break	1.4	0.46	46%
GS4: **Reflective (high)**	6-12-6	Aluminium + thermal break	1.9	0.11	7%
GS5: **Mixed (Reflective+TIM)**	Combination of light reflective coating and TIM	Aluminium + thermal break	n/a	n/a	n/a
GS6: **Noble gas**	6-12-6 w/ Argon	Aluminium + thermal break	1.04	0.47	65%

For all double skin facades, the external glazing is always considered to be a clear structural simple-glazing. Cases were also analyzed considering the 6 orientations defined in the Spanish regulatory framework for constructions, the *Codigo Tecnico de la Edificación* (CTE), that is North, South, East, West, South-East, South-West [4].

Another factor that greatly influences the overall performance of transparent buildings is the existence and type of shading element. For the purpose of this study, 3 categories of shading elements were considered: Site shading, or shading due to surrounding elements (i.e., surrounding buildings), building shading elements (i.e. the fixed shading elements mounted directly on building façade) and movable shading devices (i.e., systems that can perform a temporary obstruction of incident solar radiation incident on the facades). For the site shading case, the shadow projected by surrounding buildings was calculated considering the typical city grid found in Barcelona. For the building shading cases, a cantilever having a length equal to one third of the height of the glass surface was considered. Then, movable "horizontal slats" shading devices that cover 50% of the glazed area were considered for the last shading cases. In this case, a glare control was also considered in the simulation, so that the shading factor would be increased when there is direct incident radiation on a facade that could cause glare and disturb occupants. Fixed and movable shading elements were only considering in cases with no surrounding buildings projecting shadows.

2.3. Simulation strategy

The simulation engines used for this study were TRNSYS (used in combination with GenOpt to perform parametrical analyses) for thermal simulations and DaySim (RADIANCE Engine) for daylighting analysis. The versatility offered by TRNSYS and the widely recognized result accuracy offered by both TRNSYS and DaySim were the main reasons to use those tools. For both the thermal and daylighting analyses, the same constructive (glazing type, facade design, etc.), external (climate) and internal (operation mode, profiles, etc.) conditions were considered so that a consistency among the obtained results could be maintained. Since TRNSYS and DaySim cannot be coupled in an automated fashion, a custom strategy was employed so that variables used by both engines in their calculations (that is, lighting levels/heat gains, lighting electric consumption, shading factor due to movable shading) could be cross-coupled, and results be more accurate. This was done by using one tool's output as input to the other tool, and vice-versa. This strategy lead to a better understanding of the strong coupling that exists between thermal and daylighting issues in transparent office buildings, and made it possible to extrapolate the analysis made on the initial 6 monitored buildings monitored to the 1260 studied cases of the scenario 0, and therefore get a more complete understanding of how transparent buildings perform in Mediterranean climates.

2.4. Post-processing & analysis variables

Simulations give heating/cooling demand and thermal comfort outputs on one hand, and lighting electric consumptions and visual comfort outputs on the other hand. A post-processing of outputs is therefore necessary in order to obtain homogeneous results that can be analysed and compared.

Heating and cooling demands are translated to energy consumptions by applying conversion coefficients reflecting the performance of a conventional HVAC system typically found in Spanish office buildings. Comfort results are converted to normalised comfort indexes to make it possible to compare both thermal and visual comfort results on a same graph.

Finally, some additional analysis variables were created to extend the scope of the analysis and give a more complete picture of the energy and economic performance of the various typologies analyzed. Consumptions were therefore converted to energy costs, initial inversion costs were calculated for all studied typologies, and a life cycle costing analysis (LCCA) was undertaken to distinguish which cases were the most efficient from an economic point of view.

3. Results analysis for scenario 0

3.1. Detailed energy and economic results

In addition to the specific case analyses, and considering the large number of results to be analyzed (1260 cases and 10 different analysis variables, so a total of 12600 values to analyze), a quantitative analysis based on a graphical representation of results seemed the most sensible way to analyze results and draw conclusions. A series of result spreadsheets were therefore designed so that we could encompass all results of a particular analysis variable in a single image, and thus be able to simply and quickly find trends among the impressive amount of data generated by the project. It is not possible to reproduce here the full spreadsheets which are meant to be printed in DIN A3 format. However, in order to facilitate the understanding of the global results, a smaller version is shown below, displaying the energy consumption and LCCA results for all cases. Each cell contains the annual value for a particular variable and case, and according to the color scale, the darker the color of the cell, the higher the value, and therefore the lighter the color, the lower the value. Finally, each independent table corresponds to a different facade typology, as described in Table 1 above. Hence, we can observe that tables showing darker cells correspond to worse performing facades because of higher energy use and/or higher economic cost.

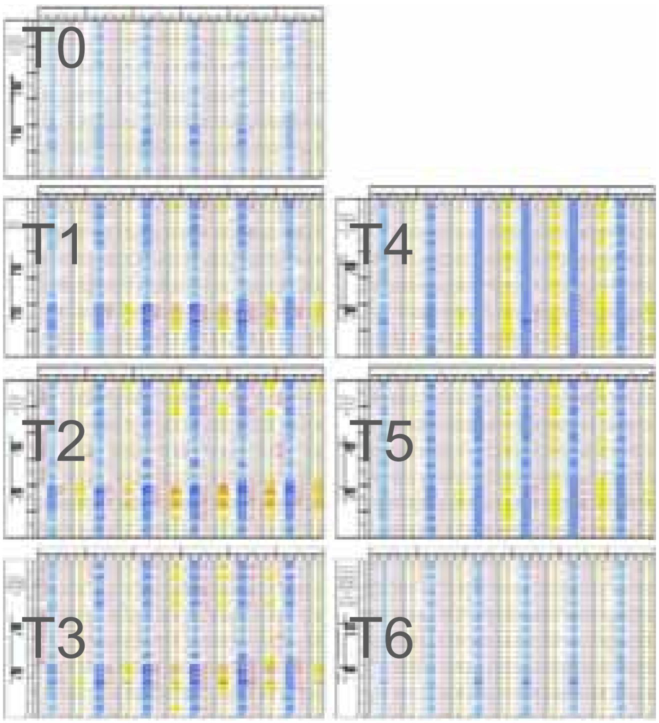

Fig. 1. Energy consumption results for all cases.

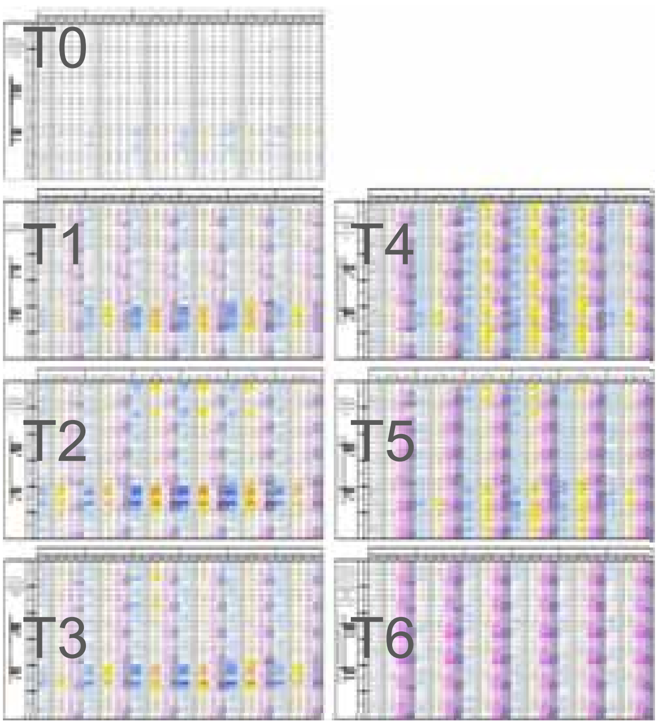

Fig. 2. LCCA results for all cases.

3.2. Conclusions for baseline scenario

Here follows a selection of the most relevant tendencies and conclusions drawn within the scope of this project:

- The magnitude of the heating demand is rather low, about half the heating demand of a typical office building in Barcelona [5]. But the total annual cooling demand is about 3 times the heating demand. In terms of consumption, 90% of the energy is used for lighting and cooling while only 10% is for heating. The sensible cooling demand is always substantially higher for transparent buildings than for the reference building with opaque façade. The great influence of orientation on energy use is confirmed, with variations in terms of energy consumption in the range between 30 and 40%.
- Overall, the worse performing facades are those with a double-skin (with the notable exception of those with air recirculation). A second skin on a transparent building façade contributes to greatly increase the cooling demand in the Mediterranean climate, no matter the glazing solution used. In contrast, façade typologies with the lowest cooling demand are opaque ones (Type 0) alongside with the mechanically ventilated double-skin façade with air recirculation (Type 5).
- The façade typology, orientation and shading strategy have more impact on the zone cooling demand than the glazing solution. Only one exception observed for Transparent Insulating Materials (TIM). In Mediterranean climates where overheating in summer is the major concern, TIMs let the incident radiation in, but don't let the heat out, which contributes to increase the cooling demand.
- Variations between the different shading strategies follow the same trends regardless the façade typology, glazing solution or orientation. The lowest cooling demand happens when fixed shading elements are used. Movable shading devices are regulated to optimize visual comfort, not thermal comfort. Hence, cooling demand for those cases tend to be higher.
- The façade typology or glazing solution does not greatly influence visual comfort. The opaque façade shows worse results in terms of visual comfort, although results at a 2m distance are rather uniform across all typologies, even the opaque one. The glazing solution affects the visual comfort index in greater proportions further away from the façade (6m distance) than close to it (2m distance).
- From an economical point of view, highly glazed building facade typologies all show a worse overall economic performance than opaque buildings because of the high investment cost required for transparent designs to be as efficient as opaque designs. For instance, the Type 6 facade which shows good energy performance according to results shown on Fig.1 (comparable to T0), appears much worse in light of the LCCA analysis results shown on Fig. 2 because of the very high cost of the proposed facade solution.

4. Optimization scenarios

Once the radiography of these 1260 cases of the scenario 0 was obtained, different operative optimizations were defined and analysed by using the same methodology. These optimization cases were grouped in the so-called scenario 1 (daylighting optimization), scenario 2 (thermal optimization), and scenario 3 (Daylighting & thermal optimizations).

4.1. Definition of optimization scenarios

The initial cases analyzed in scenario 0 intended to simulate realistic cases, and therefore didn't consider any optimization strategy in terms of building management. Analysing how better building management can improve buildings' energy use and economic balance is therefore a natural next step for our study.

The study focuses on those parameters that can be user-operated and that, according to our previous analyses, more directly affect the energy balance of highly glazed buildings, namely the regulation of movable shading devices and the control and modulation of artificial lighting fixtures.

- Scenario 0 (Base cases). This scenario groups the initial study cases described in the previous sections of the present article. In this scenario, artificial lighting is on during the entire occupation period, and operation of movable shading devices is only intended to avoid glare.
- Scenario 1 (Daylighting optimization) analyzes an operation model which aims at reducing electricity consumption due to artificial lighting by maximizing use of natural lighting. A set of light sensors controls the gradual adjustment of artificial lighting power, ensuring a minimum illuminance of 500 lux during building's occupancy hours. Movable shading devices are operated in the same way as in scenario 0.
- Scenario 2 (Thermal optimization) analyzes an operation model targeted at reducing cooling demand by regulating the movable shading devices so that overheating is avoided inside the building. Movable shading devices are supposed to be controlled by direct radiation sensors and moved as a function of the solar radiation available. Other parameters remain as in scenario 0, that is, artificial lighting is always at maximum power during the occupation period.
- Scenario 3 (Daylighting & thermal optimization) analyzes an operation model that is a combination of the above two. On one hand, artificial lighting is controlled so that the use of natural lighting is maximized, and on the other hand, and shading devices are operated to limit overheating within occupied spaces.

For this analysis, cases from scenario 0 that were seen as unrepresentative or too similar were discarded. The ultimate goal was to simplify the number of cases to be analyzed for each scenario without restricting the scope of our study. The analysis was therefore conducted for all facade typologies, but only for a selected number of cases: 2 orientations (north and south), 3 shading strategies (no shading, movable shading, fixed+movable shading) and 3 glazing types (clear, low-e and low reflectivity) only.

4.2. Results analysis for optimization scenarios

The main conclusions resulting from the analysis of optimization scenarios are summarized below:

- Overall energy savings achieved by the various operative optimizations fully justify the adoption of such measures, regardless of the type and orientation of facade. Savings are proportionally bigger for cases with higher energy demand (e.g., double-skin facades without recirculation) and significantly smaller for cases which were already more energy-efficient (e.g., opaque facade).
- Daylighting optimization (i.e., scenario 1) brings greater savings than thermal optimization. But the combination of both type of optimization (i.e., scenario 3) is the most efficient.
- Savings obtained through daylighting or thermal optimization are quite homogeneous across all facade typologies and glazing solution. In other words, the effect of optimizations strategies

on the building’s operation seems rather independent from the constructive solution considered.

- For south oriented facades, the combination of fixed and mobile shading devices brings the greatest savings. For north oriented facades, only mobile shading devices are necessary.
- Although economic savings are substantial for all facade typologies when the operation of the building is optimized, the trends observed with the scenario 0 still remain valid. This means that the reference opaque facade remains economically more profitable, while double-skin facades have the highest overall life cycle cost. In other words, the great savings obtained when optimizing building’s operation do not compensate for the much higher investment cost of double skin facades, even for the most efficient ones (e.g., Type 6).

5. Conclusions

As previously mentioned, these conclusions are valid under the assumptions made within the project and for buildings located in a Mediterranean climate. However, regardless of the climatic zone considered, it seems clear that, beyond aesthetic considerations, transparent building designs for office use are generally associated with increased energy consumption and economic cost, and should be operated in a much more efficient way to try reducing their impact on the environment.

6. Further developments

The same analysis is intended to be repeated for other southern European climatic conditions, and first of all for office buildings situated in Madrid. On the other hand, due to the impossibility to reproduce here all of the results generated within the scope of the TOBEE project, we suggest that people interested in knowing more about the project’s outcome should contact the corresponding author for more detailed information.

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