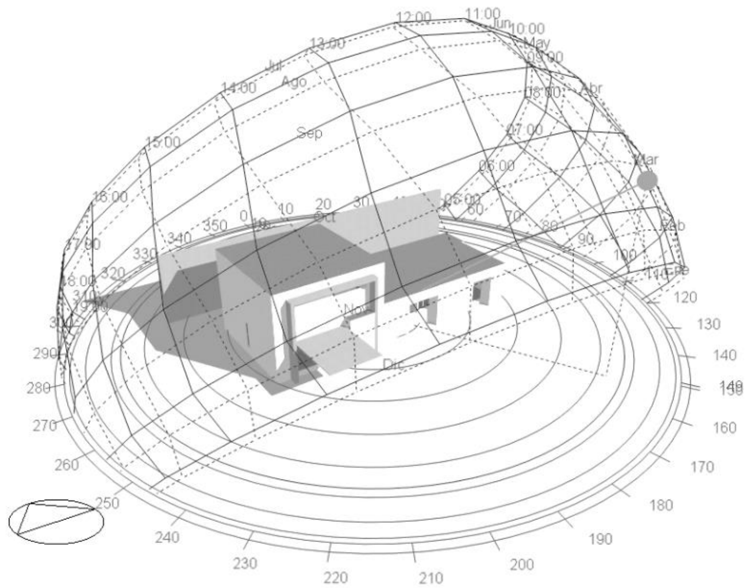
Optimizing an Eco-Friendly House Design using DesignBuilder



A project by:

sol·arq through EcoSotres

Tarragona. December 14, 2018.

1. Executive Summary

This study addresses the optimized design of a 150 m^2 3-bedroom detached house located in Els Pallaresos (6 km from Tarragona, in Catalonia, Spain). The main goals were to accomplish high energy efficiency, select materials that are healthy for occupants, have a low ecological footprint, and if possible, to achieve construction costs below those typical for this region. One key strategy to achieve these goals was to implement a simulation-driven design process from the very beginning of the project. In addition to extensive research on the materials and construction systems available in the region, the project involved three main phases, which will be further explained in this report:

a) An **optimization analysis** based on genetic algorithms aimed to investigate the architectural design solutions that offer the best performance regarding carbon emissions and construction cost.

b) Development of the **architectural design** from the results of the optimization analysis, but further considering the peculiarities of the topography and the specific requirements of the owners.

c) A **parametric analysis** aimed to verify the performance of the project as well as to further optimize constructions and glazing.

The methodology proved to be very useful to achieve the initial goals. The project obtained the highest energy rating according to the Spanish Building Technical Code. Furthermore, compared to an average project, we produce savings of 31% on global costs (above € 32,000 considering only the basic construction elements), as well as a reduction of 41% on global emissions (above 60 tons). This project demonstrates the benefit of implementing a simulation-driven design process, especially if optimization analyses are executed from the very early design stages. Also, DesignBuilder proved to be a valuable tool through the entire process, not only because it enables EnergyPlus simulations to be completed much more productively but because it performs such a wide range of analysis types. That greatly facilitates the decision-making and the interactive design process.

2. Optimization analysis

This phase aimed to explore the architectural design solutions that offer the best performance, considering two objectives: (a) to reduce the carbon emissions associated with fuel consumption and (b) to minimize the initial construction cost. We used a method that involves coupling the EnergyPlus simulation engine to a genetic algorithm using DesignBuilder's optimisation tool.

This method helps to solve problems with many design variables and options, running far fewer simulations as the genetic algorithm efficiently searches the design space to identify optimum solutions that best meet the design objectives. As shown in *Figure 1*, the optimization analysis included seven design variables:

- **Form**. Seven building forms were evaluated. The geometric models were simplified but included the internal distribution of common dwelling spaces. All have the same main spaces and the same useful floor area, although due to their geometric configuration they have different circulation areas.
- **Window-to-wall ratio**. 11 window-to-wall ratios (WWR) were considered for the main spaces of the house: living-dining room, study, and bedrooms. In those spaces, the WWR ranges from 0.25 to 0.75, in intervals of 0.05. In the remaining spaces, the windows are relatively small and have fixed dimensions.
- **Thermal mass and insulation levels**. The opaque constructions were mainly defined through the combination of two design variables: thermal mass and insulation levels. Also, they are differentiated into two groups. The first one corresponds to constructions that involve common Spanish materials. This group is made up of 36 options, which result from combining four thermal mass and nine insulation levels. The second group includes two construction systems, one with walls and slabs of cellular concrete, and other with walls made of cellular concrete and slabs made of prefabricated pieces of alveolar concrete. We combined both systems with five insulation levels corresponding to the values recommended by the Spanish Building Technical Code (CTE) for climatic zones A, B, C, D, and E. In summary, the optimization analysis included 46 options for opaque constructions.
- **Number of glass panes and glazing type**. The optimization analysis included 12 glazing options, which result from combining two design variables: the number of glass panes (2 and 3), and the glazing type (clear, absorbent, reflective, absorbent-reflective, low emissivity, and spectral selective).
- **Shading**. Four shading options were considered for the windows on main spaces: living-dining room, study, and bedrooms. The shading devices consist of overhangs and sidefins, with four possible dimensions: 0.00 (no devices), 0.50, 0.75 and 1.00 m.

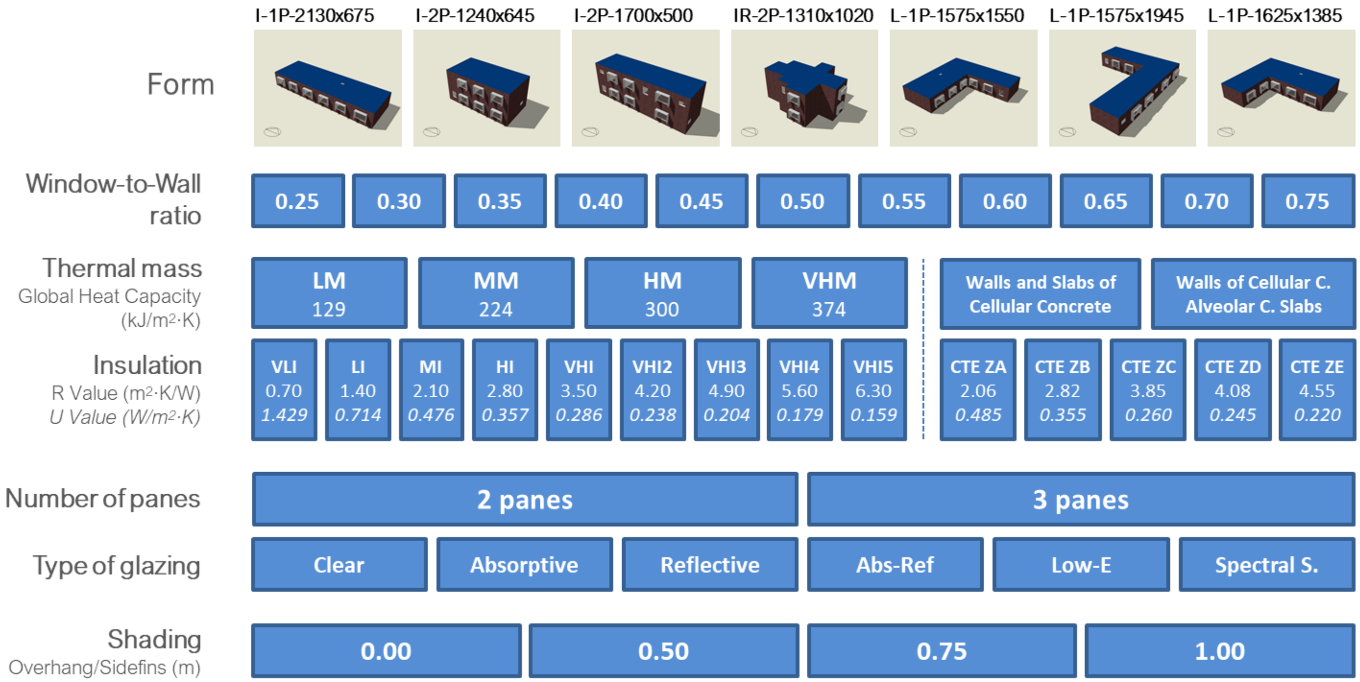


Figure 1. Matrix of design variables and options for the optimization analysis.

The total possible design solutions exceeded 170,000, considering the combination of the options included in each design variable. The genetic optimization method allowed us to identify the optimal solutions (or very close to the optimum) after simulating only about 7,000 solutions.

2.1. Optimization results

Seven optimization runs were carried out, one for each form option. The graphs in *Figure 2* shows the results of the seven runs, differentiated by a specific color. The X-axis denotes the operational CO_2 emissions, that is, the emissions associated with fuel consumptions. The Y-axis indicates the initial building costs, considering only the basic cost of constructions, glazing, and shading devices.

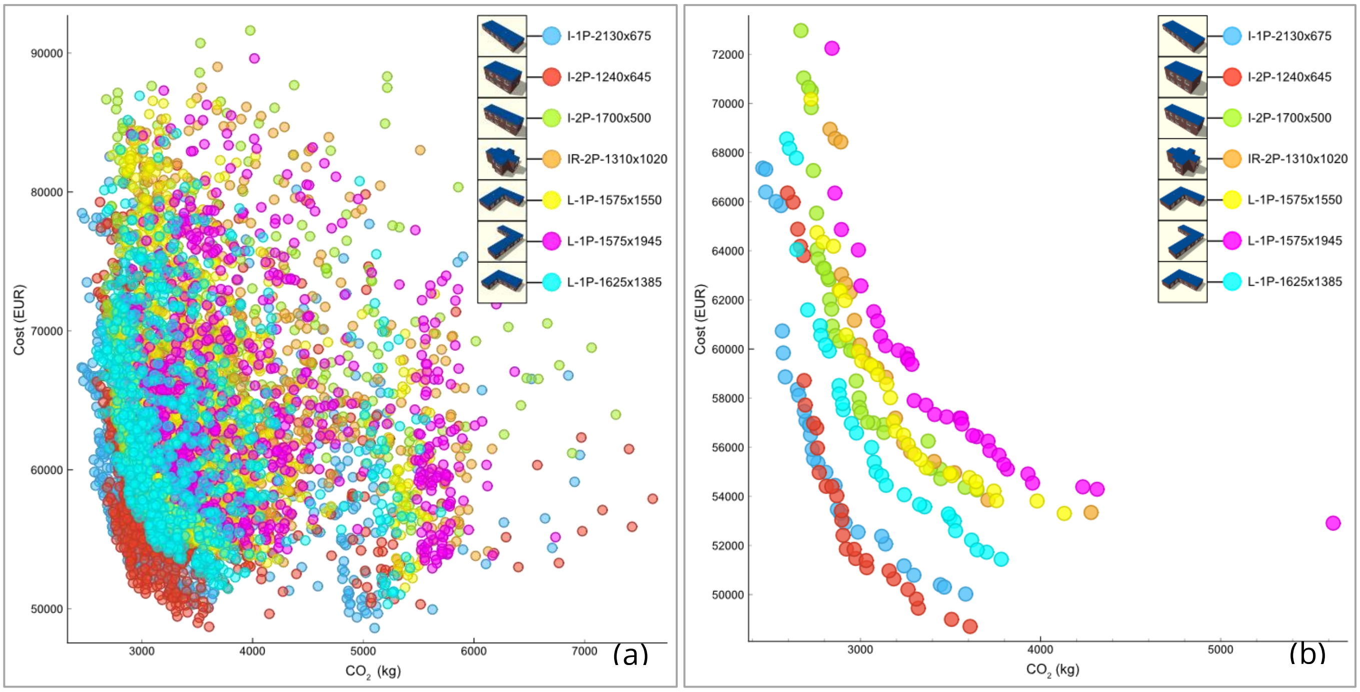


Figure 2. Results of the optimization analysis: (a) all the simulated solutions and (b) just the Pareto fronts of the seven building forms.

The results show that forms I-1P-2130x675 and I-2P-1240x645 offer the best performance since they are closer to the overall Pareto front, that is, the contour of solutions that are not surpassed by other solutions regarding cost and carbon (simultaneously). In fact, all the overall optimal solutions correspond to one of these forms. That is more clearly seen in the graph at the right (b), which shows only the Pareto fronts of the seven building forms. It is also evident that both forms have a very similar performance in the central part of the Pareto front, that is, the one that offers the most balanced solutions in terms of carbon and cost. All these findings helped the owners and the design team to focus in on which designs to consider further in the next phases.

Complementarily, *Figure 3* shows only the Pareto front of the form I-2P-1240x645 and highlights three solutions that have been selected as the "most" optimal, as they have clear advantages over the remaining ones. This selection avoids the extreme solutions, that is, the most expensive and those that generate the most CO_2, under three different selection criteria:

a) The CO_2-oriented selection (solution 7).

b) The "well balanced" selection (solution 11).

c) The cost-oriented selection (solution 18)

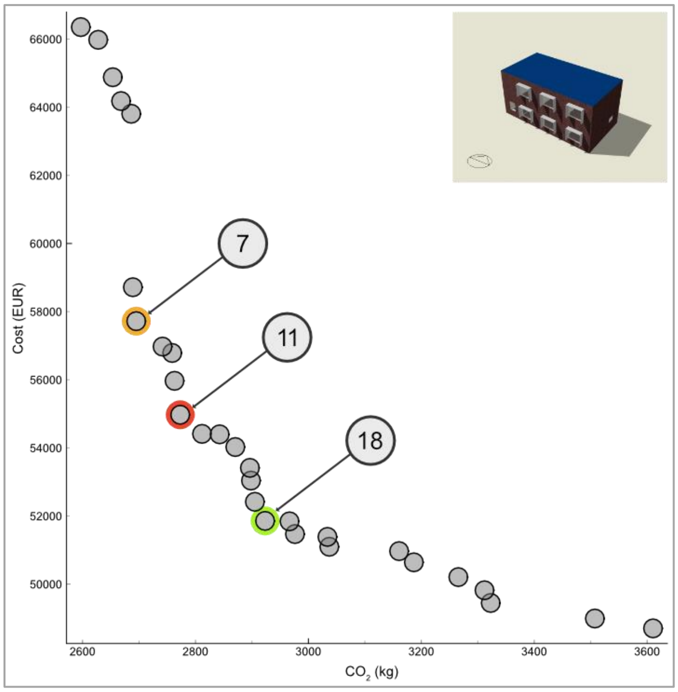


Figure 3. Pareto front of the form I-2P-1240x645, with selected optimal solutions.

Table 1 shows all the values of the solutions in that Pareto front. Rows highlighted in blue correspond to the three selected solutions. The table makes it clear the design options that tend to reduce CO_2 emissions but increase costs, as well as those that reduce costs but increase emissions.

Table 1. Design options and results of solutions in the Pareto front of the form I-2P-1240x645.

	Order	Constructions	Glazing	WWR	Shading	CO_2 (Kg)	Cost (€)
Lower CO_2 / Higher Cost >	1	03I_MM-VHI5	03f_Tryple-Spectral	25%	1.00m	2,597.7	66,352.9
	2	03I_MM-VHI5	03f_Tryple-Spectral	25%	0.75m	2,628.5	65,979.8
	3	03H_MM-VHI4	03f_Tryple-Spectral	25%	0.75m	2,654.3	64,880.8
	4	03G_MM-VHI3	03f_Tryple-Spectral	25%	1.00m	2,669.0	64,181.0
	5	03G_MM-VHI3	03f_Tryple-Spectral	25%	0.75m	2,687.0	63,807.9
	6	HCel-Alv_OrientZE	03f_Tryple-Spectral	25%	1.00m	2,689.9	58,715.9
	7	**HCel-Alv_OrientZE**	**02f_Double-Spectral**	**25%**	**1.00m**	**2,695.9**	**57,719.7**
	8	HCel-Alv_OrientZE	02f_Double-Spectral	25%	0.50m	2,742.5	56,973.5
	9	HCel-Alv_OrientZE	02e_Double-LowE	25%	0.75m	2,759.6	56,786.2
	10	HCel-Alv_OrientZC	03f_Tryple-Spectral	25%	0.75m	2,763.8	55,968.0
	11	**HCel-Alv_OrientZC**	**02f_Double-Spectral**	**25%**	**0.75m**	**2,773.8**	**54,971.8**
	12	HCel-Alv_OrientZC	02e_Double-LowE	25%	0.75m	2,812.4	54,411.4
	13	HCel-Alv_OrientZC	02a_Double-Clear	25%	1.00m	2,843.6	54,398.0
	14	HCel-Alv_OrientZC	02a_Double-Clear	25%	0.75m	2,871.4	54,024.9
	15	HCel-Alv_OrientZB	03f_Tryple-Spectral	25%	0.75m	2,897.2	53,413.0
	16	HCel-Alv_OrientZB	03f_Tryple-Spectral	25%	0.50m	2,899.1	53,039.9
	17	HCel-Alv_OrientZB	02f_Double-Spectral	25%	0.75m	2,906.0	52,416.8
	18	**HCel-Alv_OrientZB**	**02e_Double-LowE**	**25%**	**0.75m**	**2,924.1**	**51,856.4**
< Lower Cost / Higher CO_2	19	HCel-Alv_OrientZB	02a_Double-Clear	25%	1.00m	2,967.4	51,843.0
	20	HCel-Alv_OrientZB	02a_Double-Clear	25%	0.75m	2,977.0	51,469.9
	21	HCel-Alv_OrientZB	02c_Double-Reflec	25%	0.50m	3,034.5	51,386.7
	22	HCel-Alv_OrientZB	02a_Double-Clear	25%	0.50m	3,037.9	51,096.8
	23	HCel-Alv_OrientZB	02d_Double-AbsRef	25%	0.00m	3,161.5	50,968.9
	24	HCel-Alv_OrientZB	02c_Double-Reflec	25%	0.00m	3,187.6	50,640.4
	25	HCel-Alv_OrientZA	02e_Double-LowE	25%	0.75m	3,266.4	50,206.7
	26	HCel-Alv_OrientZA	02a_Double-Clear	25%	0.75m	3,312.8	49,820.2
	27	HCel-Alv_OrientZA	02a_Double-Clear	25%	0.50m	3,323.7	49,447.1
	28	HCel-Alv_OrientZA	02b_Double-Absorp	25%	0.00m	3,508.3	48,990.7
	29	HCel-Alv_OrientZA	02a_Double-Clear	25%	0.00m	3,611.3	48,700.8

3. Architectural project

The architectural design was developed from the results of the optimization analysis, but also considering the peculiarities of the topography and the specific requirements of the owners in a more detailed way. The most significant changes regarding the optimization models were the following:

- We adopted a solution that could be defined as "intermediate" since it combines the two most optimal building forms, I-1P-2130x675 and I-2P-1240x645. Almost all the main spaces are on the ground floor, but the studio is on the first floor forming a mezzanine that communicates with the dining-living room by a double height space.
- The windows have different dimensions in each space, according to its specific requirements. The total proportion of glazing in the main spaces of the house was maintained at 0.25, as suggested by the optimization analysis, while the overall glazing ratio is 0.12 (considering all the exterior walls and all the windows).
- Instead of window shading devices, the project included more architectural self-shading to reduce the carbon footprint further. On the outside part of the living-dining room, we

proposed to install a folding awning to reinforce the shading of the biggest window and also get an outdoor space protected from the sun, especially in summer.

Figure 4 shows the layout of the architectural project, including the ground floor and the first floor. *Figures 5 and 6* shows some views of the project. Note that the orientation of the property allowed us to easily orient the main windows to the south.

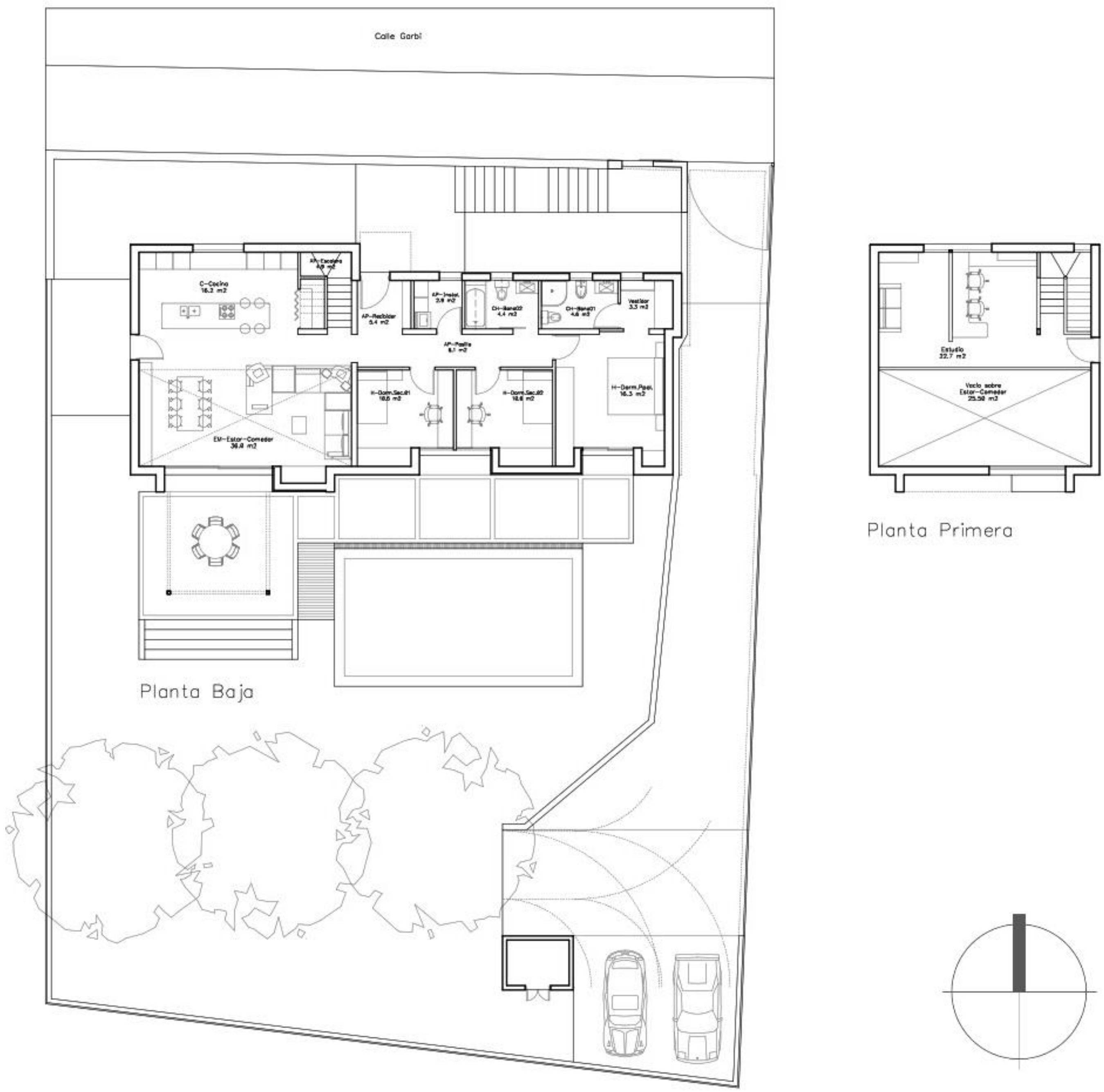


Figure 4. Architectural layout of the house.

Figure 5. External view.

Figure 6. Internal views.

4. Parametric analysis

From a more detailed simulation model, adjusted to the architectural design, we carried out a series of parametric simulations. The main objective was to verify the performance of the project, as well as to further optimize the constructions and glazing. In total, we simulated 12 solutions derived from the matrix of options shown in *Figure 7*.

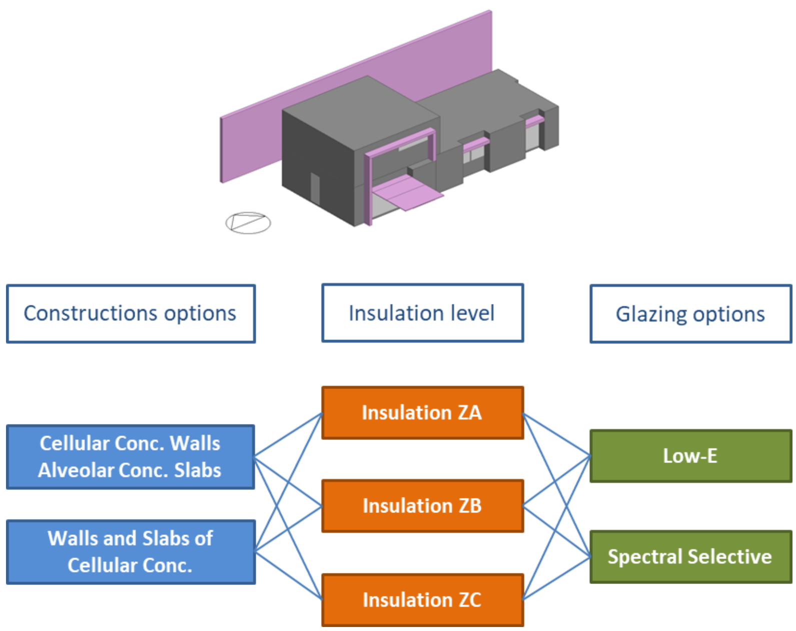


Figure 7. Matrix of options for the Parametric analysis.

In this case, to evaluate the design solutions we not only considered the operational emissions and the initial construction costs, but we also used the Global CO_2 emissions and the Global Costs. The first indicator is the sum of operational emissions and the carbon embodied in the constructions, while the second one is the sum of initial construction costs and the costs of the energy consumed during the house lifecycle. Thus, the criteria for selecting the best solutions are even more comprehensive than in the case of the optimization analysis.

4.1. Parametric analysis results

Figure 8 shows the global costs and global CO_2 emissions of the simulated design solutions. The first indicator increases gradually as the construction system switches to the cellular-concrete-only option, the insulation level increases, and the glazing performance is improved. On the other hand, the solutions with alveolar concrete slabs present much higher emissions, compared to the cellular-concrete-only solutions.

The results make it evident that the solution HCel_ZC-LowE (pointed out by the blue and red circles) has the lowest global emissions and an affordable global cost. We finally selected this solution for the project, as it is the one that better fit to our initial goals.

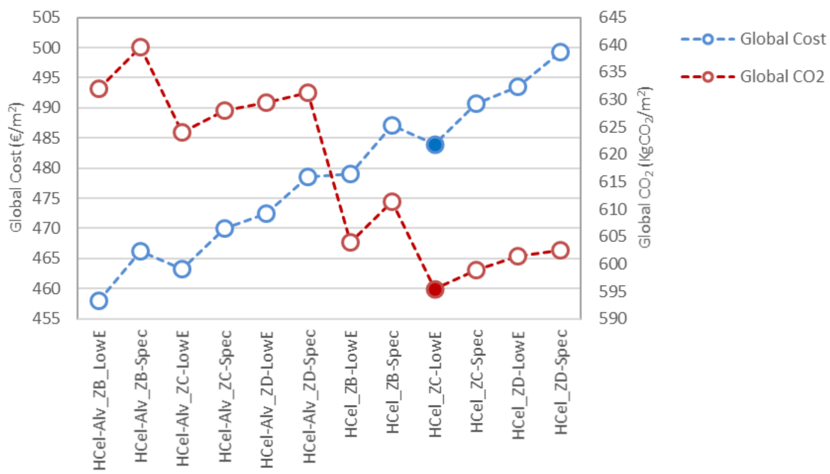


Figure 8. Comparison of the 12 evaluated solutions, considering Global Cost and Global CO_2.

5. Complementary analyses and comparisons

As a complement of the study, we developed some additional analyses and comparisons:

- The project was evaluated using the official tools to verify the compliance with the requirements of the Spanish Building Technical Code (CTE). We found that it readily complies with the limits of energy demands and consumptions. Furthermore, the project obtained the highest energy certification rating.
- Further analysis indicated that the project has high potential to meet the requirements of the **Passive House** standard. In that analysis we used the detailed **HVAC module** of DesignBuilder, modeling an air conditioning system with an air-to-air heat pump. According to the results, the heating and sensible cooling loads were of 10.6 and 11.7 kWh/m^2-year, respectively. These values are well below the limit of 15 kWh/m^2-year established by the standard (in both cases).
- Since the final project has a relatively low quantity of glazing, at least compared to other modern dwellings in the zone, we wonder if it has an appropriate daylighting performance. Thus, we developed several analyses with the **Daylighting module** of DesignBuilder. The overall results indicate that the project would get at least one credit

of **LEED v4** Option 2, with 76% of the area meeting the illuminance requirements (see *Figure 9*).

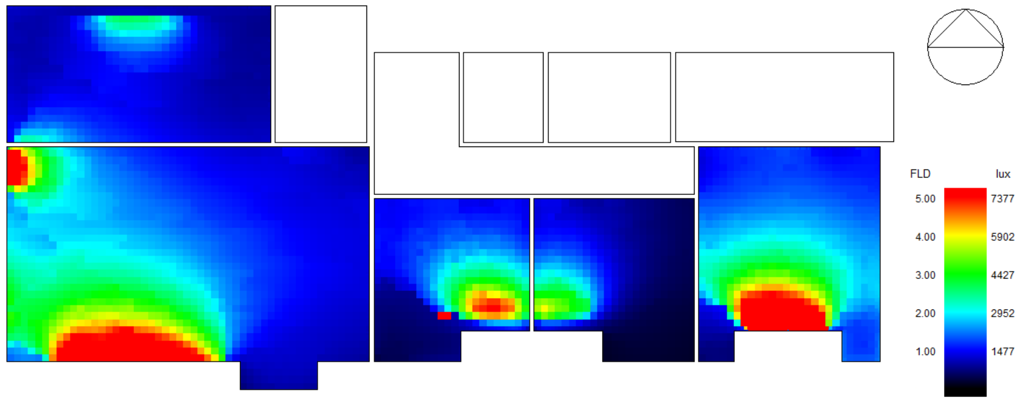


Figure 9. Complementary daylighting analysis of the project.

Another important question, to contextualize the results of this study, refers to the performance of our project compared to other possible solutions. Three additional models were developed and simulated to answer this question:

- **Previous project**: A model based on an architectural project developed before this study. That project considers the orientation correctly but has a larger glazing area and greater total floor area (for about the same useful floor area). This model includes traditional materials and construction systems.
- **IR-2P-1310x1020**: This model derives from the corresponding building form that was used in the optimization analysis but adjusted to have the same useful floor area as in our project. It represents a typical project that does not consider the correct orientation of the house, and that tends to locate in the central part of the plot. This model also includes traditional construction systems.
- **I-2P-1240x645**: The model also derives from the corresponding form used in the optimization analysis. It represents the "most" optimal solution, according to those results. In this case, the model includes the construction system that combines cellular concrete walls and alveolar concrete slabs.

The three models were simulated using the same criteria as in our project, and we also verified that they comply with the requirements of the Spanish Building Technical Code. The results, shown in *Figure 10*, are conclusive. Our project offers much better performance compared to the previous project and the typical one (IR-2P-1310x1020). For example, we have savings of more than € 32,000 compared to the previous project and more than € 17,000 compared to the traditional one (note that these are just basic costs). Also, we have a reduction of more than 60 tons of CO_2 compared to the previous project and more than 42 tons compared to the typical one. Finally, the performance of our project is very similar to that of the "most" optimal (I-2P-1240x645), especially regarding costs and emissions.

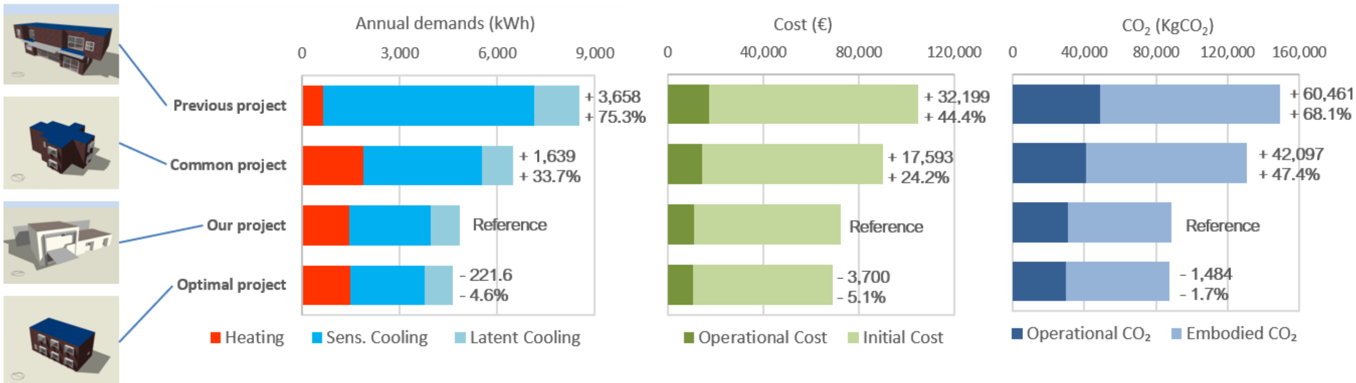


Figure 10. Our project compared to three other possible solutions.

6. Credits:

Study and project developed by **Sol-Arq**/EcoSostres, with the participation of the following persons:

Energy and environmental analysis: Arturo Ordoñez; Research on nontraditional materials and constructive systems: Salvatore Cito, Nuria Rovira; Architectural project: Arturo Ordóñez, Salvatore Cito, Nuria Rovira.