Eco-efficiency Tool for Decreasing Environmental Load in the Life Cycle of Buildings – ÁBACO – Chile

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Abstract. Chile begins to incorporate sustainability principles in its State policies at the sector level, which has created a great opportunity for the building sector, by encouraging improvements in the environmental impact on the integrated management of economic and environmental aspects in the life cycle of buildings. This article shows a comparative analysis in economic, social and environmental parameters between the two most common construction solutions proposed by the Ministry of Housing and Urban Planning in Chile: (a) structural wall of radiata pine and (b) reinforced concrete wall. For this analysis, was used a computer tool named ÁBACO-CHILE, which allows the integration of economic, social and environmental criteria from any building projects budget. ÁBACO-CHILE tool was designed to incorporate, on each budget item, an economic cost, a social cost and environmental parameters of contained energy and carbon footprint, using the first Chilean-site specific environmental Database. The results of the analysis show that the economic, social cost and environmental aspects evaluated are much higher on environmental evaluation in the case of the reinforced concrete construction solution, surpassing almost 70 times the values of the structural wall of radiata pine. Considering these results, it is possible to conclude that ABACO-CHILE is a useful tool to identify environmental impacts in the early design stage of any buildings project and also that this analysis allows an advance incorporation of sustainability criteria in buildings projects in Chile.

1. Introduction

At European level, the construction sector is responsible for 36% of greenhouse gas (GHG) emissions, so the European Union (EU) has identified the sector as a key to achieving its emission reduction objectives [1]. In Chile, the public, residential and commercial (PRC, by its initials in Spanish) sector (buildings) contributes 33% of the total national GHG emissions and is responsible for 26% of the total energy consumed by the country (only in its operational stage [2]. Therefore, the need to incorporate sustainability criteria in the design, construction and operation of housing, to manage the economic, environmental and social aspects that occur during the life cycle of the building, have led to establishing a goal of GHG emissions reduction between 30% (with the country's own resources) and 45% (with international support) by 2030 compared to 2007 [3].

To meet these objectives, the construction industry proposes as an alternative the use of more sustainable materials taking into account background based on the life cycle assessment approach [4] [5] [6] and the sustainable management of buildings [7]. The life cycle approach aims to cover the stages from the extraction of raw materials to the demolition and waste management, including
transport to and where possible the revaluation of the generated waste to be re-incorporated as a resource [8] [9].

Currently construction projects are evaluated only based on economic cost. However, it has been proven that the evaluation of the environmental profile of building projects is possible through its budget [10].

Globally, there are various budget platforms for the economic evaluation of construction projects, but they do not incorporate the integrated global evaluation. Software like: Análisis Software Cipe Ingenieros (CYPE), Newwall – México, Quercusoft – Colombia - Chile, Opus Presupuesto Programable, Software S10 - Perú, Precio Centro - México, Base de Costes de la Construcción de Andalucía (BCCA) – España, Ondac/Notrasnoches y Cubica - Chile, Ingeniería PMA, Presto Software, among others, contain private cost bases developed by construction companies or associated to the sector. These databases are not necessarily representative, since the reported costs have implicit different factors that may depend on private criteria or interests [11].

There are also tools that report general unit costs for the construction of public agents (e.g. Table of Unit Costs per Square Meter of Construction, among others), but there is no cross-sectional public reference system. In this way, the system releases the private company to prepare its offers to public entities without any traceability and environmental criteria that allow strengthening the public bidding system and decision making in construction projects with a life cycle approach [12]. From the above, it has been reported that in Chile no traceable data on the energy contained and carbon footprint of construction materials have been reported. These parameters normally depend on site-specific aspects such as the energy matrix, the technology used in each production process and transport systems [13].

In this sense, this article aims to report a comparative analysis of the application of ÁBACO-CHILE tool on a constructive system of base case and its alternative, considering the same functionality. For this, economic, social and environmental cost parameters specific to the national reality are reported. These results are intended to be inputs oriented to the design, construction and evaluation of the life cycle of public and private construction projects in Chile.

2. ÁBACO-CHILE Methodology.

The ÁBACO-Chile Platform was conceived as a tool to predict economic, environmental and social costs from the design phase of a construction project. It consists of a calculation engine and includes three databases that are associated with the necessary items in a work budget and the three dimensions evaluated: the database of resources and activities costs, which is linked to the calculation of social cost and the environmental database of resources and activities. The latter contains the quantification of two impact categories: Contained Energy (MJ) and Carbon Footprint (CO₂eq). These databases are for public use and freely accessible, which interact with each other facilitating the way of budgeting construction projects, following a hierarchical structure through an alphanumeric logic coding.

The resource cost database consists of a coded list of items that are commonly used in any construction project. It includes materials (MT, by its initials in Spanish), machinery (MQ, by its initials in Spanish) and labor (MO, by its initials in Spanish) separately, which have an associated economic cost, social cost and environmental indicators (see figure 1). Associated with it, the activity database is born, which corresponds to a coded list of items of a construction budget, which includes a list of unit price analysis, the calculation of social cost and their respective environmental indicators.
In order that environmental aspects cover the entire value chain involved and thus give an account of the real associated environmental impact, it is that the Life Cycle Assessment methodology [5] was used with an approach from the cradle to the door, for declared environmental impact categories. Both categories make it possible to quantitatively compare the environmental load between materials, activities and budgets given that data are provided from the extraction of resources, processing and transport (see fig. 2). This information was obtained from life cycle databases (Ecoinvent 3.0) and adapted to the Chilean reality by adjusting the parameters of emission factors for the electricity generation of 2017 [14]. In this first stage of development, only material resources (MT) of the database were covered, since they are the ones that involve the main environmental load. At a later stage the quantification of the environmental load of machinery (MQ) and labor (MO) will be developed.
Figure 2. ÁBACO – CHILE environmental assessment diagram.

ÁBACO-CHILE platform allows users to generate construction projects using resources available in databases or create their own resources from the modification of an existing one. In this way you can build a budget reporting the economic and social costs involved, segregating it in an itemized, unit cost analysis, resource list, general expenses list and social laws list. Likewise, the platform automatically reports environmental indicators involved in the project, thus allowing for the availability of integrated information for making early decisions in project design and project execution, based on eco-efficiency concepts. The functionality of the platform is summarized in Figure 3.

Figure 3. Functionality of ÁBACO - CHILE platform

3. Study cases
Two representative solutions of the official list of constructive solutions of the Ministry of Housing and Urban Planning (MINVU, by its initials in Spanish) are analyzed, where the application of ÁBACO-CHILE tool is shown. The construction solution defined as the base case corresponds to a structured wall of 2x3” radiata pine, coated on its outer face with 11.1mm
SmartPanel and on its inner face with Polyplac ST, formed by the union of a plasterboard with lowered edge and an expanded polystyrene plate of 15kg/m³, as detailed in figure 4.

**Figure 4.** Constructive solution analyzed as a representative base case of the official list of constructive solutions of MINVU.

As an alternative to this solution, the analysis of a normal reinforced concrete wall 200 mm thick is proposed, with thermal insulation of expanded polystyrene of 15 kg/m³ with a thickness of 50 mm. It adheres to the wall with BEMEZCLA EIFS glue. BEMEZCLA EIFS modified cementitious mortar in 2 mm thickness reinforced with fiberglass mesh is applied as exterior coating, as detailed in Figure 5.

**Figure 5.** Alternative constructive solution representative of the official list of constructive solutions of MINVU.

From the database of activities of ÁBACO-CHILE, the elements are selected and incorporated into an itemized budget. Amounts are extracted from a housing complex located in the city of Temuco, Araucanía Region, corresponding to 17 energy-improved homes, whose useful area per unit is 48.85 m² (see table 1). This project was developed by Universidad del Bio-Bío, Concepción (Chile), through the Center for Research in Construction Technologies (CITEC UBB, by its initials in Spanish) and MINVU [15]. The detail of activities of study cases is shown in Table 1.
Table 1. Specifications of the constructive solution analyzed in the base case and proposed alternative case.

| ÁBACO CHILE Code | Breakdown of elements according to the list of activities of ÁBACO-CHILE. | Unit  | Quantity  |
|------------------|--------------------------------------------------------------------------|-------|-----------|
| Base case        |                                                                          |       |           |
| DHB0002          | Structure/partition wall 2"x3" sized pine/ diagonal braces 2"x3"          | m²    | 27,00     |
| DIG0001          | Placement/coating/plasterboard plate 10mm                                 | m²    | 83,70     |
| DHA0031          | Installation/OSB board 11,1mmx1,22x2,44m structural pine/on rafters       | m²    | 96,50     |
| DKB0005          | Supply/placement/expanded polystyrene 50mm                               | m²    | 83,70     |
| Alternative case |                                                                          |       |           |
| CBW0003          | Installation/rebar A63-42H bent bar per slab                              | kg    | 2,099,00  |
| CCB0009          | Placement/concrete_G015-40-08 N.C 90% normal mix/foundations             | m³    | 18,74     |
| DKB0005          | Supply/placement/expanded polystyrene 50mm over ceiling                  | m²    | 93,72     |
| DIA0021          | Installation/exterior stucco 1: 3/without waterproofing/ e = 2cm         | m²    | 93,72     |

Considering the specifications and quantities of both previous cases in the following point, economic and social costs (broken down budgets) and environmental load are analyzed comparatively.

4. Results and Discussion
This section presents the economic and social results, followed by the environmental analysis of both addressed study cases.

4.1. Economic and social evaluation
From the data entry of elements to ÁBACO-CHILE platform, two budget items are obtained. The first corresponds to the economic evaluation and the second to the social evaluation of the Base Case, as detailed in Table 2. It should be noted that this last evaluation considers social factors applied to labor, defined by the Ministry of Social and Family Development, in its Social Prices report [16].

Table 2. Itemized economic and social budget of the constructive solution base case.

| Item | Works Specifications | Unit | Quan. | Economic Cost | Social Cost |
|------|----------------------|------|-------|---------------|-------------|
|      |                      |      |       | Unit          | Total (M$)  | Unit          | Total (M$)  |
| 1    | Item 1               |      |       |               |             |               |             |
| 1.1  | Confection/partition wall structure 2”x3” sized pine/diagonal braces 2”x3” | m²   | 27,00 | $7.501        | $202,5      | $ 5.398       | $ 145,7     |
| 1.2  | Place/cover/plasterboard 10mm | m²   | 83,70 | $8.950        | $749,1      | $ 4.058       | $ 339,7     |
| 1.3  | Place/board OSB 11,1mmx1,22x2,44m | m²   | 96,50 | $4.550        | $439,1      | $ 3.653       | $ 352,5     |
The previous table shows that the item involving a higher economic cost is the placement of plasterboard with 42.4% of the total. This same element represents 30.1% of the social cost of the solution, while the placement of OSB boards represents 31.2% of the total. This difference is due to the intensity in the use of human resources involved for both activities.

Figure 6. Economic impact percentage of the constructive solution of the base case.

Table 3. Itemized socio-economic budget of the alternative construction solution

| Item   | Works Specifications                  | Unit | Quant. | Economic Cost | Social Cost |
|--------|--------------------------------------|------|--------|---------------|-------------|
|        |                                      |      |        | Unit Total   | Unit Total  |
|        |                                      |      |        | (MS)         | (MS)        |
| 2      | Item 2                               |      |        |              |             |
| 2.1    | Installation/rebar A63-42H bent bar  | kg   | 2.099,00 | 1.037        | 2.176,63    |
|        | for slabs                            |      |        |              |             |
| 2.2    | Place/concrete_G015                   | m³   | 18,74  | 68.245       | 1.278,91    |
|        | 40-08 N.C 90% _normal_mix/foundations|      |        |              |             |
| 2.3    | Supply/place/expanded polystyrene     | m²   | 93,72  | 6.086        | 570,38      |
|        | 50mm on ceiling                       |      |        |              |             |
| 2.4    | Confection/exterior stucco 1: 3/without waterproofing/e = 2cm | m² | 93,72 | 7.689 | 720,61 | 4.709 | 441,14 |
|        |                                      |      |        |              |             |
|        |                                      |      |        | Direct Cost Subtotal | 4.746,57 | - | 3.959,18 |
From Table 3, it is evidenced that about 46% of the total economic cost of the construction alternative is associated with the configuration of the necessary ironwork for slabs, also representing 45% of the total social cost due to the high intensity of associated labor.

**Figure 7.** Economic impact percentage of the alternative construction solution.

From the results of both tables, it is inferred that the constructive solution of the base case represents an economic and social cost of 2.7 and 3.5 times lower than the alternative based on concrete, respectively. The above is directly associated with the costs of processing and manufacturing materials that comprise both solutions, being higher in the alternative based on calcareous minerals. The same applies to the social cost which is associated with the intensity of the use of labor, where the construction alternative requires more time for workers to work.

### 4.2. Environmental evaluation.

In Table 4 below, results of environmental parameters are presented for the base case, broken down by resources, where it is observed that the OSB board and the piece of sized dry pine are resources that represent 95% and 4.9%, respectively, of the total energy contained (see Figure 8). In the same way for the carbon footprint, both resources represent 94.4% and 5.4% of the total construction solution, respectively. These results imply that mainly the energy demand is associated with a fossil energy supply system, making the magnitude of both environmental parameters, for the same constructive element, totally corresponding to each other. (e.g. OSB ~ 95%).
Table 4. Breakdown of resources, contained energy and carbon footprint of the base case construction solution

| ABACO CHILE Code | Description of ABACO CHILE resource | Unit | Quan. | Contained energy (MJ) | Carbon footprint (kg CO₂eq) |
|------------------|-------------------------------------|------|-------|-----------------------|---------------------------|
| MTCCT0346        | Box of 25kg normal nail 4"x8mm      | Un.  | 0,16  | 0,48                  | 0,05                      |
| MTCCT4123        | Box of 250 units of fine tip plasterboard screw 6x1 1/4" | Un.  | 2,51  | 0                     | 0                         |
| MTCCW0002        | Box of 1000 units of galvanized screw 11/4"x6mm/trumpet head and drill tip | Un.  | 0,49  | 0,1                  | 0,01                       |
| MTHHA0008        | 4 gallons of waterproof asphalt igol dense paint | Un.  | 0,07  | 0,3                  | 0,03                       |
| MTIIA0132        | Expanded polystyrene sheet /1000x50x50mm/ 15 kg x m3 | Un.  | 83,70 | 250,3                 | 19,3                       |
| MTMB00035        | 2"x3"x3.2m premium sized dry pine piece | Un.  | 45,09 | 31.099,7              | 3,003,3                   |
| MTMMR0632        | OSB board 11,1mmx1,22x2,44m structural pine | Un.  | 32,42 | 607.464,3             | 52.318,15                 |
| MTPPX0235        | Surf./smooth polyester foam roller 15cm | Un.  | 0,11  | 109,5                 | 8,3                       |
| MTRRY0003        | Plasterboard 10mmx1,20x2,40m lowered edge | Un.  | 29,06 | 821,2                 | 65,7                       |
| **Total**        |                                    |      | **639.745,90** | **55.414,83** |                           |

Figure 8. Percentage of incidence resources, energy contained and carbon footprint of the construction solution base case

On the other hand, results of analyzing the alternative construction system are presented in Table 5, where it is observed that the greater intensity in the use of energy and carbon footprint are consistent with each other and they are 99.98% associated to concrete. As in the base case, it implies that energy sources used in the production life cycle of this material were mainly fossil energy sources involved.
Table 5. Breakdown of resources, contained energy and carbon footprint of the constructive solution analyzed as an alternative

| ÁBACO CHILE Code | Description of ÁBACO CHILE resource | Unit | Quan. | Contained energy (MJ) | Carbon footprint (kg CO\textsubscript{2}eq) |
|------------------|-------------------------------------|------|-------|-----------------------|----------------------------------------|
| MTCCA0016        | Roll 50kg annealed black wire #18/5275m | un   | 4,20  | 25,15                 | 2,34                                   |
| MTCCB0001        | 6m steel bar A440-280H Ø10mm/3,70kg x unit | un   | 0,09  | 0,72                  | 0,05                                   |
| MTCCCL0019       | 6m strip rectangular profile matte aluminum 25x75mm/ruler | un   | 0,16  | 20,89                 | 2,34                                   |
| MTHHM0010        | Mortar 340 kg/cement/m3               | m\textsuperscript{3} | 1,87  | 275,10                | 25,13                                   |
| MTIIA0071        | Roll of 12m glass wool 1,20mx60mm without insulating coating | un   | 6,51  | 24,46                 | 2,16                                   |
| MTIIA0122        | Expanded polystyrene sheet /1000x50cmx100mm | m\textsuperscript{2} | 93,72 | 651,74                | 50,19                                   |
| MTWWW0205        | Mixing pan 28lt/40x20x35cm            | un   | 0,09  | 0,06                  | 0,004                                  |
| MTCCB0002        | Bent bar for reinforced concrete/steel A63-42H | kg | 2.099 | 4.524,72              | 324,42                                 |
| MTHHH0064        | Concrete G-015-40-08 N.C 90%         | m\textsuperscript{3} | 18,74 | 41.842.751,6          | 3.827.037,75                          |

| Total            | 41.848.274,4 | 3.827.444,4 |

Figure 9. Percentage of incidence resources, energy contained and carbon footprint of the alternative construction solution

From the analysis of results of both construction solutions it is clearly observed that the concrete-based alternative represents an energy intensity and carbon footprint about 65 to 70 times, respectively, the environmental load represented by the construction solution of the base case. Although these results were possible to be intuited, the order of magnitude of differences was unknown considering an equivalent calculation methodology. These results represent a relevant input if the construction projects want to include quantifiable sustainability criteria.

5. Conclusion
From the previous results it is demonstrated that ÁBACO-CHILE tool allows the quantification and integration of economic and environmental indicators, which can serve as input for decision-making at the design stage of construction projects in Chile.
In the developed analysis, it is found that the construction solution defined as the base case implies a lower economic cost, social cost and environmental load than the alternative case based on concrete. Economic results are more discreet while the environmental results have dramatically higher differences associated with the alternative based on calcareous materials.

It is concluded that a constructive solution based on renewable materials would jointly allow better environmental, economic and social performance compared to the alternative based on fossil materials. However, these results only account for the construction phase, so any evaluation of the performance of both solutions throughout their useful life will be a matter of study in the future, in order to expand the limits of the analysis and thus be able to incorporate best usability practices of constructions in Chile.

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