Diagnosis of the Generation of Solid Waste in the Construction of a Building Under the Approach of Industrial Ecology

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Abstract. The construction industry generates 30% of the total solid waste in Chile, causing a high impact on the environment, due to the multiple inefficiencies generated in different stages of the development cycle of the projects, involving design, quality and characteristics of the materials in the construction of the referred project. The study covers only solid waste generated in the construction of high buildings, focusing on the area known as Industrial Ecology (IE). The IE aims to achieve that industrial systems have a behavior similar to that of natural ecosystems, allowing the linear model of production systems to become a cyclical model, promoting the interactions between economy, environment and society, developing the efficiency of industrial processes. The two main tools of IE were used: The Material Flow Analysis (MFA) and the Life Cycle Analysis (LCA). MFA was used to obtained indicators from the main products or raw materials that are used and that are transformed into a waste in high buildings construction processes, such as: concrete, wood, iron, sheetrock, tiles and ceramics. The LCA served to identify, quantify and characterize the different potential environmental impacts in the area, such as: climate change, depletion of natural resources and occupation of soils, associated with each of the stages of existence of a product. After these two analyses, it was possible to identify the stage of the process in which the main losses of materials occur in the construction of a high building. In addition, it was possible to identify alternative scenarios of solid waste management among different companies that want to transform this waste into raw materials or by-products, saving production costs, reducing environmental impact and creating different types of industrial symbioses.

1. Introduction

Industrial Ecology, as an area of study, aims to achieve that industrial systems produce a behavior similar to that of natural ecosystems, thus allowing the linear model of productive systems to become a cyclical model, promoting interactions between economy, environment and society, developing the efficiency of industrial processes (Cervantes, 2009).

The construction project becomes a huge waste generator, and in turn, creates a problem for future generations (Kibert, 2007), causing a high impact on the environment (Nahmens, 2009).

The causes of waste generation in the construction industry can be presented, for the most part, in two stages of the project development cycle: design and construction. In the first one, there are errors
in the contract documents, complex designs and details, poor coordination and communication (Osmani, 2008). And, in the second, incomplete contract documents, employee and equipment malfunction, improper material usage, waste from the application processes, lack of waste management plans (Bossink & Brouwers, 1996), bad project processes and manipulation of the material (Poon, 2004).

In Chile in 2016, the construction industry generated 587.865 tons of waste, of which almost zero percentage was used, 98% of this waste was inert or non-hazardous and 2% was dangerous (MMA, 2018). The waste sector is composed of a large amount of mixed materials, which makes its separation complex, and leads to little or no interest in its reuse.

The incorrect management of construction waste caused a significant number of illegal landfills to be spread throughout the Chilean territory, responsible for the serious environmental impact caused over the years. In addition to the landscape impact, the deposit of this waste on land specially prepared for this purpose may result in contamination of the soil, or even the groundwater (Sepúlveda, 2012).

This research analyzes a construction project, specifically a building project, applying Material Flow Analysis (AFM), with the purpose of determining what and how many different raw materials or products are required, including how much waste is generated after the construction project. Subsequently, waste is identified and quantified, and then analyzed using the Life Cycle Analysis (LCA) to calculate its environmental impact, and identify different valuation strategies under the Industrial Ecology approach. These three methodological steps are intended to improve the efficiency indicators of the evaluated project.

With the diagnosis made, it is proposed to implement a work strategy to identify and reduce the accumulation of solid waste in the construction industry, and make visible the possible interactions between different companies or entrepreneurs who want to make use of the construction waste, reducing production costs and environmental impacts. With these strategies is expected to promote and progress towards industrial symbiosis strategies and encouraging an industrial ecology ecosystem.

2. Objectives
Diagnosis of the generation of solid waste in a construction project (tall building), applying Material Flow Analysis (MFA) on the production processes, and evaluating the environmental impact they generate, using the Life Cycle Analysis methodology established by the family of ISO 14040 standards, evaluating the types of waste recovery, for the creation of industrial symbiosis.

3. Methodology
The methodology used to prepare a diagnosis of the generation of solid waste from the construction of a tall building, currently under construction, considered as a case study, was created from the tools of Industrial Ecology, such as the Material Flow Analysis (MFA) for the identification of the types of waste that are generated the most, and the Life Cycle Analysis (LCA), to determine the type of environmental impacts that originate in the construction for case study.

To prepare the diagnosis, the construction company responsible for the execution of the project in question, provided the following documentation: Project Location Plans; Architecture and Structure; Cubage; Unit Price Analysis (APU); List of all the activities that will be carried out for the execution of the project.

3.1. Material Flow Analysis (MFA)
This tool is used in the form of an analysis of input and output of materials, in this way all raw materials and materials of the construction process, are inventoried in unit of weight, referenced in tons. For this, each of the indicators of MFA reference model shown in Figure 1 must be calculate.
The reference MFA model (Figure 1) has three stages, among which is the manufacturing and distribution stage which is where all the necessary materials are acquired. The second is the stage of use and stock of the products, and finally, the third is the final disposal as solid waste. This analysis structure was adapted from López (2017).

a) System inputs
- DEU (Domestic Extraction Used): Input flow that counts the material resources extracted from the natural environment of the same system.
- IMP (Imports): Commercial flow of entry that originates from other systems.
- DMI (Direct Material Input): Measurement of all direct inputs of materials to the economy. The product entry phase (DMI) is given by Equation 1:

\[ DMI = DEU + IMP \]  

(Equation 1)

b) System outputs
- DPO (Domestic Processed Output): It represents the total mass of the materials that were used in the economy before leaving for the natural environment. It is presented as waste.

3.2. Life Cycle Analysis using the SimaPro Software database
The SimaPro version 8.0.430 Faculty software was used to search through the database for the technical specifications of the products or materials chosen from the results of the MFA. These characteristics of the chosen materials are obtained through the technical specifications of the materials of the work, delivered in the project documentation.

The construction industry includes several sources of pollution that can be framed in the different environmental aspects and impacts of the economic sector, and that modify the abiotic component of the ecosystems, that is, soil, air and water, which is why the impact categories to analyze are the following:
- Climate change
- Occupation of agricultural land
- Urban land occupation
- Water depletion
- Metal depletion

The first stage for the use of the Software is to create a project within the database; in this case the project will go by the name of the limited title of this research, "Diagnosis of the generation of construction waste".

As a next step, and already being in the software within the project, a product will be created that will be part of the project. This product to be analyzed will be called “Case Study Building”, and will be created within the project process inventory. Once this is done, the database must be searched for materials that are wanted to be analyzed to integrate them as materials into that product.

When the materials have already been identified in the process inventory search window, in the SimaPro database, the product “Case study building” is opened and entered in the box that says known entries from the technosphere (materials / fuels). Each material will be part of the product.

Once the materials are entered into the product, the software calculation is then performed, obtaining the quantified result of how much environmental impact the product generates with each of the materials, for each of the selected impact categories.

4. Results and Analysis

4.1. Results of the Material Flow Analysis (MFA)
With all the indicators of the MFA obtained with the methodology previously presented, the MFA reference model is shown in Figure 2, having the complete vision of the inputs and outputs of the work analyzed. The unit of the indicators will be presented in tons.
Analysis of the result of the indicators:

- **IMP**: This indicator has a value of 24.825 (Tons), which indicates the total weight of the solid materials that are part of the entrance of the system, or the construction stage of the building, which includes the materials that are part of the useful life of the building and those that are only part of the construction stage of the building.

- **DEU**: This indicator has a value of 0. This indicates that all of the materials come from manufacturing companies that are part of the construction industry, and not from materials extracted from the natural environment of the case study building.

- **DMI**: The total value of the system entry indicator is 24.825 (Tons), the result of the sum of the IMP and DEU, which shows us the weight of a case study building.

- **Stock**: This indicates the total weight that comes from the materials that are part of the structure of the building is 23.728 (Tons) and that will be a waste at the time that the case study building has fulfilled its useful life.

- **DPO**: The total value of the system output indicator is 1.097 (Tons), obtained from the percentages of material loss, delivered by the technical office of the construction company in charge of the project execution.

The percentage of waste generated (total DPO) in the case study correspond to 4% of the total input materials to the system, DMI: 24.825 (Tons).

Identification of the main waste generated by the work:

For this purpose, the final objective of the Material Flow Analysis (MFA) is shown in Table 1, indicating the percentage of its quantity with respect to the total DPO, thus demonstrating the reason why it was chosen as a critical risk in the total generation of solid waste in the construction of the case study building.

### Table 1. Loss percentages with respect to the total DPO of the selected materials.

| Material                | DPO (Tons) | Percentages |
|-------------------------|------------|-------------|
| Concrete                | 644        | 58.71%      |
| Ceramic materials       | 7          | 0.64%       |
| Wood in different formats | 198      | 18.05%      |
| Irons and Steels        | 164        | 14.95%      |
| Plasterboard            | 31         | 2.83%       |
| **DPO**                 | **1.044**  | **95%**     |
| Others                  | 53         | 4.83%       |
| **DPO Total**           | **1.097**  | **100%**    |

The 5 materials shown in Table 1 were those selected for subsequent analysis of Life Cycle and Environmental Impact, due to the fact that they represent 95% of the total waste generated and some of the most requested material in the construction of the case study building, which equals 1.044 (tons).

Figure 3 shows the percentage of loss of the 5 most used materials and with the largest amount of waste by weight, generated in the construction of the case study building.
4.2. Results of the Life Cycle analysis using the SimaPro Software database

The materials that were integrated into the created product that is called “Case study building”. They were obtained from the database found in the SimaPro software, assimilating them to the materials shown in the technical specifications of the work.

For the results of the environmental impact calculation, five categories of impacts mentioned in the methodology shown above, were considered. For this, the input quantity of each material determined in the building’s cubication, calculated by the technical office of the construction company, was used, and is represented in units required by the SimaPro software, as specified in Table 2.

Table 2. Amount of the chosen materials obtained from the cubication of the case study building.

| Material Selected           | Unit    | Quantity       |
|----------------------------|---------|----------------|
| Concrete                   | m³      | 9.085.6        |
| Ceramic materials          | kg      | 107.425        |
| Wood in different formats  | m³      | 231.373        |
| Irons and Steels           | kg      | 1.278.37       |
| Plasterboard               | kg      | 230.426        |

Table 3 was exported from the SimaPro software in Excel format. It shows the amount of environmental impact generated by the product called “Building case study” that was created within the software database, from the selected materials.

Table 3. Analysis of the general environmental impact of the product "Case study building ".

| Impact analysis SimaPro 8.0.4.30 |
|----------------------------------|
| Project: Diagnosis of the generation of Construction Waste |
| Calculation: Impact Evaluation |
| Product: 1 p Building case study |
| Method: ReCiPe Midpoint (H) Thesis V1.11 / World Recipe H |

Figure 3. Analysis of the percentage of loss with respect to the quantity of each of the materials analyzed.
Indicator: Characterization

| Impact category          | Unit   | Case study building |
|--------------------------|--------|---------------------|
| Climate change           | kg CO₂ eq | 6.918.539,5          |
| Agricultural Land Occupation | m²    | 8.133.62,8           |
| Urban land occupation    | m²    | 71.317,6             |
| Water depletion          | m³    | 60.711,8             |
| Metal depletion          | kg Fe eq | 2.569.408            |

In summary from an environmental and economic point of view, it is considered that the construction of the case study building, with its great request for materials and its high generation of waste, is inefficient. The clear example of inefficiency is structural steel, which after having reached a 12-meter bar, is cut immediately because it does not have the necessary length. All the loss of energy in the creation of a single bar is not valued, nor is it made aware. And this happens because of the insularity that exists between the design of the project, the manufacturing, and the construction process of the building.

As a solution to these inefficiencies that occurred in the construction process of a building, it is recommended:

- Coordination between participants of the construction’s industry, such as the process of project design, process of sale and purchase of construction materials, the on-site construction process of a project, academy preparing professionals in the field and laws and State standards concerning the industry.
- Eco-design in construction, and equivalent expressions such as green design, sustainable design, design for environment or responsible design, refers to the methodology applied to the design of a product and its manufacturing process oriented towards the prevention or reduction of the environmental impact of those products and processes.

5. Valorization of construction waste

For a better representation of the types of recovery treatment for the waste of the chosen materials, Table 4 is presented, which shows the five materials chosen in this investigation, the waste generated in each of them and the types of valorization and uses that can be given to each one. This information will be provided in part by the Department of Waste Management and Environment (REMA) of the construction company responsible for the execution of the case study building, and also information and experiences of other international industrial symbiosis, collected through bibliographic review.

| Materials     | Solid waste       | Valorization Treatment | Applications                                           |
|---------------|-------------------|------------------------|-------------------------------------------------------|
| Concrete      | Concrete chopped  | Reuse                  | Landfills and stabilizations, urban furniture.         |
|               |                   | Recycling              | Embankments, Roads, Building and public works, Light   |
|               |                   |                        | concrete, Concrete blocks, Palms for cladding.         |
|               | Leftover mix      | Recycling              | Concrete blocks, Pallets for coating.                  |
|               |                   |                        | Creation of obstacles and stirrups.                   |
| Iron and Steel | Steel Bounce | Reuse |
|---------------|--------------|-------|
|               | Recycling    | New steel profiles, auto parts, appliances, machinery. |
| Metal struts rise | Recycling | New aluminum profiles, Aluminum structures. |
| Ceramic materials | Ceramic or porcelain tiles | Recycling | Embankments, Roads, blocks for coating, Fillers and stabilizations. |
|                 | Reuse       | Mosaics, cladding walls or floors of bathrooms and kitchens. |
| Plasterboard    | Plasterboard cardboard | Recycling | Plaster powder replaces up to 25% of natural plaster, sludge drying, pens, and moldable plaster paste. |
|                 | Reuse       | Fillings and Stabilization of slopes, false skies, interior partition walls. |
| Wood in different formats | Wood trim (tables, quarters, slats etc.) | Recycling | Manufacture of chipboard with chips. |
|                 | Reuse       | Structures of reused wood (Railings, stairs, benches, platforms, etc.) |
|                 | Energy recovery | Energy recovery, Combustion for other processes. |
| Wood in different formats | Ironing off (Phenolic, OSB and tertiary) | Recycling | Manufacture of chipboard with chips. |
|                 | Reuse       | Wooden structures (Railings, stairs, benches, platforms, etc.), interior and exterior wall cladding. |
|                 | Energy recovery | Energy recovery, Combustion for other processes. |

From the point of view of Industrial Ecology, which seeks a system and a circular economy, it can be said that the proposals and solutions shown in Table 4 are useful, in order to benefit from the following points:
- Tendency to a closed cycle industrial system.
- Savings in the extraction and use of natural resources.
- Eco efficiency.
- Inclusion of environmental costs in products or services.
- Networking between the participating entities and the environment.

The most efficient option is always to reuse the waste generated. In practical terms, the reuse of the waste mentioned in Table 4 are simpler to do since it implies less process and energy consumption. Recycling requires more complex processes to produce new items. Creativity and innovation is needed to find new uses for materials or objects. This not only prevents to producing more garbage, but also encourages responsible consumption in society.

6. Conclusions
For the development of this research was helpful to choose a case study building, currently in execution, for analysis and evaluation. By having available access to the information of the project, together with performing continuous field visits, it allowed to observe in greater depth the exact place where the inefficiencies of the construction process occur, and the residue originates in the work.
Regarding the results of the Material Flow Analysis (MFA), the following stand out:

- The most requested materials identified during construction process of a tall building are: concrete, steel, wood, plasterboard and ceramics.
- The most generated waste based on the percentage of losses in the productive processes of the construction of the building was determined, those that included concrete cutting, steel, wood, plasterboard (sheetrock) and ceramics.

In relation to the total waste generated in the construction of the case study building, 1.097 tons, an indicator of 65.7 (kg / m²) is obtained. This represents the weight of the solid waste generated in the construction phase of the building, with respect to each square meter constructed of a building as shown in Table 5.

**Table 5.** Indicators of solid waste generation with respect to the square meters of building permit for the case study building.

| Building Permit (m²) | Waste generated (Tons) | Indicator obtained (Tons / m²) | Indicator obtained (Kg / m²) |
|----------------------|------------------------|-------------------------------|----------------------------|
| Case study building  | 16.691                 | 0.0657                        | 65.7                       |

Regarding the results of the Life Cycle Analysis (LCA) with the use of the SimaPro Software, the following stand out:

- The identification of different environmental impact indicators, which are generated at the construction stage of a tall building. These can be used for different studies and subsequent research, such as for example: for each cubic meter of concrete 399.8 kg CO₂ eq is generated, both its transport from the concrete mixer, its placement and curing on site.
- The identification of the material with the highest rate of waste generation, that requires the most attention in order to achieve an efficient use in the construction stage of the building, in order to reduce its environmental impact.

In relation to the types of valuations and uses that can be given to the different residues of the chosen materials, encouraging industrial symbiosis, the following characteristics of positive impact on the quality of the work in progress are derived:

- Greater order and cleanliness in the work, which also reduces the accident rate.
- Saving of raw materials due to reuse.
- Better performance of environmental management.
- Business opportunity thanks to the sale of recyclable material.

With respect to the Industrial Ecology approach, it is a constant long-term search. The recycling market for construction waste is small, and for this reason, a majority of the construction companies have little interest in conducting waste segregation programs, since that implementation cost make them economically little attractive economically. On the other hand, many reglamentary restrictions limits your reuse or recycling.

Consequently, the state must boost this market, promoting industrial symbiosis between companies, supported by recycling plants and treatment of solid construction waste. This need must be generated by an entity or agency that allows the development of regulations that establish the minimum requirements for the use of by-product and recycled materials.

It is necessary that the state and private sector that are fundamentally involved in the construction industry assume the commitment to improve the quality in the production of the works, achieving a responsible position towards sustainable development by implementing waste management plans.
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References
[1] Alvarez, R. (2009). Aplicación de las técnicas de Análisis de Ciclo de Vida (ACV) al ambito de la impresión OFFSET. Madrid.
[2] Bossink, B., & Brouwers, H. (1996). Construction waste: Quantification and source Evaluation. Netherlands: Journal of Construction Engineering and Management.
[3] Cervantes, G. (2009). Ecología Industrial y desarrollo sustentable. Yucatan: Universidad Autónoma de Yucatan.
[4] Ghisellini, C. C. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems.
[5] Gil, D. (2016). Cómo influye el crecimiento económico en el medio ambiente. Valencia, España: Universidad de Valencia.
[6] Kibert, C. (2007). The next generation of sustainable construction. Building Research & Information, v 35.
[7] López, C. (2017). Efectos del modelo de economía circular del acero secundario, sobre el uso de recurso e impactos ambientales de la producción de acero en Chile. Santiago: Centro de investigación para la sustentabilidad, Universidad Nacional Andrés Bello.
[8] MMA. (2018). Cuarto reporte del estado del Medio Ambiente. Santiago: Ministerio de Medio Ambiente.
[9] Nahmens. (2009). From Lean to Green Construction A Natural Extension. Proceedings of the 2009 Construction Research Congress.
[10] Osmani, M. (2008). Architects' perspectives on construction waste reduction by design. United Kingdom: Department of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU.
[11] Poon, C. (2004). Reducing building waste at construction sites in Hong Kong. Construction Management and Economics, v 22 (5) pp 1147-1158.
[12] Rodríguez, G. (2006). The contribution of environmental management systems to the management of construction and demolition waste: The case of the Autonomous Community of Madrid. Madrid: Municipal Directive for the transport and disposal of earth and debris of the City Council of Madrid.
[13] Sepúlveda, C. (2012). Identificación de residuos inertes en Chile. Santiago: Centro nacional del Medio Ambiente (CENMA) para Ministerio del Medio Ambiente.
[14] UNEP. (2015). Global waste management outlook. ISWA.
[15] Xercavins, V. (1996). Que es el desarrollo sostenible? Barcelona: I Jornades: Construcción y Desenvolupament sostenible.