Energy footprint reduction of Chile's social interest homes: an integer linear programming approach

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1 Introduction

In the last few years the energy efficiency concept is becoming increasingly relevant, both on energy production and on public opinion, being year 2018 an inflection point at international level due to ecologist movements across different countries [1]. Although developed economies have had the biggest part of pressure, reappraising productive process becomes essential for developing countries, whose productive sectors may be affected if its energy efficiency is not improved [2]. Building sector is not independent of this tendency. In Europe, the building sector is responsible of about 40% of the total energy consumed and the 45% of the CO2 emissions [3].

According to the International Energy Agency (IEA), energy efficiency is the management and restriction of energy consumption growing [4]. The energy footprint (ot embodied energy) is the total amount of consumed energy above all stages of a product's life cycle, from its raw material extraction to recycle or process waste [5].

With respect to buildings, energy efficiency is strongly attached to their envelope, which separates and controls thermal energy transmission between outside and inside the building. The building's envelope thermal insulation capability from its environment is measured by the thermal transmittance U ($W \cdot m^{-2} \cdot K^{-1}$), defined by McMullan [6] for a n-layer wall by Eq. 1:

$$U = \frac{1}{\dfrac{1}{h_{int}} + \sum_{i=1}^{n} \dfrac{e_i}{\lambda_i} + \dfrac{1}{h_{ext}}} \tag{1}$$

In Eq. 1, for each layer i, λ_i represents its thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) and e_i its thickness (m), while $1/h_{int}$ and $1/h_{ext}$ ($m^2 \cdot K \cdot W^{-1}$) represent the standard internal and external thermal superficial resistance.

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IEA reports that during year 2019, heating represented half of energy consumption of homes [7]. Heating is the main component of buildings' energy footprint in its service life.

In Chile, in 2015, during COP21, the government took the commitment of reducing country's emissions at least a 30% by year 2030 [8]. According to the Comisión Nacional de Energía of Chile, residential sector represents a 22% of country's energy consumption, and 37% of this consumption is located in the central zone among Valparaíso and Metropolitana Regions [9]. Furthermore, building's energy consumed on operation phase represents from 75% to 80% of its energy footprint [10].

80% of Chile's homes belong to single-family home typology [11]. The Cámara Chilena de la Construcción has counted a 425.600 homes deficit in the country, and there are 313.943 existing homes in damage condition which need to be replaced [12]. Size, quality and population density from social houses to middle top class ones have minimum differences [2]. The State of Chile, through Housing and Urban Planning Ministry (MINVU) has developed a subsidiary policy for the missing homes [13].

Chile's residential buildings have a lack of isolating in their envelope. This fact together with the materials used on their construction process deeply increase their energy footprint. By using an Integer Linear Programming (ILP) procedure and considering the MINVU's budget, the aim of this work is to select the optimal combination of materials for the opaque part of the envelope of a house in order to achieve the maximum reduction of its energy footprint, while improving at the same time the home's energy efficiency.

2 ILP problem formulation

The problem of minimizing the total energy footprint associated to the opaque part of the envelope of a house can be formulated as an ILP problem. Considering that the façade walls and the roof have a given surface, it is necessary to know the data for each m^2 surface type. For a better understanding of the formulation, the variables and parameters used are presented:

1. Let S_M be the total opaque part of the façade walls and let S_C be the total opaque surface part of the roof.
2. Let n be the number of the different envelope's layers. Each layer $i \in \{1, \ldots, n\}$ can be made of m_i different materials available for this layer, and each material $j \in \{1, \ldots, m_i\}$ is available in r_{ij} different commercial thicknesses. We will suppose that the first l layers belong to the façade wall's layers (the first layer is the outside one and the l layer is inside one), the rest of the layers $(n - l)$ belong to the roof, in the same order.
3. For each $i \in \{1, \ldots, n\}$, $j \in \{1, \ldots, m_i\}$ and $k \in \{1, \ldots, r_{ij}\}$, the following parameters are considered:
    (a) Let $k_{i,j,k}$ be the mass in kg of $1m^2$ of layer i, made of material j and in thickness k.
    (b) Let $E_{i,j,k}$ be the energy footprint in MJ for each kg of material j on layer i with thickness k.

(c) Let $t_{i,j,k}$ be the thickness in m corresponding to value k of material j on layer i.

(d) Let $c_{i,j,k}$ be the cost in UF (Unidad de Fomento) of $1m^2$ of material j, with thickness k on layer i. The UF is a non-physical Chilean currency, which is used to adjust commercial, accounting and banking transaction up to inflation variation.

4. The envelope's thickness will be between a minimum value, T_{Mmin} (for the wall) and T_{Cmin} (for the roof), and a maximum value, T_{Mmax} (for the wall) and T_{Cmax} (for the roof).

5. Let U_{Mmax} be the maximum thermal transmittance in $W \cdot m^{-2} \cdot K^{-1}$ allowed for the façade wall and let U_{Cmax} be the maximum thermal transmittance allowed for the roof. Opaque parts, in both cases.

6. Let P_{max} be the maximum budget in UF allowed for the construction.

7. There may be incompatibilities among two consecutive layers.

8. The ILP $x_{i,j,k}$ variables are binary type. Value 1 means that layer i is made of material j with thickness type k, and 0 otherwise.

9. If λ_j is the thermal conductivity in $W \times m^{-2} \times K^{-1}$ of material j, from Eq. 1 can be deduced that:

$$\sum_{i=1}^{n}\sum_{j=1}^{m_i}\sum_{k=1}^{r_{ij}} \frac{t_{i,j,k}}{\lambda_j} \geq \frac{1}{U_{max}} - \frac{1}{h_{int}} - \frac{1}{h_{ext}} \tag{2}$$

The ILP formulation of the problem is given by Eqs. 3 to 11:

$$Minimize\ S_M \cdot \sum_{i=1}^{n}\sum_{j=1}^{m_i}\sum_{k=1}^{r_{ij}} E_{i,j,k} \cdot k_{i,j,k} \cdot x_{i,j,k} + S_C \cdot \sum_{i=l+1}^{n}\sum_{j=1}^{m_i}\sum_{k=1}^{r_{ij}} E_{i,j,k} \cdot k_{i,j,k} \cdot x_{i,j,k} \tag{3}$$

s.t:

$$\sum_{j=1}^{m_i}\sum_{k=1}^{r_{ji}} x_{i,j,k} = 1 \ \forall i \in \{1, ..., n\} \tag{4}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m_i}\sum_{k=1}^{r_{ij}} c_{i,j,k} \cdot x_{i,j,k} \leq P_{max} \tag{5}$$

$$T_{Mmin} \leq \sum_{i=1}^{l}\sum_{j=1}^{m_i}\sum_{k=1}^{r_{ij}} t_{i,j,k} \cdot x_{i,j,k} \leq T_{Mmax} \tag{6}$$

$$T_{Cmin} \leq \sum_{i=l+1}^{n}\sum_{j=1}^{m_i}\sum_{k=1}^{r_{ij}} t_{i,j,k} \cdot x_{i,j,k} \leq T_{Cmax} \tag{7}$$

$$\sum_{i=1}^{l}\sum_{j=1}^{m_i}\sum_{k=1}^{r_{ij}} \frac{t_{i,j,k}}{\lambda_j} \geq \frac{1}{U_{Mmax}} - \frac{1}{h_{int}} - \frac{1}{h_{ext}} \tag{8}$$

$$\sum_{i=l+1}^{n}\sum_{j=1}^{m_i}\sum_{k=1}^{r_{ij}}\frac{t_{i,j,k}}{\lambda_j} \geq \frac{1}{U_{Cmax}} - \frac{1}{h_{int}} - \frac{1}{h_{ext}} \tag{9}$$

$$x_{i,j,k} + x_{(i+1),j',k'} \leq 1 \ \forall (i,j,k-(i+1),j',k') - incompatible \tag{10}$$

$$x_{i,j,k} \ \in \{0,1\} \ \forall i \in \{1,...,n\}\,, j \in \{1,...,m_i\}\,, k \in \{1,...,r_{ji}\} \tag{11}$$

Where:

1. Eq. 3 represents the objective function, that is, the total energy footprint of the opaque part of the house's envelope.
2. Eq. 4 guarantees that each layer is made only of one material and thickness.
3. Eq. 5 ensures that the maximum budget is not exceeded.
4. Eq. 6 restricts façade wall's thickness.
5. Eq. 7 limits roof's thickness.
6. Eq. 8 ensures façade wall's maximum thermal transmittance allowed is not exceeded.
7. Eq. 9 ensures roof's maximum thermal transmittance allowed is not exceeded.
8. Eq. 10 forbids that material j' with thickness k' appears in layer next to i containing material j with thickness k. That is, at most one of those two materials will appear (see [14] for more details about incompatibility between materials).
9. Eq. 11 defines the problem variables as binaries.

Note that to fit as much as possible real problems, this ILP formulation could contain additional constraints involving other parameters.

3 Case study

We present in this work a case study consisting in a social interest home type, where two sections from the opaque part of the envelope are considered, one from the façade walls and one from the roof.

For these sections, different designs with up to 6 layers will be studied according to solutions and real constructive systems which give interesting proposals to each one of the considered scenarios. The function of each layer, depending on the construction solution, may be (from outside to inside): Layer 1, outside facing or structural element; Layer 2, isolating layer; Layer 3, structural element or isolating; Layer 4, isolating; Layer 5, secondary structural element or isolating; Layer 6, inside facing.

In this case study we consider a house from a social interest executed in Villa Alemana (Región de Valparaíso, Chile) by Quinta Servicios Ltda. which has an façade surface of $77,91m^2$ and a roofing surface of $60,83m^2$.

4 Results

This paper presents the optimal solution of the ILP problem, obtained using Wolfram Mathematica software. The materials considered were: clay bricks, galvanized steel profiles, steel stays, copper impregned pine wood, plaster panel, fibrocement plates, steel framework, expanded polystyrene, glass wool, roofing zinc plates, tiles, asphaltic felt, concrete, ceramic and painting. All chosen materials are presented on the Chilean market and on the MINVU's official list of prices and materials (Tabla Referencial de Precios Unitarios).

Using *Procasaclima 2018 version 1.1* software the following properties of the materials were obtained: thermal conductivity, density and primary energy input. And, from MINVU's list of prices were taken de prices of the materials, which include labour costs and tools needed.

The optimal solution obtained with *Mathematica* to the ILP problem provides a façade made of (from outside to inside) layers: fibrocement plates with asphaltic felt, copper impregned pine wood as main structure, an air layer, copper impregned pine wood as second structure and plaster panel as inter cover. For roofing layers, the optimal combination is made of, from outside to inside, are tiles, asphaltic felt, glass wool and galvanized steel for roofing structure (see Figure for details). The main results are given Table 1.

	Proposal	**Type House**	**Diference**
Energy Footprint $[MJ]$	41.320	57.079	-28%
Cost $[UF]$	$76,62$	$46,47$	$+65\%$
Walls thermic resistance $[W/(m^2 \cdot K)]$	$4,69$	$0,60$	$+682\%$
Roofing thermic resistance $[W/(m^2 \cdot K)]$	$3,98$	$3,96$	$+0,50\%$

Table 1: Results

5 Conclusions

The results show that if the economic effort is increased, the energy footprint of each new social interest house can be reduced an amount of 28%, considering Chile's lack of houses, this could mean saving an order of 6.700 millions of MJ.

The proposal of this work means an increase of 65% payment, but the total amount of this solution represents a 16% of the amount available for this part of the house. Its important to know that if MINVU allows a maximum budget of 1.400UF per house, MINVU gives up to 520UF pear each house [15]. The reason of not using 100% of maximum budget allowed is because most of the families who apply to these houses cannot pay the difference up to 1.400UF.

If the social interest houses were constructed using this paper proposal the increment of thermic isolation would mean a huge energy and money saving on Chile's homes for heating in winter and cooling in summer for people and minimize the impact on the environment.

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