A realistic proposal to considerably improve the energy footprint and energy efficiency of a standard house of social interest in Chile

Felipe Monsalve ♭,1 and David Soler♮

(♭) Escuela Técnica Superior de Ingeniería de la Edificación,
Universitat Politècnica de València, Camí de Vera s/n 46022, Valencia, España.
(♮) Instituto Universitario de Matemática Multidisciplinar,
Universitat Politècnica de València, Camí de Vera s/n 46022, Valencia, España.

1 Introduction

More and more researchers use Linear Programming (LP) to solve optimization problems in the field of building management, and particularly in problems related to environmental impact, energy consumption and energy efficiency. To be brief, three very recent articles will be cited. Brütting et al. [1] use Mixed Integer Linear Programming to minimize the environmental impact comparing the reuse of construction waste for the production of structural elements with structural elements made with new materials. Salandin et al. [2] use Integer Linear Programming (ILP) to minimize the cost of the refurbishment of a façade to improve its energy efficiency. Finally, Soler et al. [3] also use ILP to obtain the adequate material for the different layers of the opaque part of a façade in order to minimize its embodied CO2 emissions.

Following the ideas of the two last cited articles, the authors [4] used an ILP approach to minimize the total energy footprint associated to the opaque part of the envelope (façade plus roof) of a Chile's social interest home in the zone named central Chile, the most populated area. This approach took into account all legal conditions, available materials and their prices in Chile, and budgetary limitations imposed by the government of Chile. Comparing with the data corresponding to a typical social house in this zone of Chile, in the obtained optimal solution the energy footprint decreased by 28% and the thermal resistance of the walls increased by 546% (very excellent results), but at the cost of increasing the budget for the opaque envelope by 65%, due to the much more efficient materials chosen. Although this optimal solution meets all constraints, particularly budget constraint, and a part of this budget is assumed by the Chilean government, this extra 65% cost of the opaque envelope must be assumed by the buyer, who is a very humble family whose income probably does not allow this extra cost, and even if it could, the family would prefer to live in a more "polluting" house but having better conditions of life. For these families, any extra Chilean peso is good for buying food, clothes, etc.

This work tackles the problem commented above: how to reduce the energy footprint and improve the energy efficiency of social houses for humble families without excessively affecting the economic

[1] felipe@monsalve.es

conditions of the family. To do this, the same ILP model created in [4] is used as follows:

1. The set of materials that can be used for the different layers for both the walls and the roof has been considerably increased. This implies that the number of possible solutions also increases, and then the probability of a lower cost.

2. By using Mathematica 12.1 [5], the ILP problem is executed iteratively, decreasing the upper bound of the budget, until the minimum budget necessary to meet the rest of the conditions is obtained. From all the solutions obtained, a balanced solution (budget vs energy conditions) is chosen.

The chosen solution improves the energy conditions of the initial optimal solution thanks to the new materials: the energy footprint decreases by 43% and the thermal resistance of the walls is the same (increases by 546%). But it only uses a 24% of extra cost for the opaque envelope (almost a third of the initial optimal solution), which approximately represents a 6% of the total value of the house.
Chile's housing deficit is 425,000 homes together with the 314,000 that need replacement. Therefore, given the potential saving of energy footprint and oil (Chile is 100% dependent on oil) due to the high growth of energy efficiency of the solution, a realistic proposal is for the Chilean government to assume this 6% of extra cost in the part that it subsidizes for social houses.

2 Optimal solution

As stated before, the problem of minimizing the total energy footprint associated to the opaque part of the envelope of a Chile's social interest home, has been modeled as an ILP problem. The general formulation of the ILP problem is the same that was given in [4]. Therefore, it will not be repeated here, and the reader is referred to that article to see the objective function, equations and other details. In the same way, due to the page limitations for this article, it is impossible to show here the tables with all the possible materials used for each layer of the walls and roof, with their different characteristics (price, thickness, thermal resistance, energy footprint, etc.). An exhaustive information of all these data can be found in [6].

It is relevant to mention that in this case, the façade will have up to 8 layers (exterior termination of walls, exterior wall cladding, wall structure, air chamber walls, thermal insulation walls, secondary wall structure (for internal cladding support), interior wall cladding and interior finishing of walls), while the roof will have up to 5 layers (exterior deck cladding, protective barrier against roof the moisture, cover air chamber, indoor thermal insulation and roof structure).

Taking into account all the conditions imposed on this type of construction for Central Chile zone by the Chilean legislation, and all the data on the possible materials to be used for each layer of the walls and roof, an ILP problem has been formulated according to the general formulation given in [4] and solved with Mathematica 12.1, obtaining an optimal solution with the following opaque part of walls and roof composition:

Perimeter walls:

- Exterior cladding: 6 mm thick fiber cement plate with felt.
- Main structure: wooden partition with 3"x2" slats.
- Insulation I: slightly ventilated air chamber 30 millimeters thick.

- Insulation II: glass wool R122.
- Secondary structure: wooden partition in 2”x2” slats.
- Inner lining: plasterboard cardboard (laminated plaster) 8 millimeters thick.

Roof:

- Cover: concrete tile.
- Moisture barrier: asphalt felt.
- Insulation I: lightly ventilated air chamber 80 millimeters thick.
- Insulation II: Glass wool R122.
- Structure: wooden trusses.

Note that the CPU time to obtain the optimal solution was only 0,015625 seconds, in a HP Pavilion 24-b215la with Intel Core i3-7100T processor 3.40 GHz, 4 cores, and 8.00 GB RAM.

The main data of the optimal solution have been compared (see Table 1) with those corresponding to a house from a social interest executed in Villa Alemana (Región de Valparaíso, Central Chile) by Quinta Servicios Ltda. which has a façade surface of 77,91m2 and a roofing surface of 60,83m2. This comparison is used because this type of house is the most representative among all the social interest houses built. Note that due to Chilean legislation [7], the cost is not given in Chilean pesos but in “Unidades de Fomento” (UF). A UF is a non-physical currency, which its Chilean Peso value is actualized every day by the Servicio de Impuestos Internos (tax office).

	Typical house	Optimal solution	Difference
Energy footprint [MJ]	71,703.24	25,409.19	-65%
Cost [UF]	48.19	71.78	+49%
Thermal resistance walls [W/(m^2K)]	0.39	2.52	+546%
Thermal resistance roof [W/(m^2K)]	1.25	2.38	+90%

Table 1: Comparison between a typical house and the optimal solution

Table 1 shows that the energy footprint decreases by 65% and the thermal resistance of the walls increases by 546%, which are very excellent results, but the cost increases by 49%, which in any case is a 25% less increase compared to the solution obtained in [4].

3 Obtaining solutions with lower cost

As commented in the Introduction, although the obtained optimal solution meets all constraints, and a part of the budget is assumed by the Chilean government, this extra 49% cost of the opaque envelope must be assumed by the buyer, who is a very humble family whose income probably does not allow this extra cost. Since the savings obtained by the optimal solution in both energy footprint and thermal insulation are spectacular, it could be considered sacrificing part of these energy improvements if this sacrifice implies a reduction of the total cost of the house envelope. Taking into account this last comment, in this section the same ILP problem used in Section 2 to obtain the optimal solution is solved iteratively, but putting as upper bound to the budget, one UF less (in integer units) each time, starting from the cost of the optimal solution (71.78

UF), until the ILP proposed is unfeasible. Therefore, the last feasible ILP problem will give the solution of minimum cost complying with all Chilean legal regulations for Central Chile.

Table 2 shows that when moving from the case with a minimum cost (55.59 UF) to those that allow up to 60 UF and 65 UF (which present identical solutions), it is possible to considerably reduce the energy footprint (to less than half) at the cost of losing thermal insulation, particularly in the walls. The same happens when moving from the minimum cost solution to the optimal solution. This is due to the materials used. Both in the optimal solution and in the budgets of up to 60 and 65 UF, glass wool is used as an insulating material. Although wool meets the requirements of the Chilean legislation, it has a worse performance as a thermal insulator than expanded polystyrene, which is much cheaper, and therefore, it has been used in the solution with minimum cost.

The solution proposed for the scenarios with cost upper bounded by 60 UF or 65 UF would be positioned as the most recommended, because although it is not the one that reduces the energy footprint of the house the most, it is the one that presents a better balance between the environmental impact, economic resources allocated and thermal comfort for its end users. Note also that its thermal resistances, both for the walls and the roof are practically the same than those given by the optimal solution.

	Typical house	Optimal solution	Minimum cost solution	Cost bounded to 60UF/65UF	Difference optimum vs typical house	Difference 60UF/65UF vs typical house
Energy footprint [MJ]	71,703.24	25,409.19	91,843.18	41,131.66	-65%	-43%
Cost [UF]	48.19	71.78	55.59	58.33	+49%	+24%
Thermal resistance walls [W/(m^2K)]	0.39	2.52	3.96	2.52	+546%	+546%
Thermal resistance roof [W/(m^2K)]	1.25	2.38	2.33	2.36	+90%	+89%

Table 2: Comparison between maximum cost scenarios

Both the optimal solution (71.78 UF) and the proposed as more realistic solution (58.33 UF) have the same walls structure and only differ in two layers of the roof. Next, the five layers corresponding to the roof of the realistic solution are given:

- Cover: 0.35 mm zinc ribbed plate.
- Moisture barrier: asphalt felt.
- Insulation I: lightly ventilated air chamber 100 millimeters thick.
- Insulation II: Glass wool R122.
- Structure: wooden trusses.

Note that the use of wooden structures has been common in all the scenarios considered. This is due to the fact that, although the production process from the time a tree is felled until the wooden ribbon is placed in the house entails an energy cost, while the tree is alive, through the process of photosynthesis it contributes to the reduction of the level of CO2 in the atmosphere, so that it compensates for the environmental impact of its production process. Alternatives to this structure cannot compensate CO2 emissions in this way. The difference between the impact on the environment between the optimal solution and the selected as more realistic solution lies in the material selected for the roof: the production process of metal roofs is much more harmful to the environment than the one of the of concrete tiles (although its production is much cheaper).

The proposed solution allows a reduction of the energy footprint of the house of 43% on the type housing analyzed that, considering the housing deficit of the country of 425,000 homes along with the 314,000 that need replacement, the potential impact could reach around $22,610x10^6$ MJ (twenty and two thousand six hundred and ten million mega joules).

This study shows that, without making profound changes in the materials or construction techniques present in Chile, the impact of construction activity in the republic can be greatly minimized, thus delivering concrete measures that allow the declarations of intent that the country has shown to materialize with the environmental commitments to which the country has committed.

Table 2 shows that the proposed solution increases by 24% the resources allocated to the envelope of the house. But if this increase is taken over the total cost of the house, adjusted to the total 550 UF available (the minimum cost allowed by the Chilean legislation for his type of houses, 520 UF subsidy and 30 UF paid by the buyer), this increase represent a 6% of additional cost, which when applying 25% of industrial profit and indirect expenses and, subsequently, the VAT tax, would be a total budget of 581.45 UF.

If the Chilean government assumed this difference by increasing the subsidy provided from 520 UF to 552 UF, it would not only be contributing to the materialization of this reduction in the energy incorporated into the houses, but it would be quintupling the thermal insulation in the façade walls and increasing by 89% that of the roof, which would substantially improve the comfort of the home and consequently the quality of life of its end users.

This improvement in insulation would not only affect the quality of life in the housing of families, but would also improve the economic situation, especially of vulnerable families, by reducing the needs of spending on heating during the winter and, to a lesser extent, on refrigeration during the summer.

4 Conclusions

The results presented in this paper show that with a reasonable increasing of the economic effort, the energy footprint of each new social interest house can be reduced an amount of 43%. Considering the country's housing deficit of 425,000 homes along with the 314,000 that need replacement, the potential impact could be around $22,610x10^6$ MJ. Moreover, with the proposal presented here, the increment of thermic isolation would mean a huge energy and money saving on Chile's homes for heating in winter, which is also subsidized by the government. Therefore, the application of the proposal presented here will allow not only to improve the quality of life of people, but also to guide Chilean housing policies towards the fulfillment of the environmental objectives acquired by the country, and also to improve the country's economy, this last considering that Chile is 100% dependent on oil. The final conclusion is therefore that the Chilean government should assume this 6% of extra cost in the part that it subsidizes for social houses.

Acknowledgments

This work was partially supported by the ”Ministerio de Ciencia, Innovación y Universidades, Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad, Proyectos I+D+I 2018”, Spain, under Grant RTI2018-096384-B-I00.

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