BUILDING STRUCTURE MODELS. IMPACT ON CUMULATIVE ENERGY DEMAND AND CARBON FOOTPRINT

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ABSTRACT
This paper assesses the impact of the arrangement of pillars and building height and its effect on the environmental impacts for the structural solution. Impacts are analyzed in the elements of the structure: foundations, pillars, and slabs. By embodied energy and carbon footprint, both, the manufacturing process of materials and the process of implementation of the proposed structure are measured. The results are obtained per executed square meter. The analysis provides the optimal arrangement for the pillars and the height of the building; the increase in separation of the pillars causes greater impacts, and the design of tall buildings also drives to an important increase of resource consumption.

Keywords: Reinforced concrete. Cumulative energy demand (CED). Carbon footprint. Building structure models.

1. INTRODUCTION
Today's society is fully aware of the need to limit the environmental impacts. The activities to be carried out in industrial processes are responsible for unavoidable environmental impacts. Building projects have a long implementation time and imply a series of necessary activities for their implementation. This work focuses on assessing the environmental impacts of different structural solutions through the use of reinforced concrete.

Building activities using reinforced concrete has its own characteristics. On the one hand it is necessary to know the amounts of the materials incorporated permanently in the structural solution. These materials mostly consist of reinforcing steel and structural concrete. In addition, to favor the construction process, a series of auxiliary materials for the forms are required on the construction site, which are also consumed. This work focuses on the valuation of both groups of materials and the corresponding impact generated.

The life cycle analyses present an important number of indicators. For this work we opted for two very representative indicators: embedded energy and carbon footprint. These two variables have been used in previous studies as indicators in scientific and technical literature. Both will be used to estimate both, the impacts generated in the manufacture of materials, and the construction of the project structure. To assess the execution of the structure, an average distance from the fixed manufacturing facilities to the location of the work has been estimated.

The impact of manufacturing and construction phases in structures dedicated to residential buildings are representative today, as the use phase represents zero impact. In the future, if the objectives of achieving virtually zero consumption buildings are reached, these two phases will record most of the impact generated by the buildings.

The number of columns or supports and the building height have been considered as representative geometric variables in defining building. For the structural solution of the floors a bidirectional slab of recoverable coffer with a constant structural depth of 30 centimeters has been implemented. The paper presents a range of solutions and assesses the impacts generated by each proposal. These impacts have been divided into two phases: production phase of the necessary materials in fixed industrial installations and transportation, and construction phase at the location of the work.

2. METHODOLOGY
The proposed methodology focuses on assessing the environmental impact incurred in the process of building a reinforced concrete structure. This paper assesses the entire structure, including the foundation. For horizontal reticular structure of recoverable coffer and 80 centimeters interaxis is used. All structural elements are made in reinforced concrete. Prefabricated elements are not used, and assembly operations are developed in the work area but with the support of a fixed industrial facility of steel. Thus, materials permanently incorporated into the structure are only two in this case: B-500S steel and HA-25/P/20/IIa concrete.

To execute these structures, once consolidated the pillars, a provisional structural framework of floorboard is used to hold the caissons (Figure 1). Once the structure is consolidated, these elements are retrieved and used in subsequent structures.

Figure 1 Provisional floorboard framework.

Obviously the environmental impact associated with the implementation of a structure will be lower when the material consumption is optimized (reducing the amounts of concrete and steel) as well as the use of formwork materials and labor.
This research is to model a building of square floor of dimensions 24x24 meters with different column layouts and number of floors (Figure 2). For the column layout three values of the grid have been selected: a situation of short span of 4x4 meters, another common situation in building of 6x6 meters, and an alternative with overhead span of 8x8 meters. The modeled cases include 4 slabs, 6 slabs, 8 slabs, and 10 slabs. The buildings all have a height on the ground floor of 4 meters and the other floors with heights of 3 meters, devoting the last floor to a flat roof.

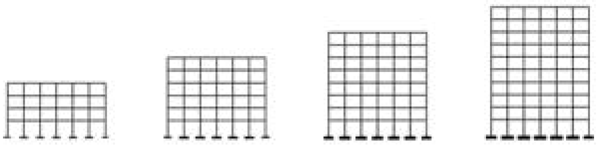

Figure 2 Section of buildings from 4 to 10 slabs 10.

The loads considered are selected from the usual building, based on the guidelines of the Technical Building Code (CTE) of Spain. In this way, facade loads are modeled as uniform loads, with a value of 7 kN/m in the perimeters of the slabs, and on the deck this value is reduced to 3kN/m. For surface loads on the various intermediate levels, 2kN/m2 have been estimated for permanent loads and also 2kN/m2 for use overload; in the flat desk these values have changed to 3 kN/m2 for permanent loads and 1kN/m2 for use overload. Wind loads have been implemented considering the Spanish legislation and snow loads are included in overload considered in use. For foundation dimensioning, an average performance of land bearing capacity has been considered, with a maximum permissible pressure of 0.2 N/mm2.

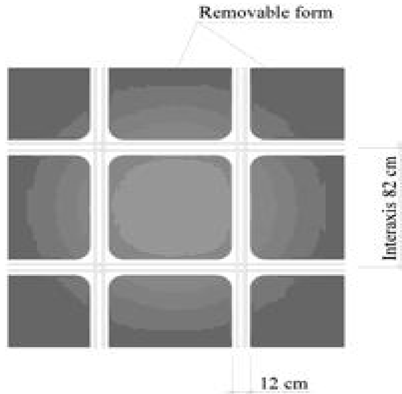

Figure 3 features of the selected slab

All the slabs have been solved using a structural depth of 30 centimeters (25 cm of caisson plus 5 cm of compression layer) and 80 centimeters of interaxis, 12 centimeters of nerve width, and constant coating (Figure 3). Thus the weight of the implemented slab is 4.03 kN/m2. This weight and dimensions are common in the structures of residential buildings and parking.
The structural analysis was carried out following the Spanish legislation and using a structural calculation software tool: CYPECAD. This structural analysis provides data relating to the consumption of materials, which in the selected typology represent the significant values to be used for the comparison. By using a construction database that is implemented in the own CYPECAD the impacts generated by each material used for the execution of each of the items are obtained. The phases covering this LCA range from cradle to grave. The reinforced concrete structure during the use phase does not require maintenance or energy inputs. The future regulation, which imposes almost zero consumption buildings, drives the focus to the impacts generated in the production phase. In the case of in situ concrete structures of this study we focus on the A1-A2-A3 and A4-A5 phases. The identification of the phases and scope of this study can be seen in Table 1.
The structure is divided into three sections: foundation, columns and slabs, following the construction process.
For the case of foundation four representative items are set: square meters of framework for foundation, cubic meters of cleaning concrete, cubic meters of structural concrete, and kg of reinforcing steel. Data of the considered steps are observed in Table 2. For cleaning concrete, a thickness of 10 centimeters and shrinkage in the execution of 5% have been considered. Columns consist of the materials used for formwork (considering 50 applications), structural concrete, and reinforcing steel. In the case of slabs, in addition to the materials permanently incorporated to the structure (steel and concrete) it is considered the materials used for the total framework and the recoverable caissons. In the case shown in the table, a repercussion of a caisson per square meter has been estimated, with fifty uses. For the proportional part of the materials used in the construction process the impact generated in its manufacture is also recorded.

Table 1 Considered phases of the LCA

	Product Stage			Construction process Stage		Use Stage							End of life Stage				Supplementary information beyond building life cycle
	Raw material supply	Transportation	Manufacturing	Transportation	Construction-installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy	Operational water	De-construction demolition	Transportation	Waste processing	Disposal	Reuse-Recovery-Recycling Potential
	A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
CYPE	X	X	X	X	X												

Table 2 Impacts of representative items.

			A1-A2-A3 Production of the materials used		A4 Transport Construction Zone A5 Placement and Execution.	
			Embodied energy (MJ)	Emissions CO_2 eq.(kg)	Embodied energy (MJ)	Emissions CO_2 eq.(kg)
m² framework for foundation	Materials	Weight (kg)				
	Steel	1,14	39,900	3,192	0,080	0,006
	Galvanized steel	0,05	1,950	0,140	0,017	0,001
	Auxiliary elements				0,081	0,012
	Transport to landfill				0,046	0,003
	Total:		**41,850**	**3,332**	**0,224**	**0,022**
m³ cleaning concrete in foundation	Materials	Weight (kg)				
	Concrete	2.300	2392,000	224,848	40,848	3,019
	Auxiliary elements				0,027	0,004
	Transport to landfill				0,106	0,008
	Total:		**251,160**	**23,609**	**42,114**	**3,133**
m² framework for m³ of columns	Materials	Weight (kg)				
	Steel	14,222	497,770	39,822	4,793	0,355
	Auxiliary elements				0,231	0,033
	Transport to landfill				1,643	0,122
	Total:		**497,770**	**39,822**	**6,670**	**0,510**
m² framefork for slab	Materials	Weight (kg)				
	Wood	0,599	1,797	0,052	0,027	0,002
	Plastic and steel	10,475	36,663	5,427	2,134	0,159
	Gasoil				10,488	0,776
	Auxiliary elements				0,108	0,016
	Transport to landfill				0,685	0,051
	Total:	**11,07**	**38,460**	**5,479**	**13,442**	**1,004**
m³ concrete	Materials	Weight (kg)				
	Concrete	2.530	2.631,200	247,333	44,931	3,325
	Total:	**2.530**	**2.631,200**	**247,333**	**44,931**	**3,325**
kg steel B500S for reinforc.	Materials	Weight (kg)				
	Steel	1,1	35,000	2,800	0,337	0,025
	Total:	**1,1**	**35,000**	**2,800**	**0,337**	**0,025**

These results combined with consumption impacts allow us to obtain the full impacts of the proposed solutions. Two different consumptions are made, the materials incorporated permanently to the structure and materials consumed in execution. Table 3 identifies the items that are consumed in each block with the units used.

Table 3 Items incorporated for each block of the structure

	Items	Units
Fundation	Cleaning Concrete foundation HL-15/P/20	m^3
	Reinforcing steel B 500 S	kg
	Concrete HA-25/P/20/IIa	m^3
	Framework for fundation	m^2
Columns	Framework for columns	m^2
	Reinforcing steel B 500 S	kg
	Concrete HA-25/P/20/IIa	m^3
Slabs	Framework for slabs	m^2
	Reinforcing steel B 500 S	kg
	Concrete HA-25/P/20/IIa	m^3
	caissons	Ud

3. OBJECTIVE

The focus is to have a vision of the environmental cost of the entire structure using two indicators: the embodied energy and the generated carbon footprint. The inclusion of two variables that change will allow to compare different alternatives and select the one that is most feasible from an environmental standpoint.

The inclusion of variations in the geometry of the building (arrangement of the columns and building height) allows us to observe the impacts generated in the different proposals. To facilitate monitoring the impact generated, the structure has been divided into three blocks with different treatment. The foundation with four corresponding headings: cleaning concrete, steel foundation, structural concrete, and formwork. The columns with: formwork, structural concrete, and reinforcing steel. And finally slabs, in which the definition of the form and the materials must be incremented with the placement and rental of the caissons.

4. CASESTUDY

Performing calculations by regulations currently in use in Spain the technically viable alternatives are determined. Steel, concrete and auxiliary elements (formwork and caissons) at different values for each block of the structure are found for the viable alternatives. The model analysis allows to control the deformations and adjust the arrangement of the reinforcements, all rigorously complying with current regulations.

Once data consumption are known and the impacts of each item are established, we can determine the environmental cost of each alternative. Obtaining the impact through two indicators (CED and CO2 equivalent) and in two distinct phases (production of necessary materials, and transport / placement / execution on site) requires us to present the results in four figures. Figures 4 and 5 show the corresponding phase production of materials (A1-A2-A3) displaying the corresponding impact to each of the blocks studied (foundation, columns and slabs).

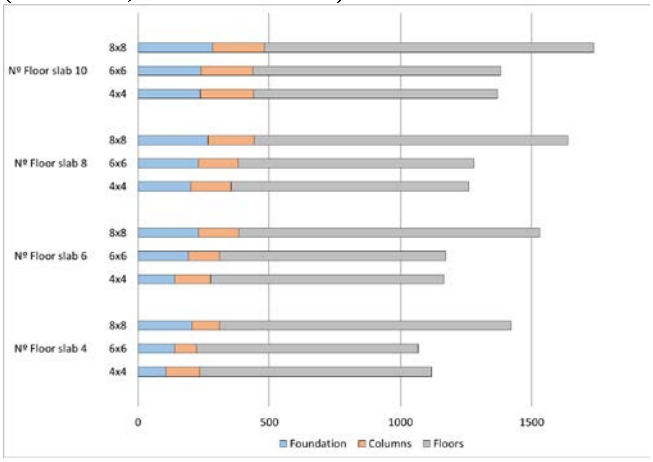

Figure 4 Embodied energy for the manufacture of materials (MJ/m2).

In order to compare the results, the ratio for each square meter of structure has been obtained. Values corresponding to the CED range from 1066.75 to 1735.97 MJ / m2 which is a variation of 62.73%. If we look at each of the blocks, biggest oscillation occurs in the foundation, with 165.01%, and the lowest in the slabs, with a total of 48.69% variation. The most attractive option is found in a building of four floors and with the grid of 6x6 meters. In this case the foundation represents 13.04%, columns 7.81%, and slabs the 79.15%, presenting the absolute minimum in the last two blocks.

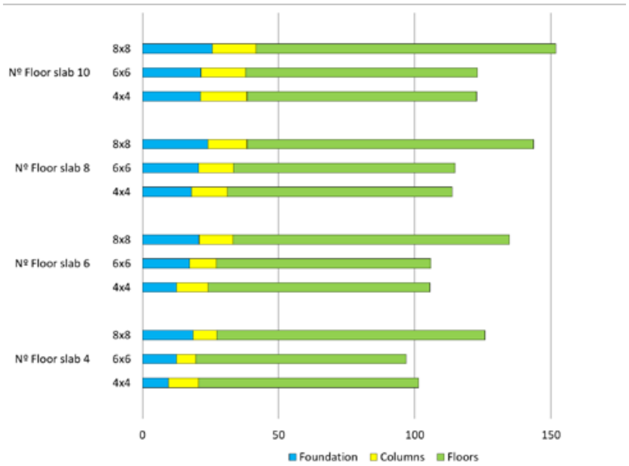

Figure 5 CO2 emissions for the manufacture of materials (kg CO2 Eq/m2).

For the ratio of equivalent CO2 emissions, results vary from 96.76 to 151.70 kg CO2 Eq/m2 which is a variation of 56.78%. The variation in emissions is lower than in embodied energy. If we look at each of the blocks, the biggest is again in foundations with 166.74%, and the lowest in slabs, with a total variation of 42.61%. The most attractive option is located again by a solution of four floors and with the grid of 6x6 meters. In this case the foundation represents 12.96% columns 7.31%, and slabs 79.73%.

Figures 6 and 7 show the corresponding phase transport of materials definitively incorporated into the structure (steel, concrete) as well as the necessary for the mounting (formwork) and execution in work (A4 -A5) displaying the corresponding impact to each of the blocks studied (foundation, columns and slabs). The transports are counted from the fixed industrial installations to the place of execution. This result records labor consumption and materials required for formwork and concrete placement. Its environmental impact is much lower than that recorded in the production phase.

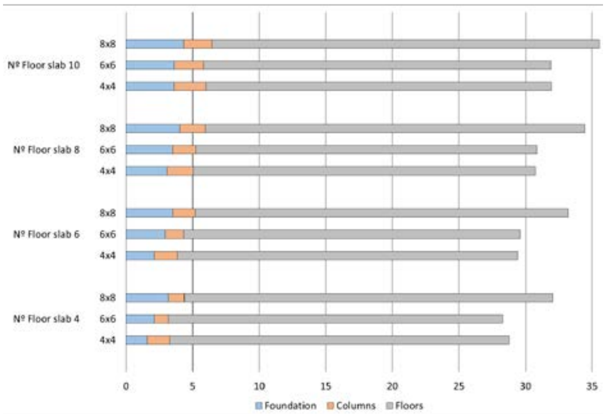

Figure 6 Embodied energy to transport of elements and execution on site (MJ/m2).

Now we assess the results of the energy embodied in the implementation process for each square meter of structure. Corresponding ratio values range from 28.29 to 35.54 MJ / m2, which is a variation of 25.63%. If we look at each of the blocks, the biggest oscillation occurs in the foundation, with 171.70%, and the lowest in the slabs, with a total variation of 15.76%. The most interesting option is achieved by solving a building of four floors and with the grid of 6x6 meters. Analyzing the impact of blocks for this case, the foundation represents 7.53%, columns 3.68%, and slabs the 88.79%, presenting the absolute minimum in columns and slab.

If we value the transportation and execution of the structure in the work based on equivalent CO2 emissions, results vary from 2.10 to 2.64 kg CO2 Eq / m2, which is a variation of 25.71%. In this case the variation in the output is slightly higher than that produced in the indicator of embodied energy. If we look at each of the blocks, the biggest variation occurs in the foundations, with 166.67%, and the lowest in the slabs, with a total variation of 15.51%. The most attractive option again is found by using four floors and 6x6 meters grid. In this case the foundation represents 7.58%, columns 3.79%, and slabs 89.63%.

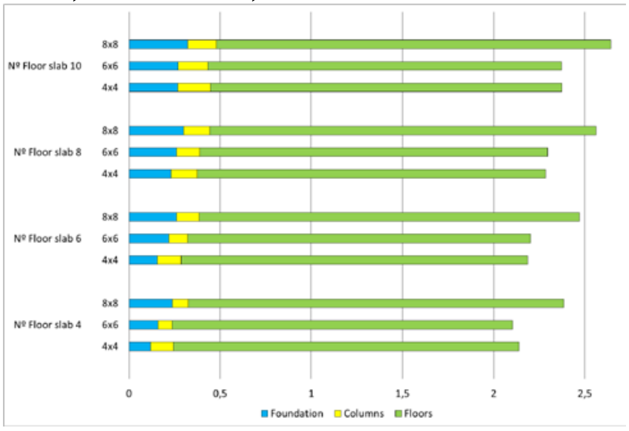

Figure 7 CO2 emissions for the transport of elements and execution on site (kg CO2 Eq/m2).

5. CONCLUSIONS

As a preliminary conclusion, it is important to note that variations make the results present significant oscillations. These oscillations are most important in the production phase of materials.

The production phase (A1-A2-A3) has a much higher impact than transport and execution stages (A4-A5). For the optimal case this value is 37 times higher. This is because the production of materials includes those definitively incorporated and also the ones consumed during the construction process.

The blocks in which the structures (foundations, columns, and slabs) were fractionated have different weights. The block most representative is slabs, hovering around 80% compared to 7% of the columns and 13% of the foundation. The starting volume is higher and therefore also impacts are. The greatest variations occur in column and foundations blocks. These items suffer the greatest variations in the ratio per square meter. The columns represent for example in 4x4 grid 49 units per slab, compared to 16 used in the 8x8 grid. In this aspect also the foundation is conditioned due to the number of elements. In both cases the change of heights affects the amounts of the materials used.

With the contemplated structural thickness, the option of 8 meters for slabs represents an increased generated impact around 20% compared to options of 6 meters. This situation is generated in part by the high stresses to which the slabs are subjected and consequently the necessary amounts of reinforcing steel increase.

The increased height in buildings drives to an increase of impact per square meter of the implemented structural solution, while the slab block has small variation compared with variations in the foundation and column blocks. In the latter, impact double the value because of the effect of height.

Since slab is the most representative block, optimal solutions are found for a grid of 6x6 by using low-rise buildings (four floors).

On the horizon, regulations promoted by institutions to achieve almost zero consumption buildings are presented. This situation will make tools like the one proposed here in combination with the use of Building Information Modeling (BIM) allow assess constructive alternatives and locate those representing the lowest environmental impact.

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