Proceedings of the 8th World Congress on Civil, Structural, and Environmental Engineering (CSEE'23)
Lisbon, Portugal – March 29 – 31, 2023
Paper No. ICSECT 125
DOI: 10.11159/icsect23.125

Optimization of a Waffle Slab for a Reinforced Concrete Structure. Economic and Environmental Comparison

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Abstract – The aim of this research is to optimise a waffle slab for a reinforced concrete structure of a multifamily residential building. For this modelling, CYPE structural software has been used, as well as its respective economic and environmental database for the subsequent analysis. The optimisation of the floor slab has been achieved through various study alternatives, with the modification of its most characteristic parameters such as the type of concrete used, geometric distances of the various elements that make up the floor slab, as well as the material used for the coffer. All of this gives rise to a series of floor slab alternatives that allow a subsequent economic analysis to be carried out. This shows variations of up to 10% in the cost depending on the features of the floor slab. After this analysis, an environmental comparison of the alternatives is carried out by means of a life cycle analysis (LCA) of the floor slab, for which the results are significant with variations of 37% in kg of CO_2 - equivalents emissions from one alternative to another. Through this research, it is possible to establish which parameters are the most important and have the greatest relevance when designing a floor slab. All of this, taking into account their economic and environmental impacts.

***Keywords*:** Waffle slab, Reinforced concrete, Structural Alternatives, Economic Analysis, Environmental Analysis.

1. Introduction

The global situation marked by the health crisis, fuel and raw material price inflation, is creating a very unfavourable scenario. The construction sector uses more than 40% of the annual energy demand and as a result of this activity approximately 33% of the annual carbon dioxide emissions are generated [1]. It is therefore of increasing interest to design structures in an optimal and efficient way. This leads to an effective use of the material resources incorporated in the building, without ever losing the integrity and safety of the structure, integrating the concept of sustainable construction into new buildings.

Among the structural elements that make up a structure, the floor slab is one of the most significant. It provides the floor for the users of the building, transfers the loads to the beams and columns [1] and these in turn to the foundation. However, this structural element consumes huge amounts of energy and material resources compared to other elements that make up the whole structure such as foundations, columns, beams, etc. As consequence, when designing a structure, importance must be given to the optimisation of the floor slab through its characteristics variables such as: material of the vaults, height of the floor slab, type of joists etc [2]. In this way, it can have a direct impact on the economic level. Key factor for decision making [3] when a project is in the design phase.

For all these reasons, there are several investigations [4] that try to optimise the design of floor slabs, not only with the objective of an efficient improvement of the economic item but also in the environmental framework. As a result of this, the current trend considers it necessary to evaluate the whole structure [3], [5] as in civil engineering projects such as hydroelectric plant [6], railway [7] or sewage treatment plants [8], [9]. This is done through the Life Cycle Assessment (LCA) methodology [10], [11] in which the various environmental impacts produced can be assessed and, in this way, a more global perception of the impacts of the structure can be obtained.

The objective of this research will therefore be the optimisation of the waffle slab for a civil building such as a block of flats, generating a series of alternatives and subsequently an interpretation of the results at an economic level to put into context which are the variables that most influence this item. And finally, an LCA, where the product and construction process stages are evaluated, since these are where the greatest impacts are produced.

2. Methodology and case of study

The concrete structure corresponds to a multifamily residential building located in Logroño, in the north of Spain. The geometry of the building is simple in order to eliminate long simulation periods in the CYPE software. Therefore, stair and lift shafts were omitted. The building is composed of four floors, which have a rectangular base of 22x17.5m, reaching a floor area of 385m^2. The floor slab under study corresponds to floor 2 and it is here that the alternatives are modelled. However, for the floor slabs of floors 1 and 3, the parameters of the waffle slab are invariable.

Given the location of the building in Spain, the current regulations [12] on concrete structures were used, which define the actions to which the structure will be subjected, as well as the various parameters and technical characteristics of the rest of the structural elements.

2.1. Foundation

The material used for the foundations is HA-25 reinforced concrete with B500S steel reinforcement. The proposed configuration consists of 20 footings, with the perimeter footings being of the off-centre type and those located inside of the isolated type. The connection between these footings will be by means of 13 tie beams and 18 centring beams in order to avoid the eccentricity of certain footings.

2.2. Pillars

The geometry of the pillars has a square cross section of 30x30cm with a total of 20 pillars in plan, spaced 5.5 and 5m apart depending on their distribution. All the pillars start at the foundation and reach the roof slab.

2.3. Floor slab 1 and 3

Since these floors are not going to be modified in the various simulations of the alternatives, fixed parameters (Table 1) of a waffle slab are chose.

Table 1: Technical characteristics waffle slab floors 1 and 3

Element	Description
Thickness of floor slab	25+5cm (Lightening + compression)
Type of floor slab	Lost Coffer
Nº of parts making up the coffer	4
Material of coffer	Concrete
Distance Interaxis	60cm
Thickness of rib	12cm
Reinforced (cloth floor slab)	Lower: X/Y 1xØ12 Superior: X/Y 1xØ12
Reinforced (abacuses)	Lower: X/Y 1xØ12

Where the waffle slab meets the columns, a solid slab called an abacus is used to transmit the loads from the slab to the columns. In these areas, the problem of structural punching is very common. In order to avoid this problem, a series of base reinforcement and additional reinforcement are designed for all the connections between the columns of the structure and the floor slab, as shown in Table 2.

Table 2: Reinforced characteristics of abacuses

Element	Configuration
Reinforced base	Superior: X/Y 2 x Ø10 Lower: X/Y 2 x Ø8
Additional Reinforced	Longitudinal: 2 x Ø12
Type of beam	Transversal: 12Øc 15

2.3. Floor slab 2

The floor slab on floor 2 is the floor slab under study in this research, and it is here that the different parameters that define it will vary. It should be noted that it is still a waffle slab. Firstly, among the various variables, an initial classification classification is made, such as the material. In this case, if we are talking about concrete, three variables of characteristic resistance (N/mm^2) at 28 days are chosen, HA-25, HA-35, HA-45. Another parameter is the material of the coffer, i.e., the the lightening element. It will be modified with the configuration of concrete, expanded polystyrene and ceramic materials. The other variables that have been altered correspond to the geometrical parameters. These parameters have been the spacing between the ribs, i.e., the distance between the axes. It has been varied in configurations of 60cm, 70cm and 80cm. The width of the rib which takes values of 12cm, 15cm, 18cm and finally the height of the cassette varying vales of 20cm, 25cm and 30cm. Figure 1 shows the combination of the alternatives.

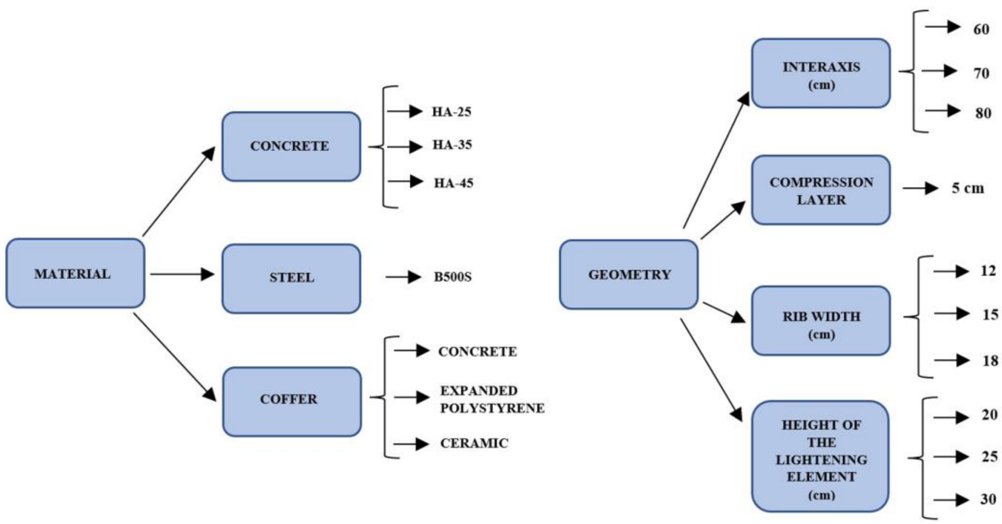

Fig. 1: Diagram of the alternatives analysed

Having defined the structural model and the configuration of the various alternatives, the comparative methodology used is explained below. The first of these is an economic comparison. The budgets generated for each of the alternatives will be divided into two subtotals, material and labour, in order to better visualise the results and see how the variation of the parameters influences these two items. It should be noted that the prices of the work units are used from CYPE´s internal database.

The next comparison will be to define the environmental impact of each alternative. For this purpose, the LCA methodology is used, In the definition of the LCA stages, only the product manufacturing stage and the on-site construction process will be considered in the analysis, as these are the most relevant stages in the generation of impacts. Table 3 shows the various internally defined processes within each stage assessed.

Table 3: Definition of the processes of each stage

LCA Stage	Process/Activity
Product stage	Extraction of raw materials (A1) Transport to factory (A2) Manufacturing (A3)
Construction process stage	Product transport (A4) Product installation and construction process (A5)

3. Results and Discussion

The first results shown are for the economic item. Figure 2 shows the unit price per square metre of floor slab as a function of the characteristic's strength of the selected concrete, plus the amount of steel (kg/m^2) required for the floor slab.

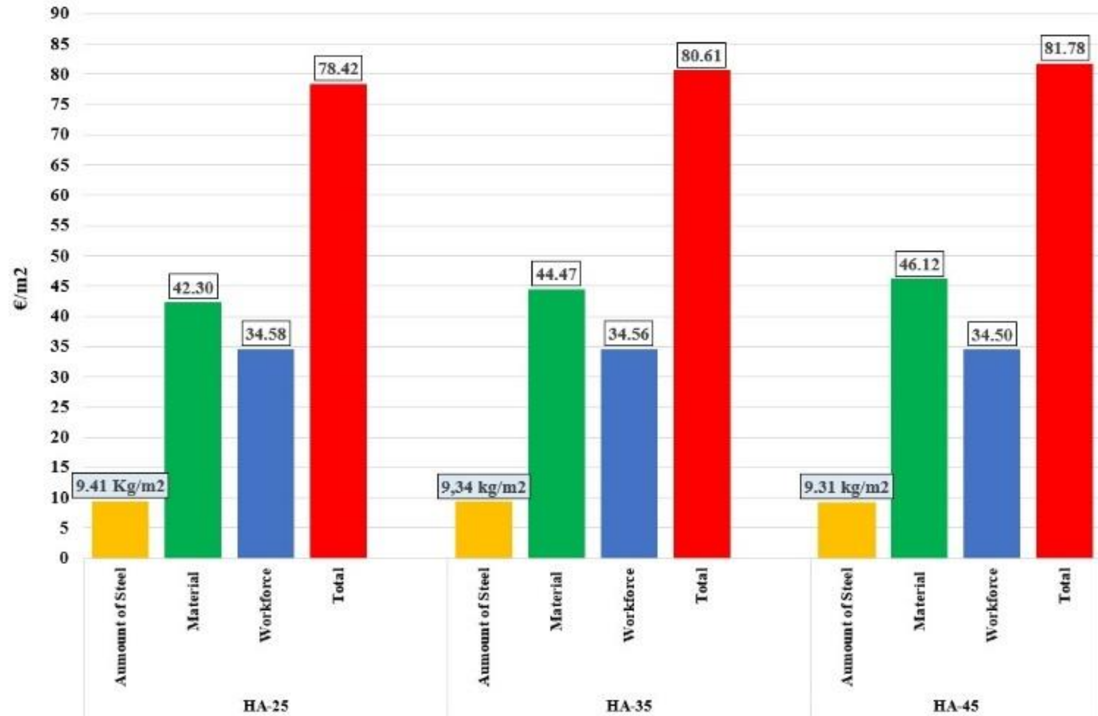

Fig. 2: Comparative €/m2 floor slab – Type of Concrete

As can be seen, the waffle slabs in which the material used is HA-25 are economically cheaper than those built with HA-35 and HA-45, since there is an increase in the price per square metre of 2.79% and 5.23% respectively. This means that the higher the characteristics strength of the concrete, the higher the price. This increase in performance is not cost-effective for this structural element. On the other hand, the variable amount of steel has an inverse relationship to the strength of concrete, since increasing the strength slightly decreases the amount of steel (1.07%) of the reinforcement required. This decrease does not compensate for the increase in the cost of concrete.

The following result is shown in Figure 3, which shows the comparison, as before, of the unit price per square metre of floor slab. However, in this case, the variables to be analysed are based on the material of the coffer that makes up the floor slab. It can be seen that the price of floors slabs using expanded polystyrene coffers is higher than floors slabs with concrete and ceramic material coffer, with an average increase of 3.2% in the price per square metre of floor slab. However, although expanded polystyrene is more expensive, it has the advantage of easy implementation on site. Consequently, as the graph above shows, the labour cost items are lower for the alternatives using this type of concrete and ceramic coffer than for the concrete and ceramic coffer alternatives. Specifically, there is a 12% saving in labour costs. This can be an advantage since a reduction not only in labour costs but also in the time taken to execute the structure and therefore the project can be more important than the economic aspect.

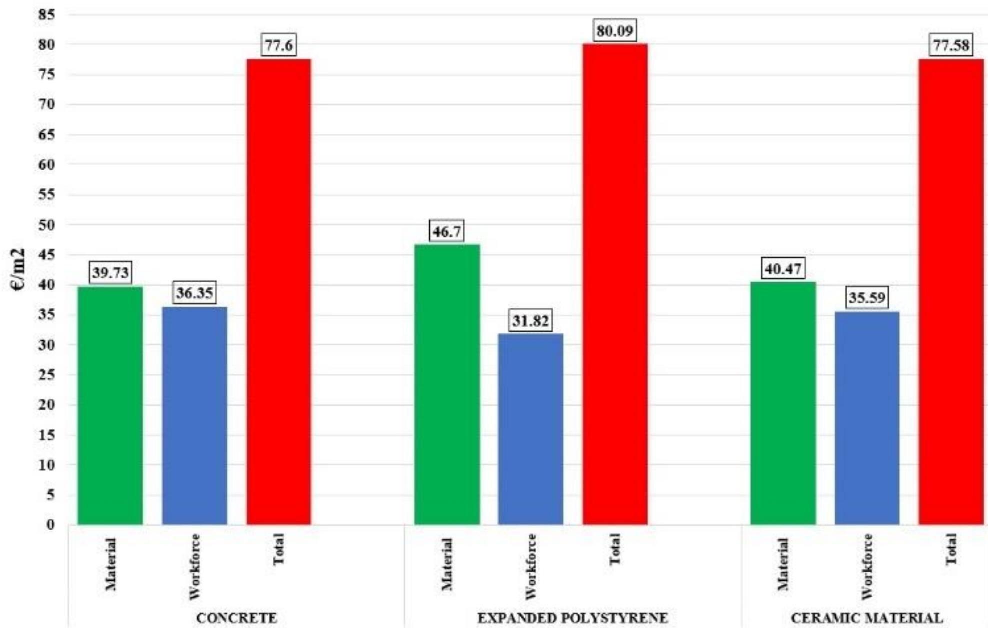

Fig. 3: Comparative €/m2 – Type of coffer

The results obtained by modifying the parameters of the geometric variables of the floor slab are discussed below. The first of these is the distance between axes, commonly known as the centre-to-centre distance. Figure 4 shows the simulation results.

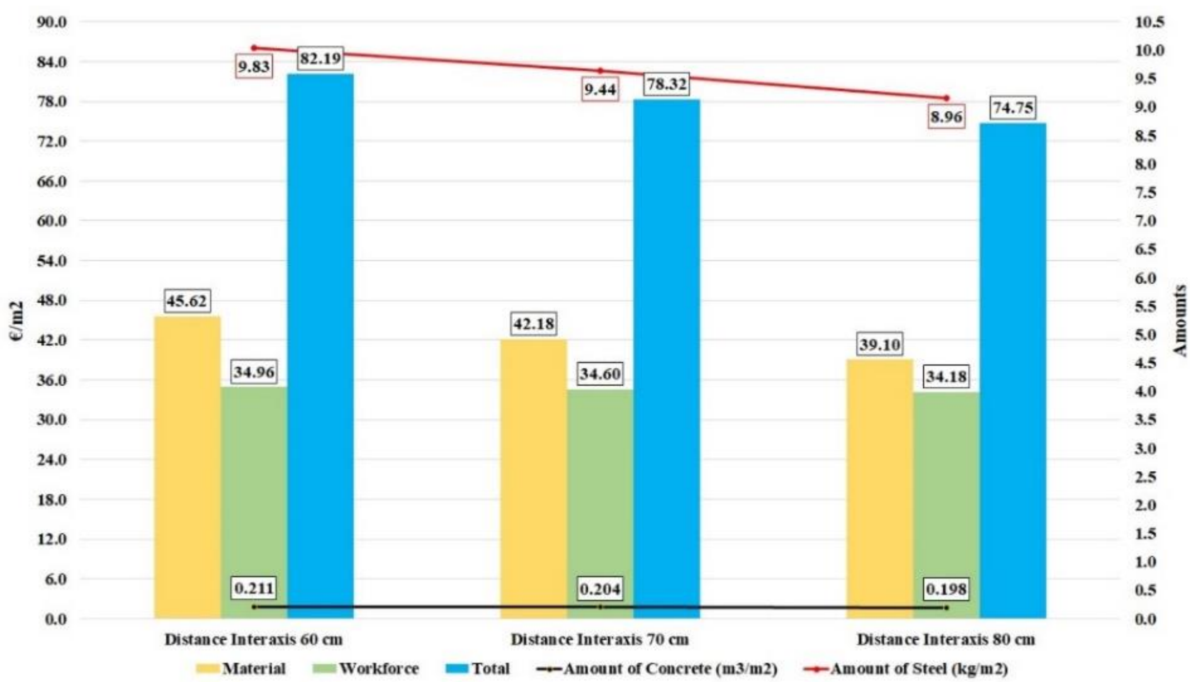

Fig. 4: Economic comparison according to distance between interaxis

As can be seen in the results, as the distance between axis increases, the price of the floor slab decreases and the same occurs with the variables of concrete and steel quantities. This is a consequence of the fact that a greater distance between centers means an increase in the dimensions of the coffer and therefore a smaller number of shafts per floor slab and, consequently, a lower consumption of steel and concrete. In overall results, going from 80cm to 70cm spacing means an increase in the price of the floor slab of 4.8%, and if the spacing is further reduced to 60cm, it is 10% more expensive compared to 80cm spacing.

Finally, we proceed to comment on the variations produced by the geometric parameter of the rib width, the results obtained from the study show that the larger the rib section, the grater the material required to execute it and, consequently, an increase in the use of materials means an increase in the price per square metre of the floor slab. In general terms, this means that a floor slab with a rib width of 18cm is 1.9% more expensive than a floor slab with a rib width of 15cm and 3.8% more expensive than a floor slab with a rib width of 12cm.

Once the economic results have been analysed, the environmental results obtained through LCA are analysed. Firstly, the results obtained at the complete level of the four-floor multifamily building are shown, in which the floor slab typology is the same for all floors. A distinction is made between the various structural elements such as foundations, pillars and floor slabs. Table 4 shows the kg of CO_2-equivalents and MJ of PERNRT (Total use of non-renewable primary energy resources).

Table 4: LCA results by element

Structural Element	kg of CO_2-eq	MJ
Foundation	15792.34	103514.56
Pillars	5242.12	42167.64
Floor Slab	70728.71	609189.38
Total	91763.17	754871.59

Of the 100% of the kg of CO_2-equivalents produced by the execution of this building, 77% of the emissions are produced by the floor slabs, hence their great environmental weight in the structures. It should be noted that practically 97% of the emissions are emitted during the product phase, since during the manufacturing processes of concrete and steel, large amounts of electricity and fossil fuels are consumed, which are associated with a large release of CO_2.

The results of the most representative alternatives will be presented. All of them present a concrete type HA-25, Table 5 shows the values of geometric variables.

Table 5: Environmentally studied alternative characteristics

Alterative	Interaxis	Rib	Height of coffer	Material of coffer
1.1	80cm	12cm	20cm	Concrete
1.2				Expanded Polystyrene
1.3				Ceramic
2.1	60cm	18cm	30cm	Concrete
2.2				Expanded Polystyrene
2.3				Ceramic

Figure 5 plots the values of kg CO_2-equivalents and MJ of energy produced by a single storey slab for the technical characteristics given in Table 5.

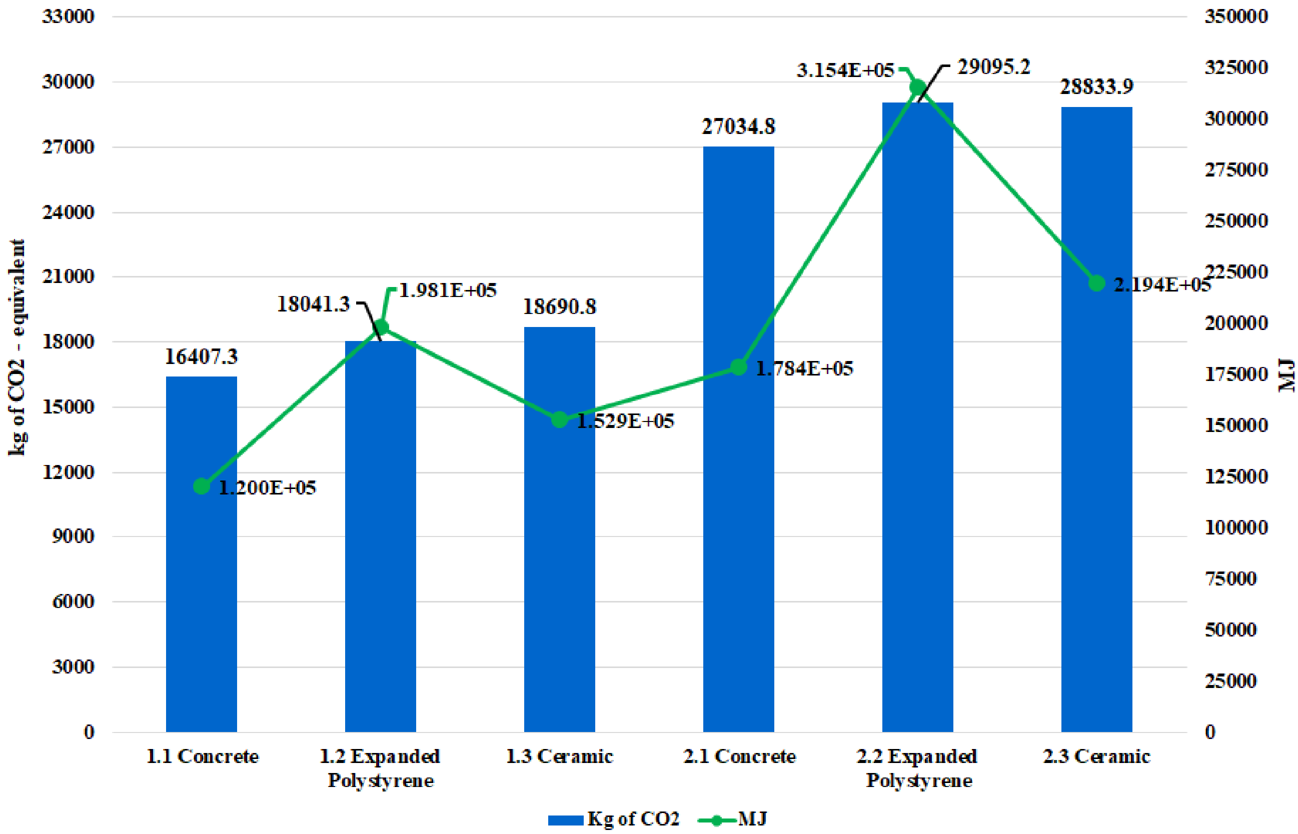

Fig. 5: Alternative results – kg de CO_2/MJ

As can be seen there is a big difference between the alternatives. For the first group, which has a value of interaxis, rib width and height of the lower cassette, it emits on average approximately 17713.13 kg of CO_2-equivalents. However, for the second group of alternatives where the values of the variables are maximised, this reaches 28321.29 kg of CO_2-equivalents, which is an increase of 37%, a rather high percentage that must be taken into account.

Of the three materials used for the construction of the concrete cofferdam, the option of concrete seems the most sustainable, as, although its generation process has a high environmental impact in terms of CO_2 emissions, both expanded polystyrene and clay require laborious industrial processes, with a very high emission of CO_2 into the atmosphere due to the chemical processes undergone during the manufacturing stage.

4. Conclusions

The conclusions of this research are divided between economic and environmental. On the economic level, there are parameters which, if they increase or decrease, can increase the price per square metre of the floor slab. These are listed below in order of importance when it comes to making the items more expensive.

The first of these is the centre-to-centre distance of the strong ribs. This variable has the greatest influence on determining the final price. The cost of the structure increases the shorter the distance between the ribs that make up the waffle slab, since, as the surface area of the slab is an invariant value, if the separation between ribs is greater, there will be fewer ribs and, therefore, the material used to configure them will be less. In the case studied, there may be a price variability of 9.95%.

The second most important parameter is the height of the cassette. The lower the height of the cassette, the lower the final price of the slab. Because less material is consumed and for thicker floor slabs, the amount of concrete per square metre increases considerably. The results show that an increase of 10 cm has an impact of 8.38% on the economic alternative.

The third variable is the characteristic strength of the concrete. The variations detected increase by up to 5.2% when using high-strength concrete. The penultimate parameter is the material used for the casing, in this case the differences minimal and in some specific cases it can be an irrelevant item. In terms of economics, the cheapest are concrete or cassettes, leaving expanded polystyrene cassettes as the most expensive lightening agent. On average, they represent an increase of 4.25%. Finally, the last economic parameter studied is the width of the rib. The larger the section of the rib, more concrete will be needed. An increase of 6cm in width represents an increase of 3.8%.

Based on the results obtained from the life cycle analysis of the building under study, it should be noted that, in construction, and more particularly in the manufacture of floor slabs, it is necessary to opt for sustainable construction, as environmentally friendly as possible, since the floor slab emits 77% of CO_2 emissions and consumes 80% of the energy in its manufacturing, transport and construction process. The alternatives of those floor slab whose configuration allows the minimisation of the amounts of material (which have also been the cheapest) produce a considerably lower environmental impact than those whose amounts are greater.

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