Comparative environmental and economic analysis of South European building constructive systems

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Abstract: - The choice between different materials and constructive systems can influence significantly the environmental impact and economic cost of construction. In this context, four constructive systems used in South European were studied: one conventional - composed by hollow brick walls and steel reinforced post and beam concrete structure; and three non-conventional - light steel framing (LSF); wood frame (WF); and insulation concrete form (ICF). Using a case study based on a contemporary Portuguese typology of a single family dwelling, some environmental impact indicators, as well as the weight and the economic cost of these solutions were evaluated.

Key-Words: - Environmental impact, constructive solutions, economic analysis, functional analysis

1 Introduction

The construction industry plays an important role in the economy, being responsible for the generation of great amounts of capital and employment. However, it is also a sector that is associated with significant environmental impacts. Construction industry consumes more raw materials than any other economic activity (around 3.000 Mtons/year, almost 30% by weight) [1], accounts for 30% of carbon dioxide emissions, the building stock consumes 42% of the energy consumed in Europe [2,3] and produces 500 million tons of construction and demolition wastes, which represents 40% of all waste produced in Europe [4]. The problems of pollution, the large amounts of energy spent and the high consume of raw materials make this sector one of the most problematic in terms of environmental impact.

This work studies the viability of four constructive systems used in South European (France, Greece, Italy, Portugal, Spain) in terms of economic costs, considering the cost of materials, shipping cost and labour cost. The four selected constructive systems studied were defined for a current Portuguese typology of a single family housing dwelling: conventional (CS, made with non-structural hollow brick and structural reinforced concrete frames); light steel framing (LSF); wood frame (WF); and insulation concrete form (ICF). All systems were analysed without finishing materials, as these were assumed as equal.

The analysed solutions were defined to have in common the same heat transfer coefficient for opaque horizontal elements 0,25W/m^2.ºC and vertical opaque elements 0,30W/m^2.ºC. These coefficients were based on the Portuguese thermal regulation, with values responding already to the required demands for 2015 and beyond to the more severe climatic zones in Portugal [5].

For each of the four solutions the construction time, the economic cost and the environmental cost were quantified.

Four environmental parameters were considered: embodied energy (EE), global warming potential (GWP), acid potential (AP) and photochemical ozone creation potential (POCP).

This study was also focused on the evaluation of the energy performance cost of the studied constructive solutions in its design stage by using thermal simulations. It follows previous works from individuals of this research team, such as the sustainability assessment of an innovative lightweight building technology for partition walls (ADjustMEMBRANE) where it was also considered the environmental, functional and economic performances of a conceptual lightweight sandwich membrane partition compared with conventional technologies. The study took place in Portugal and it concluded that, at that research stage, the solution development under this research project is more sustainable than the reference solutions used in the Portuguese building market [6].

An economic and construction analysis about the use of lightweight membranes in the envelope walls of housing was presented in a scientific journal paper by two of the present paper authors. It concludes that it is possible to reduce the environmental impact and cost of buildings by using lightweight instead of heavyweight solutions, even in temperate climates [7]. This paper presents the embodied energy of the materials, labor and material costs, heating and cooling needs, and the ratio between useful/gross areas of lightweight solutions.

Another previous research study by one of the authors of the present paper refers the potentialities of using innovative mixedweight solutions in temperate climates to achieve more sustainable housing constructions, even considering a cradle to grave LCA analysis, from the materials production to the building use, regarding functional aspects related with comfort, like thermal, acoustic and natural illumination [8].

2 Description of the case study

According to recent statistic data (2011) the T3 type dwelling is the most frequent typology in Portugal (about 57%) [9]. This predominance has been a constant reality in the last 15 years and this type of housing is usually suitable for a household consisting of 3 to 4 people. The T3 typology consists in three bedrooms, one living room, one kitchen and two sanitary compartments. A contemporary Portuguese T3 reference residential dwelling was developed for this conceptual study based on the average area of T3 dwellings in the I3 climatic zone – the most demanding in accordance to Portuguese thermal regulation [10].

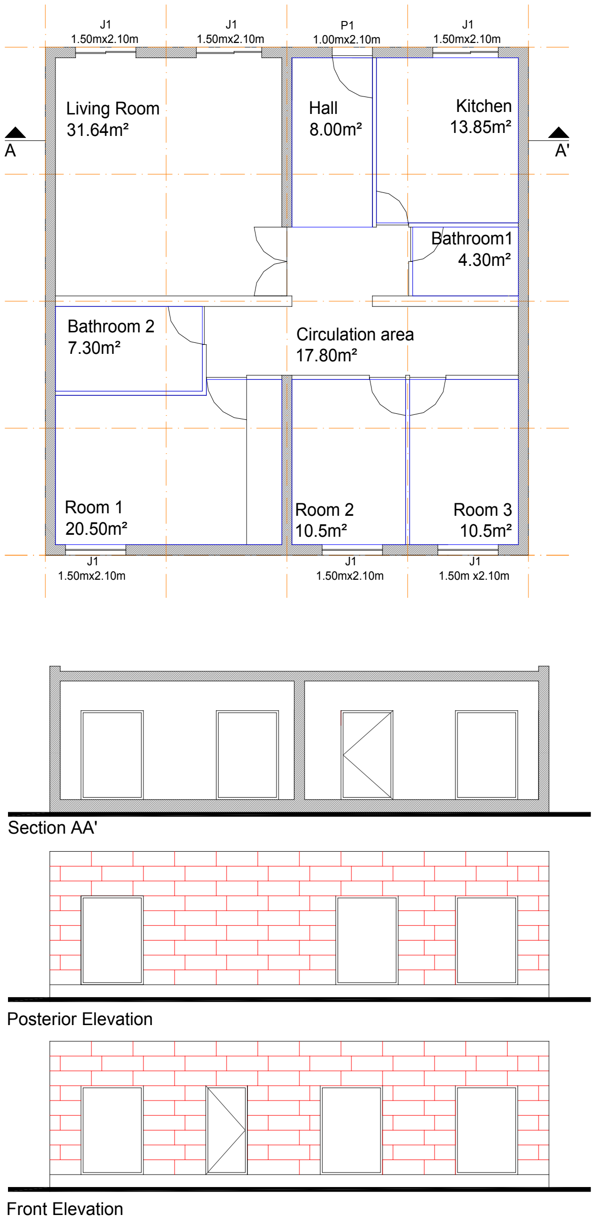


Fig. 1: Reference typology used for the case study

As it can be seen through Figure 1, the reference typology studied has an area of $144m^2$ resulting from the association of 4 square shaped modules of 6x6m. The compartments and total areas of the case study are shown in Table 1. The rooms' sizes are compatible with the Portuguese Buildings General Regulation (RGEU) [11].

Table 1: Comparative analysis between the areas in the case study and the minimum areas allowed by Portuguese Buildings General Regulation

	RGEU (m^2)	**Case Study (m^2)**
Space Distribution (to distribute between living-room and kitchen)	8	
Hall	-	8
Circulation Area	-	17.8
Living-Room	12	31.64
Kitchen	6	13.85
Bedroom 1	10.5	20.5
Bedroom 2	9	10.5
Bedroom 3	9	10.5
Bathroom 1	4.5	4.3
Bathroom 2	-	7.3
Gross Area (ga)	**91**	**144**

3 Studied constructive solutions

The CS, LSF, WF and ICF systems were analysed in relation to its ultimate limit state and service limit state according to the relevant Eurocode. The structural design was performed using modal dynamic analysis and the determination of its response was performed considering the seismic and wind actions.

For the structural analysis of the building it was necessary to quantify the actions and estimate their effects on the structural elements. The permanent actions considered correspond to the self-weight of materials (structural and non-structural). To calculate the weight of the structural elements it was considered specific reference weights. For the roof it was considered 3,00kN/m^2 with an overload of 1,00kN/m^2, considering that the roof was not accessible [12].

According to Eurocode [13], for the wind actions it was considered that the building is located in zone B and presents a roughness of type II and for the seismic action it was considered a type II soil.

The whole procedure of structural design and verification of safety was conducted considering the Eurocode [12,13,14,15,16].

3.1 Conventional Solution (CS)

The conventional constructive solution consists on non-structural partition interior and exterior walls made of hollow ceramic bricks and a reinforced concrete structure comprising slabs, beams, columns and foundations. Acting loads are transmitted from slabs to beams that in turn transmit them to columns and afterwards to its foundation. Continuous footer foundations are connected by lintel beams, both in reinforced concrete.

The first element to be built is the footer. After its concreting, the reinforced steel armour of the columns is mounted and after the concrete is placed on the formworks. The beams are performed in the same manner. Before concreting the beams the slabs must be placed. Usually, the reinforced concrete slabs are lightened ones made with precast beam-and-block floor system. The beams are pre-stressed ones and the blocks are non-structural lost formwork ones. The concreting of slabs and beams is made simultaneously.

The ceramic hollow brick is one of the most widely used materials for partition walls, both interior and exterior ones. In the inner partition walls single 30x20x11cm brick is used. For the facade walls, due to insulation requirements, a double brick solution is commonly used. The selected solution was composed by 30x20x15cm brick in the external face and 30x20x11cm in the other. The air gap was partially fulfilled with 9cm XPS insulation plate as one can observe on Figure 2.

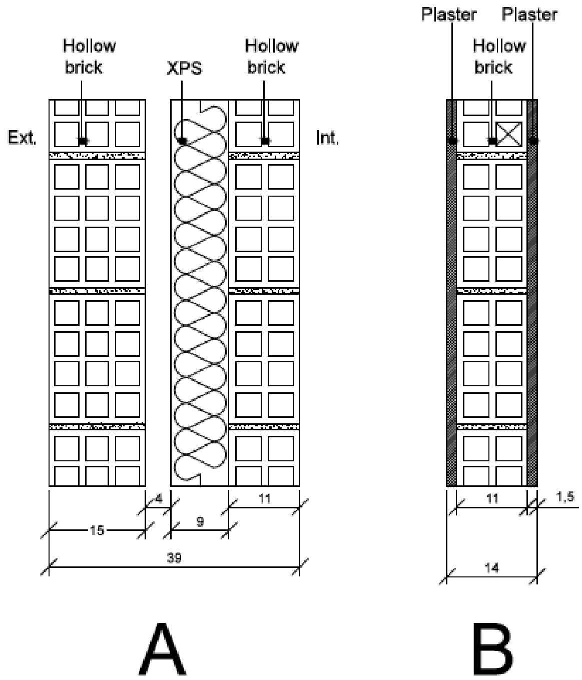


Fig. 2: Conventional constructive system solution for walls

The design of the reinforced concrete sections for slabs, beams, columns and footings were made according to Eurocode 2 [13] comprising the structural plant presented on Figure 3.

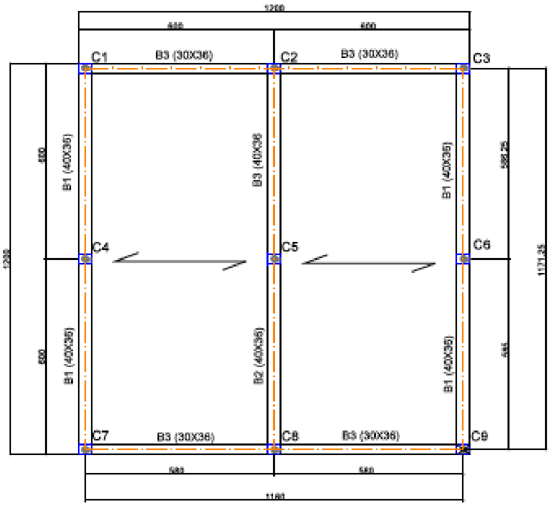


Fig. 3: Structural plant

The adopted dimensions for columns and beams could be observed in Figure 4.

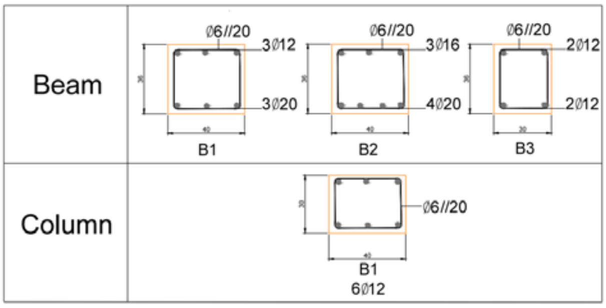
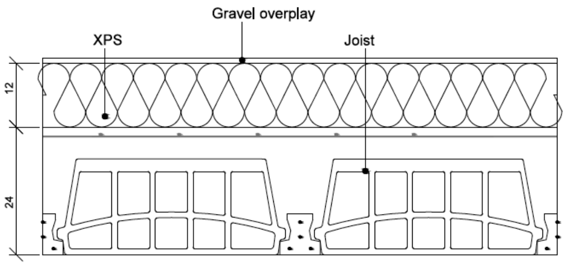


Fig. 4: Section of the beam and column

For slabs one has selected the thickness of 24cm and XPS insulation of 12cm. The type of beam-and-block floor system adopted is showed in Figure 5.



. Fig. 5: Conventional constructive system solution for slabs

3.2 Light Steel Framing (LSF)

LSF is a constructive system which structural elements are made of galvanized cold formed steel profiles. This construction method can be used in the execution of exterior walls, interior walls, slabs and roofs on all types of building such as single family, multifamily, commercial and industrial buildings [17].

This system is characterized by a higher manufacturing technological level than conventional reinforced concrete construction because a large part of its elements is produced at the factory and not on site. With such prefabrication one can reduce the time required for the construction, the required workmanship and heavy equipment, increasing hygiene health and safety at work, on the construction site, and decreases the amount of generated waste.

The LSF walls are responsible for supporting loads from adjacent slabs and from the upper floors. However, one must take into account that there are two types of walls that can be used in cold formed profiles construction: structural and non-structural partitions walls. A structural wall, beyond the resistance to vertical loads, must also resist to horizontal applied loads such as those due to wind or earthquake, which can generate shear and bending stresses in addition to axial ones. Thus, if necessary, one can design LSF interior structural walls besides the exterior ones. Structural walls shall consist of a structure with steel profiles spaced from 150mm to 600mm, having greater thickness than the inner non-structural walls [14,15].

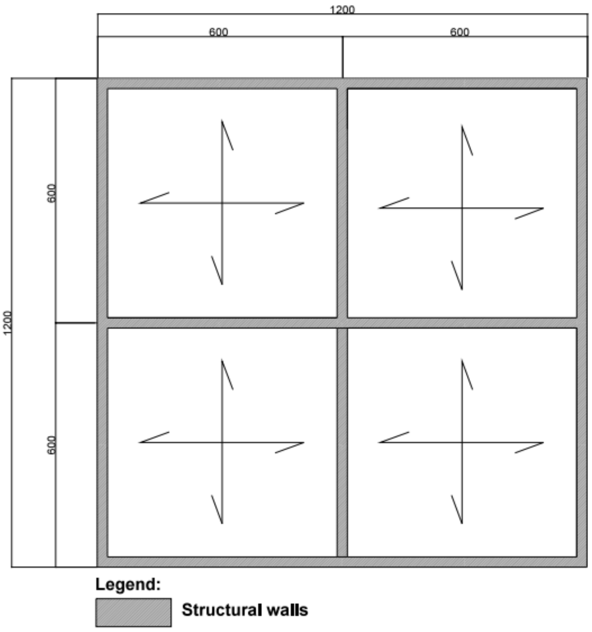


Fig. 6: Structural plant

In this studied case the partitions walls do not need to have structural capacity or thermal properties. The LSF adopted solution uses a partition wall made with galvanized cold formed steel profiles and gypsum plasterboard according to Figure 7.

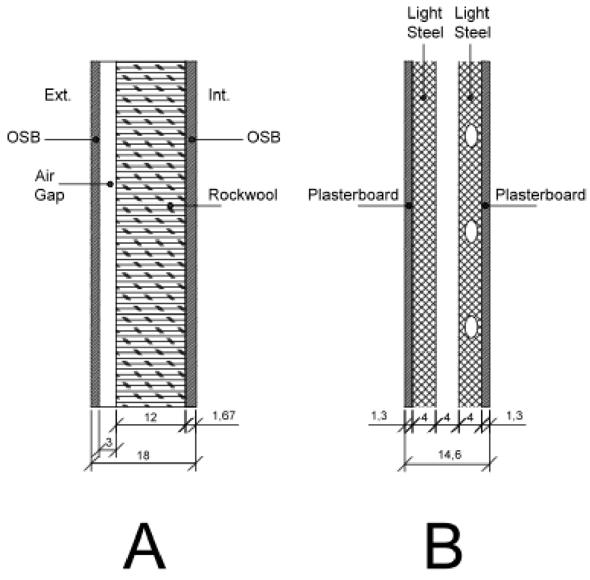


Fig. 7: LSF constructive system solution for walls

The LSF slabs are composed by a galvanized cold formed steel profile structure with a height of 180mm coated with a 20mm thickness OSB panel in both faces as showed in Figure 8. The OSB panels are structural ones and are fixed to steel profiles. Usually, the OSB panels are of Grade 3 or 4 and its minimum thickness is of 18mm.

For the finishing of the floors various solutions are commercially available, being possible to apply a lightweight screed, thereby improving its acoustic behaviour, and thus increasing the thermal inertia of the floor.

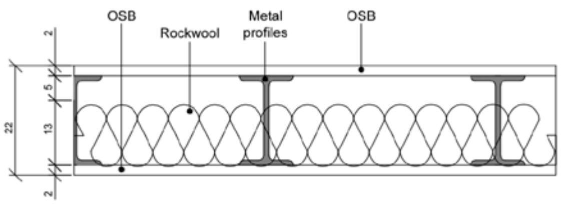


Fig. 8: LSF constructive system solution for slabs

As insulation material is usually used rockwool with a density of 70kg/m^3. The U-values of opaque horizontal (0,25W/m^2.ºC) and vertical opaque elements (0,30W/m^2.ºC) were achieved by calculating the required thickness of thermal insulation, as shown in Table 2.

Table 2: Thickness of insulation and heat transfer coefficient

	Vertical elements (Walls)		Horizontal elements (Slabs)	
	Insul.	U (W/m^2.ºC)	Insul.	U (W/m^2.ºC)
LSF	RW 110mm	0,30	RW 130mm	0,25

3.3 Wood Frame (WF)

This system is structurally composed by glued laminated wood and OSB boards. Upon execution of the concrete foundation wooden structural elements will be assembled using some steel device such as screws, bolts or steel fasteners [18,19].

Like in LSF construction, if necessary, one can design WF system interior structural walls besides the exterior ones. The interior and exterior WF walls adopted are presented in Figure 9 A and B respectively.

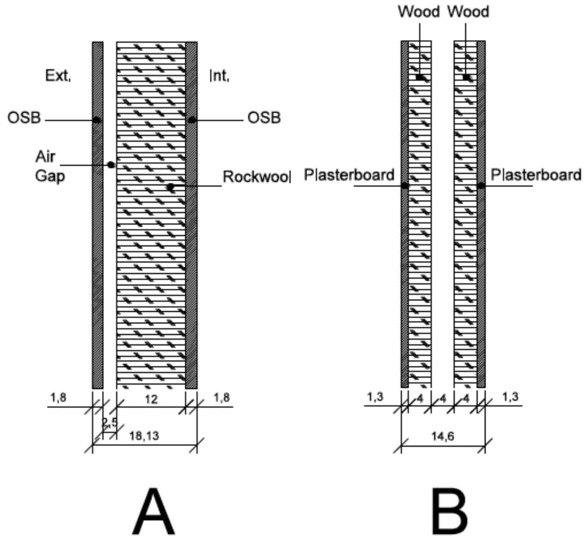


Fig. 9: WF constructive system solution for walls

In Portugal, before the common usage of reinforced concrete, slabs were currently made with WF technology. Nowadays, its usage is not common. However, the constructive system is similar to LSF slabs. The difference among the two systems is only related to the type of supporting beams adopted: while in the LSF system the beams are steel cold framed profiles, in the WF system the beams are made of wood [19].

As insulation material is usually used rockwool with a density of 70kg/m^3. In Figure 10 one can observe the WF solution slab adopted.

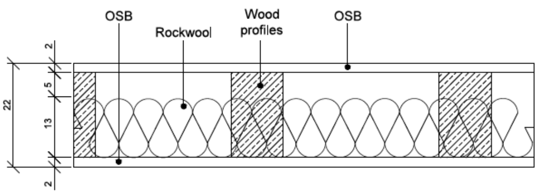


Fig. 10: WF constructive system solution for slabs

Table 3: Thickness of insulation and heat transfer coefficient

	Vertical elements (Walls)		**Horizontal elements (Slabs)**	
	Insul.	U (W/m^2.ºC)	Insul.	U (W/m^2.ºC)
WF	RW 110mm	0,29	RW 130mm	0,25

3.4 Insulation Concrete Form (ICF)

Insulation Concrete Form is a constructive block system comprising expanded polystyrene (EPS) that is mounted with a Lego-like shape and filled with steel rebars and concrete, thus forming a reinforced concrete structural wall system [21].

This system is composed by concrete placed between two plates of EPS joined by tie rods that may be of various materials such as PP, PE, steel, among others. The thickness of EPS may vary by manufacturer and can respond to different climate requirements of the construction zone.

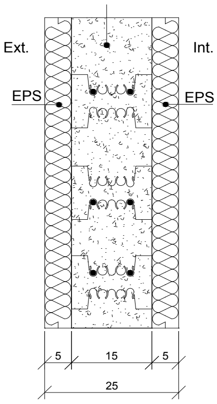


Fig. 11: ICF constructive system solution for walls

The thickness of the concrete wall was fixed at 15 cm because it corresponds to a commercial available system used in Portugal. The reinforced concrete design of the walls of the studied building was performed according to EC2 [13] and results in the need of minimum steel reinforcement area along the concrete section.

In the ICF structural system, there is no specific type of slab associated. However, a conventional lightened beam-and-block concrete slab type was chosen in order to ensure the thermal inertia of the housing and also represents the option with lower cost.

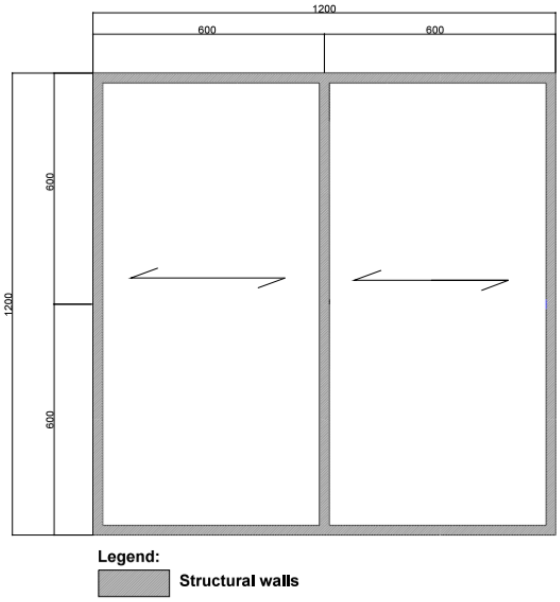


Fig. 12: Structural plant

4 Presentation and analysis of results

Although all these constructive solutions are already established in the market, the traditional system continues to be the most widely used solution in Portugal. In this study a comparison analyses is made among the various constructive solutions, partitions, structural walls and slabs, regarding construction time, economy and environmental impact.

The construction time, represents the sum of all working time needed to build the typology under study, as the construction details for each constructive solution.

For calculation of income and time to build one national database were used, considering only one more official a helper for building any constructive solution.

The economic cost of dwelling results from the sum of various costs of materials, cost of labour, and cost of equipment needed to support the construction [22,23,25].

The final cost of materials, can be divided into two different costs: the cost of acquisition; and the cost of transportation. This last cost depends on the distance from the factory to the building site, the volume and weight.

To compare all solutions it was assumed that all materials are transported by road with heavy vehicles. Thereby, it is necessary to consider the maximum capacity that can be carried by each heavy vehicle; in this case it was considered that each heavy vehicle could carry a maximum bulk of 67m^3 and a weight of 26.500kg.

According to Portuguese National Road Carriers Association of Public Goods [25], the reference price per km for the first half of 2014 for the transportation of goods, results from the sum of the cost of unloading cargo (average price - 150€) with travel cost per km (average price - 0,847€/km).

To synthesize the environmental impact that each material used in the construction has on the environment, three parameters were considered: global warming potential (GWP), acid potential (AP) and photochemical ozone creation potential (POCP) [26,29].

4.1 Non-structural partition walls

Some internal partitions walls do not have structural capacity, however must be able to withstand the stresses induced by coating and other elements. This type of wall has no thermal requisites for meeting the housing interior, however, the acoustic level should have a good performance.

4.1.1 Construction time

The construction of the walls can be performed after applying the ground floor, no longer depends on any task.

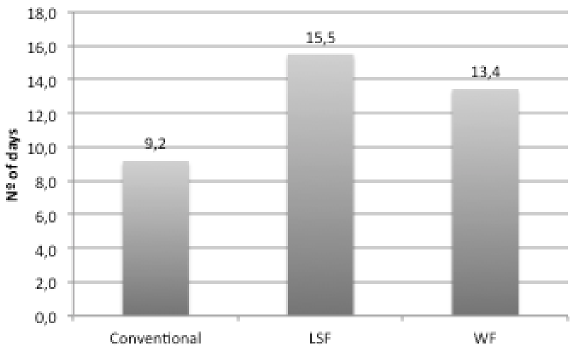


Fig. 13: Construction time of the non-structural partition walls

As it can be seen through observation of Figure 13, the conventional construction system for non-structural partition walls have lower construction time, however to place finishes, such as a smooth finish is required much more labour-intensive than other systems because they already have a smooth surface, and it is only necessary to regulate them and apply a painting.

4.1.2 Economic analysis

Table 4 presents the total weight and bulk of each material for each constructive solution as walls dividing and cost [22,23,28].

Table 4: Quantities (kg and m^3) for non-structural partition walls

System	Materials	Bulk (m^3)	Weight (kg)
CS	Mortar	2,1	4158,0
	Brick 30x20x11	16,5	421,2
	Sum	18,6	4579,2
	Cost sum (€)	3 983,15 €	
LSF	Profiled steel	0,7	338,0
	Rockwool	4,3	46,1
	Plasterboard	2,7	907,2
	Sum	7,7	1291,4
	Cost sum (€)	7 333,20 €	
WF	Lumber	0,8	166,3
	Rockwool	4,3	53,4
	Plasterboard	2,7	907,2
	Sum	7,8	1126,9
	Cost sum (€)	6 576,25 €	

The conventional solution is more economical than the other considered building systems for non-structural internal partition walls, costing less than 50% the remaining solutions. However, as the conventional solutions have rough aspect, finishing will require different materials to have a smooth aspect, being also affected the associated construction time.

This cost is the cost of materials factory, missing even to consider the cost of transportation, based on the volume and the maximum weight that each truck can carry.

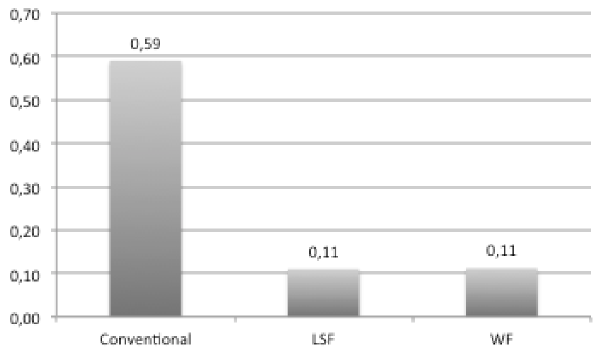


Fig. 14: Number of heavy vehicles need for transportation construtive solutions partitions

According to Figure 14 and as expected, the heaviest solutions and greater volume needs more transportation resources. The LSF and WF solutions have the same transport needs, which are the best performing in transportation issues.

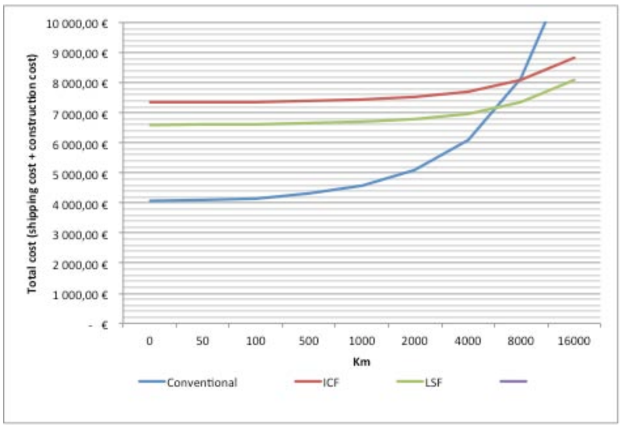


Fig. 15: Sum of the cost construction with cost of transport the partitions

The results from adding construction costs and transportation ones are presented in Figure 15. Observing this Figure 13 one can conclude that from distances higher than 6000km conventional solution ceases to be more the most economical one. WF solution becomes the better economic performance one. The LSF and WF evolution of costs are based on the same distance, because the number of vehicles required for transportation is the same for both solutions.

4.1.3 Environmental impacts

To synthetize the environmental impact that each material used in the construction has on the environment, three parameters were considered: global warming potential (GWP), acid potential (AP) and photochemical ozone creation potential (POCP) [26]. For this study, the results of the environmental parameters are show in Figure 16 GWP (Fig. 16 A), AP (Fig. 16 B) and POCP (Fig. 16 C).

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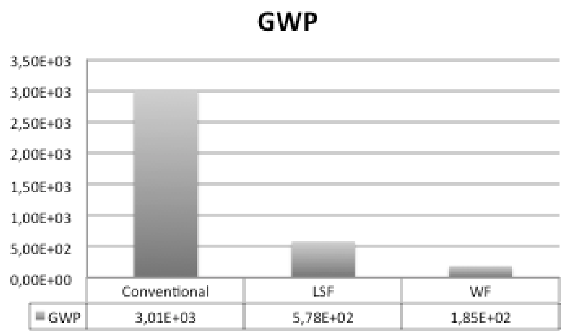

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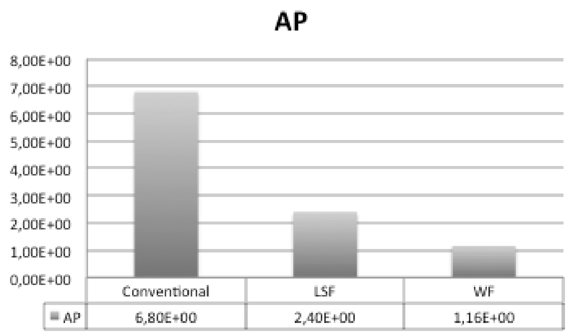

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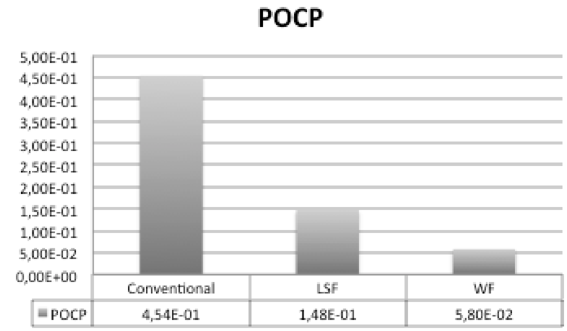


Fig. 16: Environmental assessment of the analysed partitions

As it can be seen, the conventional solution presents the worst performance in all environmental parameters due to the use of large amount of material. The LSF and WF solutions have relatively next weight, however WF solution, which uses wood profiles vertically, has the best performance of any of all because it uses materials of renewable origin.

The performance of the WF and LSF solution for partitions walls could be further improved if other materials originating from green materials replaced the gypsum boards.

4.2 Structural walls

For conventional solution the walls do not need to have structural capacity. So, convectional solution is composed of concrete slabs, beams, columns and non-structural brick walls. For the remaining solutions LSF, WF and ICF all the walls were considered as structural ones.

Structural walls made of reinforced concrete must be capable of supporting the efforts from the slabs, earthquake, wind and others.

As mentioned previously by scaling issues there is a need to make structural walls within the housing, however these do not need to have heat requirements.

In ICF solution it is not common to remove the EPS after application and curing of the concrete, the inner walls why this solution has thermal requirements.

4.2.1 Construction time

For the construction of structural walls the foundation element must already be completed, regardless of the type of foundation, general mat foundation, shoe continues or cuttings**.** The obtained results for the case study are presented in Figure 17.

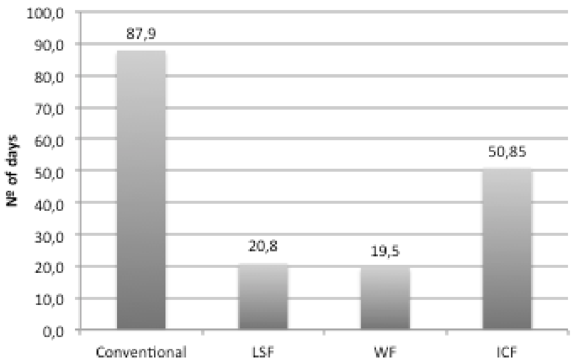


Fig. 17: Construction time for structrual walls

According to Figure 15, solutions using concrete, as the case of CS and ICF are those that require more days for completion compared to other solutions.

For the completion of the masonry wall and the structure for conventional solution various tasks are required. The placing of formwork for concrete beams and columns, the placing of steel rebars armour and, after, the removing of the formwork when the concrete is cured. Only after that it is possible to start masonry construction. Thus a large difference among LSF and WF solutions that do not require concrete curing time or the application and removal of the formwork can be expected.

ICF solution reduces the construction time by 37 days compared to conventional one, despite using concrete and requiring curing time also. This aspect can be explained by the use of a formwork that is lost during the construction, causing in addition, as it is composed of EPS boards, much better thermal behaviour.

4.2.2 Economic analysis

Table 5 presents the total weight and bulk of each material for each constructive solution as walls dividing and cost [22,25,28].

Table 5: Quantities (kg and m^3) for structural walls

System	Materials	Bulk (m^3)	Weight (kg)
CS	Reinforced concrete	20,6	47472,0
	XPS	11,8	384,3
	Mortar	6,0	11957,4
	Brick 30x20x11	20,1	8711,8
	Brick 30x20x15	14,7	11615,8
	Sum	73,3	80141,3
	Cost sum (€)	15 840,77 €	
LSF	Profiled steel	4,5	4221,3
	Rockwool	15,8	1011,8
	OSB	4,7	3831,6
	Sum	25,1	9064,7
	Cost sum (€)	28 243,37 €	
WF	Lumber	4,9	4189,7
	Rockwool	15,8	1011,8
	OSB	4,7	3831,6
	Sum	25,5	9033,1
	Cost sum (€)	21 913,56 €	
ICF	Reinforced concrete	27,0	62100,0
	EPS 200	26,1	940,6
	Sum	53,1	63040,6
	Cost sum (€)	10 416,15 €	

Economically analysing the costs of the various constructive solutions one can conclude that the ICF solution has lower construction price, not even considering the cost of transportation associated with it.

Despite the LSF and WF solutions are less labour-intensive, the cost of these materials solutions is quite high, moreover the hourly cost of labour, working time for these solutions is higher.

To determine the shipping cost that is associated on the basis of kilometres travelled, it is necessary to know the number of trucks needed to transport each solution. The obtained results are presented in Figure 18.

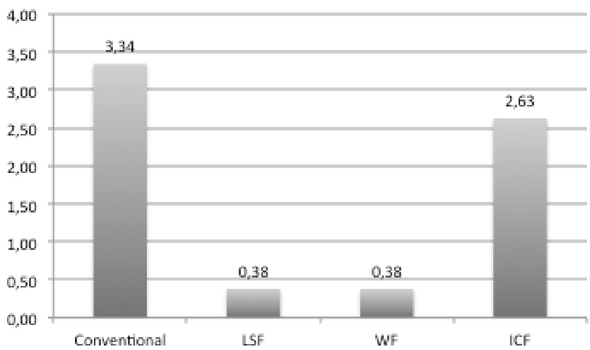


Fig. 18: Number of heavy vehicles need for transportation construtive solutions strutural walls

As in partition walls, conventional solution requires heavier vehicles than the ICF and LSF and WF solutions needs the same number of vehicles (see Figure 18).

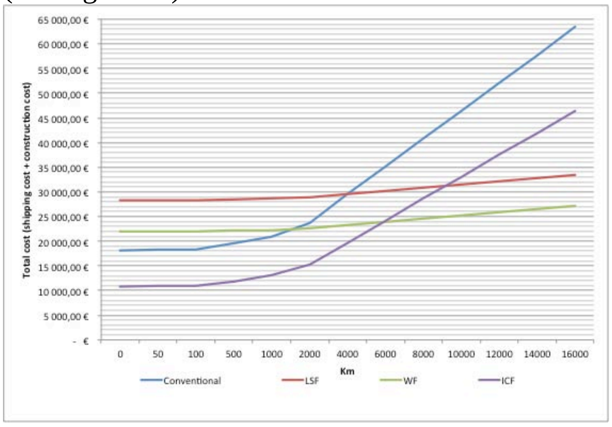


Fig. 19: Sum of the cost construction with the cost of transport of structural walls

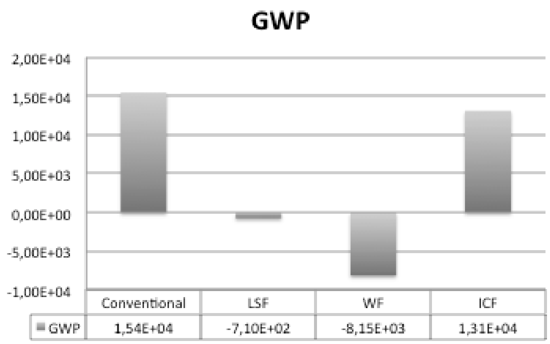
Including the shipping cost in the final cost (Figure 19) the ICF solution becomes the low cost one until a distance of transportation above 6000km. For higher distances WF becomes the most economical solution.

The conventional solution despite the second lowest cost until the distance of about 3000km, due to the high number of trucks needed it exceeds all other solutions for distances higher than 4000km.

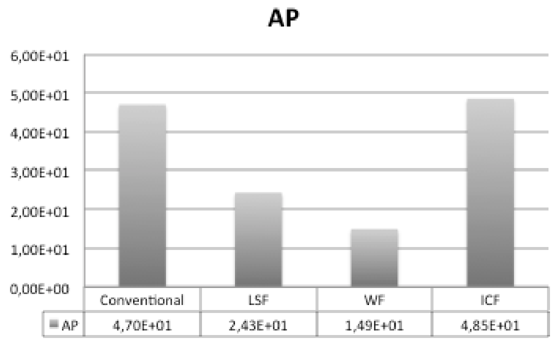
4.2.3 Environmental impacts

To synthesize the environmental impact that each material used in the construction has on the environment, three parameters were considered: global warming potential (GWP), acid potential (AP) and photochemical ozone creation potential (POCP) [22]. For this study, GWP (Fig. 20 A), AP (Fig. 20 B) and POCP (Fig. 20 C) evaluated.

A



B



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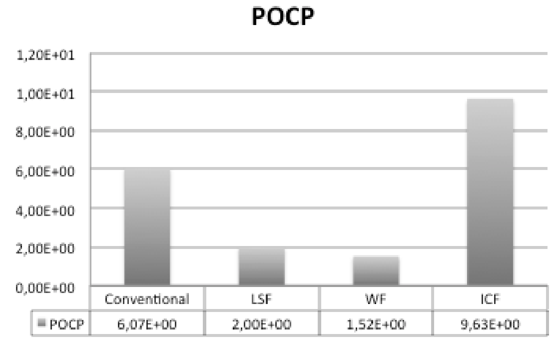

Fig. 20: Environmental assessment of the analysed structural walls

Solutions using concrete (CS and ICF) have a worse environmental performance in all parameters. In GWP parameter, a conventional solution can overcome the ICF solution. The use of reinforced concrete and insulation also uses other products such as bricks and mortar which manufacture is very harmful to the environment.

The use of wood in the LSF solution leads to a negative value of the GWP parameter even when using materials such as rockwool and steel.

For the AP and POPC parameters the ICF solution shows the worst performance, by using large amounts of EPS and concrete.

4.3 Slabs

The slabs are the horizontal element of the housing and may be floor when it is inside the housing or cover when in contact with the outside.

In the case of typology study there is only one slab cover and be in contact with the outside needs to thermal requirements, as previously described details.

At this point only three types of slabs were analysed: conventional, LSF and WF, because the ICF solution does not present any type of specific slab.

4.3.1 Construction time

For the slab manufacturing, regardless of the constructive solution that is needed reinforced concrete structure, in the case of conventional solution or resistant walls, LSF, WF and ICF solutions is now completed.

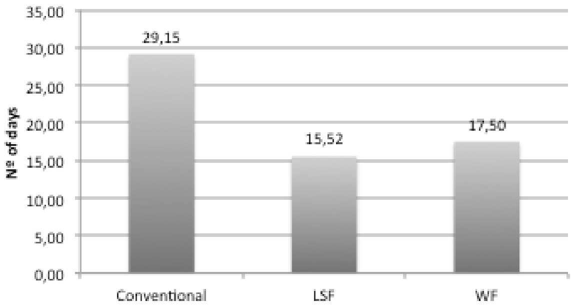

Fig. 21: Construction time for slabs

For conventional lightened concrete slabs is necessary to fulfil various tasks already presented in 4.2.1 such as concrete placement and curing. Moreover, this kind of slabs also requires lifting means due to the weight and quantity of materials, thus presenting the longer construction time (Figure 20).

The LSF solution is faster for building slabs, applying the former the metal profiles after the OSB plates and finally the insulation material.

4.3.2 Economic analysis

Table 6 present the total weight and bulk of each material for each constructive solution as walls dividing and cost [22,23,28].

Table 6: Quantities (kg and m^3) for slabs

System	Materials	Bulk (m^3)	Weight (kg)
CS	Reinforced concrete	12,3	28218,2
	XPS	17,3	561,6
	Girder-slabs	2,1	5225,5
	Joist	22,1	12181,0
	Steel	1,9	106,6
	Sum	55,7	46292,8
	Cost sum (€)		9235,67 €
LSF	Profiled steel	3,4	3185,3
	Rockwool	18,7	1310,4
	OSB	2,6	2099,5
	Sum	24,7	6595,2
	Cost sum (€)		18 105,66 €
WF	Lumber	5,9	5040,0
	Rockwool	18,7	1310,4
	OSB	2,6	2099,5
	Sum	27,2	8449,9
	Cost sum (€)		13 996,80 €

As for the partition walls, without considering the cost of transport, the conventional solution for slabs continues to be the lower cost one. The LSF solution is the most expensive one featuring a cost of 125,73€/m^2.

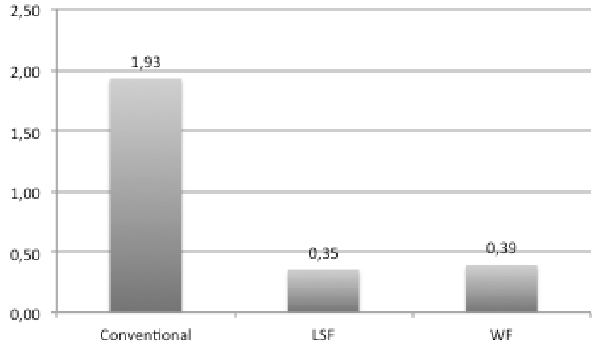

Fig. 22: Number of heavy vehicles need for transportation construtive solutions slabs

Evaluating the number of heavy vehicles needed for transportation (Figure 22) one can conclude that the conventional solution needs more heavy transport vehicles, while the LSF and WF solutions.

Taking into account the variation of the distance travelled one can check the most economical solution for a given distance, as the following Figure 23 reports.

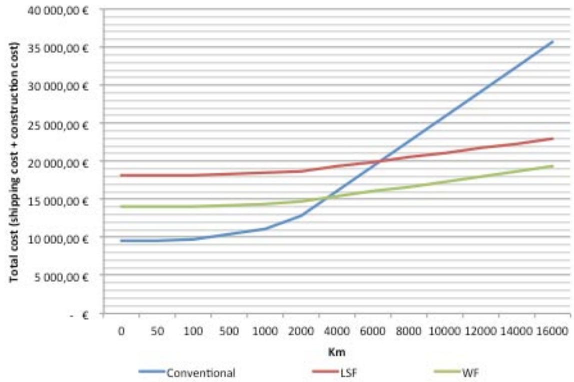

Fig. 23: Sum of the cost construction with cost of transport the slabs

Analysing Figure 23 one can observe that the conventional solution, despite the need for greater number of heavy vehicles, is competitive within a nearby distance of 6000km due to its low initial cost. For superior distances WF solution becomes more competitive.

4.3.3 Environmental impacts

To synthesize the environmental impact that each material used in the construction has on the environment, three parameters were considered: global warming potential (GWP), acid potential (AP) and photochemical ozone creation potential (POCP) [25]. The obtained results are presented in Figure 22. For this study, GWP (Fig. 24 A), AP (Fig. 24 B) and POCP (Fig. 24 C) values in gr of

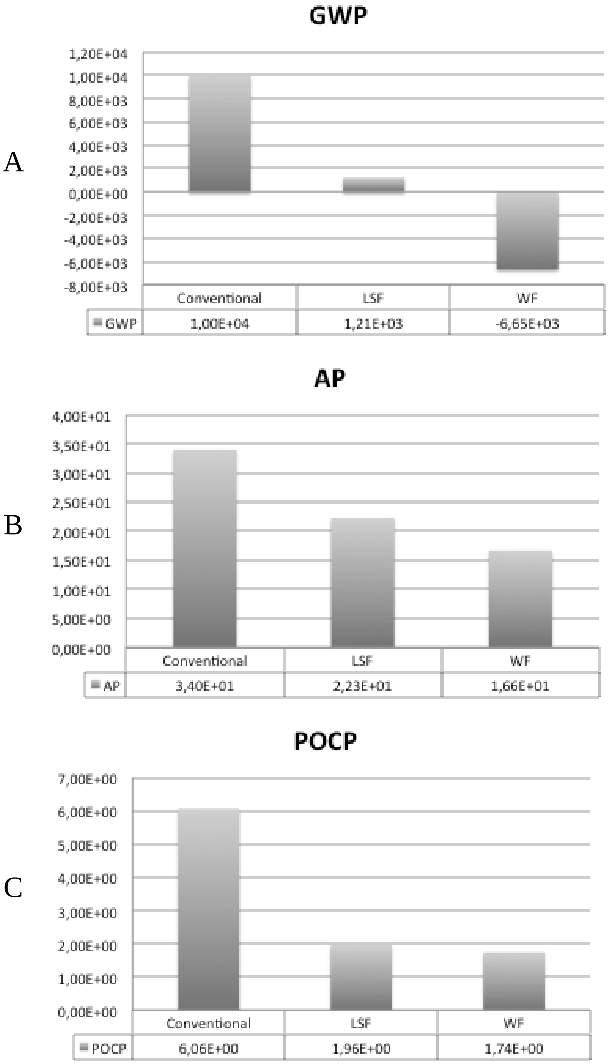

Fig. 24: Environmental assessment of the analysed slabs

The WF slab solution consists mainly of wood. Being wood a renewable source material, its environmental performance is always better than all others, with even negative value in GWP parameter.

4.4 Global

The partition walls, structural walls and slabs were analysed individually. However it is also important to consider the overall construction time, economic and environmental impact.

4.4.1 Construction time

Figure 25 shows the total time of construction for partitions and structural walls, slabs. The number of days required for construction of the type under consideration does not correspond to the sum of days required for each type of construction element. This is because there are elements that can be built in simultaneously and have precedence and thus decreases the number of total days for construction.

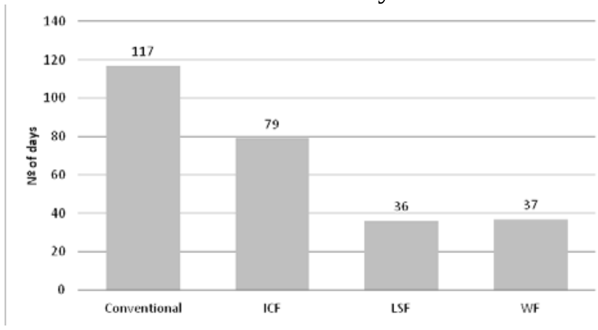

Fig. 25: Construction time of the solutions

As it is possible to observe in Figure 25 the constructive solutions with greater construction time are conventional (117 days) and ICF (79 days). Construction time in LSF and WF is reduced at least 50% compared to other solutions.

4.4.2 Economic analysis

The overall cost of the construction is the sum of the cost of construction of each building element.

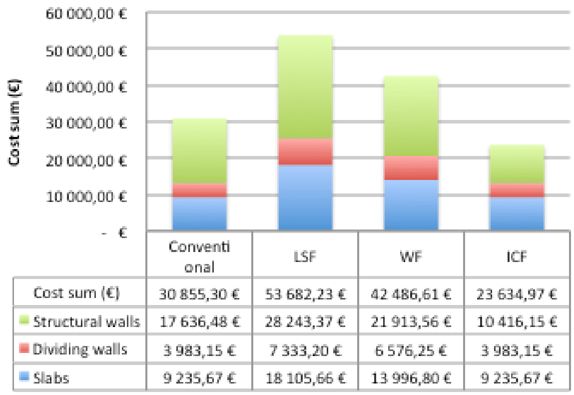

Fig. 26: Construction cost

As expected, the heavy solutions have lower construction cost (conventional and ICF) compared to lighter solutions, LSF and WF. For this case study the cost of ICF is around 157€/m^2.

Based on the bulk and the maximum weight that each heavy vehicle can carry, the number of vehicles required to transport each constructive solution was determined (Figure 27).

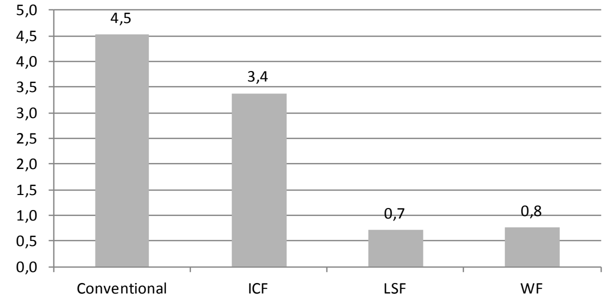

Fig. 27: Number of heavy vehicles need for transportation construtive solutions**.**

Due to its large bulk and weight, the conventional and ICF solutions require greater number of heavy vehicles to be transported, while LSF and WF housing solutions under study can be carried by a single heavy vehicle.

Based on the number of heavy vehicle needed to transport the constructive solutions it is possible to determine the total cost of housing under study in function of transport distance (km) of materials for the construction site. The obtained results are presented in Figure 28 and the total cost represents the sum of the cost construction with cost of transport.

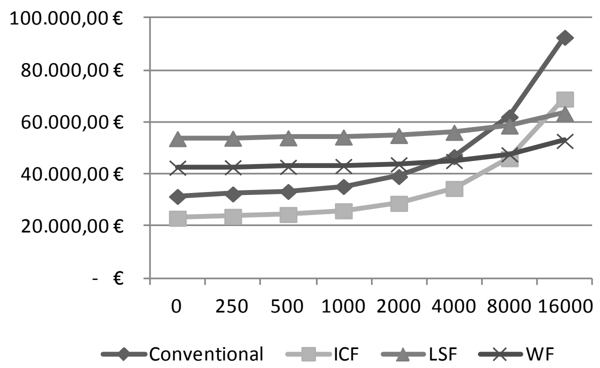

Fig. 28: Sum of the cost construction with cost of transportation

By analysing Figure 28 one can see that the ICF solution is economically competitive with up to a maximum distance of 8000km from the factory to the building

4.4.3 Environmental impacts

To synthesize the environmental impact that each material used in the construction has on the environment, three parameters were considered: global warming potential (GWP), acid potential (AP) and photochemical ozone creation potential (POCP) [25]. For this study, GWP (Fig. 29 A.), AP (Fig. 29 B) and POCP (Fig. 29 C)

Figure 29 presents the environmental assessment indicators comparison graphs for the constructive systems analysed.

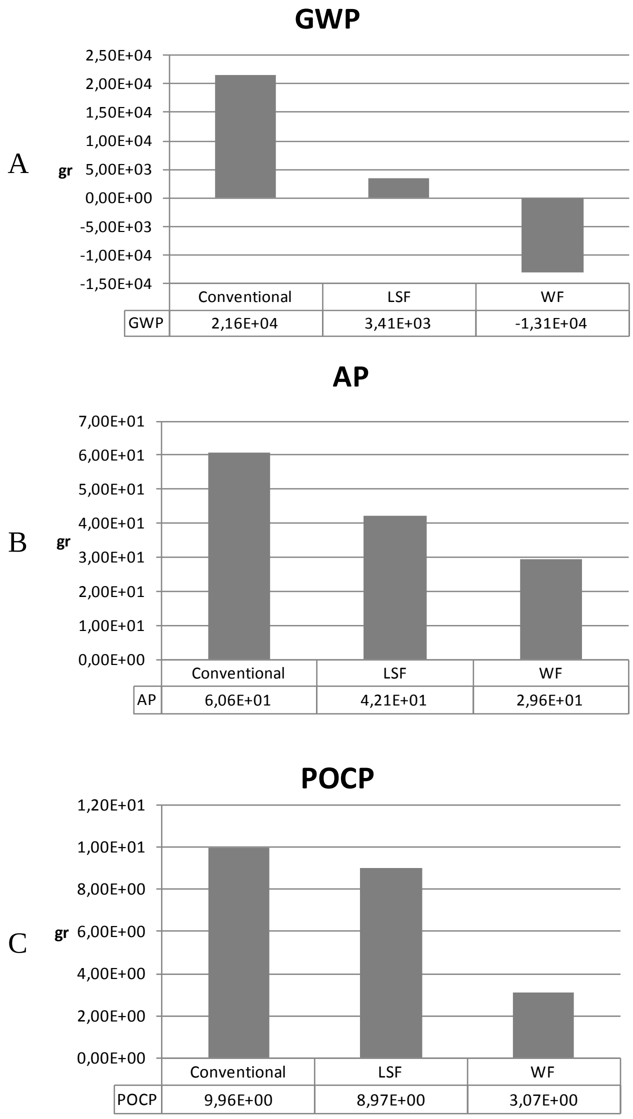

Fig. 29: Environmental assessment of the analysed structural solutions

As it would be expected, the WF structural solution is the best solution at the environmental level, although being negative in the global warming potential parameter, despite having an equivalent weight to a LSF with the same insulation thickness. It's quite different performance is due to the fact that wood is a renewable source natural material.

The conventional solution presents the worst performance in the GWP parameter. ICF solution evidences the worst performance in AP and POCP.

4.4.4 Embodied Energy

The total embodied energy associated with each solution, meaning the sum of all the energy required to produce the materials used, was estimated (Figure 30). The emissions produced by the materials' transport were also calculated [29] and its results are presented in Tables 7 and 8.

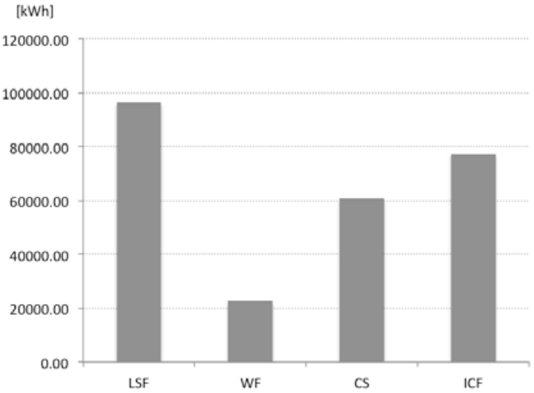

Fig. 30: Embodied Energy of the structural elements in the analysed solutions

Table 7: Emissions from transported km [25]

	Weight	CO_2	CH_4	NO_x	CO	VOCs	kWh/km
	T	kg/km					
LSF	3390,24	701,78	1,02	12,20	8,14	3,73	2722,36
WF	3720,52	770,15	1,12	13,39	8,93	4,09	2987,58
CS	22532,2	4664,17	6,76	81,12	54,08	24,79	18093,36
ICF	19279,92	3990,94	5,78	69,41	46,27	21,21	15481,78

Table 8: Emissions from transport considering an average distance of 200km

	Weight	CO_2	CH_4	NO_x	CO	VOCs	kWh
	T	kg					
LSF	3390,24	701,78	1,02	12,20	8,14	3,73	2722,36
WF	3720,52	770,15	1,12	13,39	8,93	4,09	2987,58
CS	22532,2	4664,17	6,76	81,12	54,08	24,79	18093,36
ICF	19279,92	3990,94	5,78	69,41	46,27	21,21	15481,78

4.5 Thermal simulation

The simulations carried on were done with EnergyPlus dynamic thermal simulation engine [27], a software that can account for complex time-varying climatic and occupation conditions in the prediction of heating and cooling loads, and indoor environmental conditions in a building.

4.5.1 Analysed solutions

All simulations were done using the same case study T3 dwelling previously described, but differing only in the constructive elements. LSF and WF solutions only differ between them in the profile material for the partitions. CS and IFC solutions only differ between them in the envelope construction. The choice of the materials can influence the achievement of thermal comfort requirements and it should be taken into account some criteria and characteristics that were inputted in the simulation such as the specific heat and thermal conductivity [31]. The compositions and U-values of the simulated solutions are shown on Table 9. The compositions of the other constructive elements considered for thermal simulation are presented on Table 10 and the materials characteristics are defined on Table 11 [28,29]. The layers are listed from the outdoor to the indoor in the envelope and partition walls, and from the top to the bottom on the roof and floor.

Table 9: Composition and U-values in W/m^2-K of the solutions

Light Steel Framing - LSF								
	Envelope	**mm**	**Partition**	**mm**	**Roof**	**mm**	**Floor**	**mm**
1	OSB	18	Plaster board	13	OSB	20	OSB	20
2	Air Gap	35	Air Gap	120	Rock wool	130	Air Gap	180
3	Rock wool	110	Plaster board	13	Air Gap	50	OSB	20
4	OSB	18			OSB	20		
U	0.298				0.259		1.588	
Wood Frame - WF								
	Envelope	**mm**	**Partition**	**mm**	**Roof**	**mm**	**Floor**	**mm**
1	OSB	18	Plasterboa rd	13	OSB	20	OSB	20
2	Air Gap	35	Air Gap	120	Rock wool	130	Air Gap	180
3	Rock wool	110	Plaster board	13	Air Gap	50	OSB	20
4	OSB	18			OSB	20		
U	0.298				0.259		1.588	
Conventional Solution - CS								
	Envelope	**mm**	**Partition**	**mm**	**Roof**	**mm**	**Floor**	**mm**
1	Hollow Brick	150	Plaster	15	XPS	120	Con-crete	240
2	Air Gap	40	Hollow Brick	110	Con-crete	240		
3	XPS	90	Plaster	15	Plaster	15		
4	Hollow Brick	110						
U	0.296				0.284		3.546	

Insulation Concrete Form - ICF								
	Envelope	**mm**	**Partition**	**mm**	**Roof**	**mm**	**Floor**	**mm**
1	EPS 200	50	Plaster	15	XPS	120	Con-crete	240
2	Concrete	150	Hollow Brick	110	Con-crete	240		
3	EPS 200	50	Plaster	15	Plaster	15		
U	0.307				0.284		3.546	

Table 10: Composition and U-values in W/K.m^2 of other constructive elements considered

Other Constructive Elements				
	Window	**mm**	**Doors**	**mm**
1	Glass	6	Wood	6
2	Air Gap	12	Air Gap	30
3	Glass	6	Wood	6
U	2.4		2.523	

Table 11: Material characteristics

Material	**Roughness**	**Conductivity** (W/m -K)	**Density** (Kg/m^3)	**Specific Heat** (J/kg-K)
Concrete	Medium Rough	2,000	2350	940
EPS	Medium Rough	0,033	30	1550
Hollow Brick	Rough	0,423	1900	960
OSB	Medium Smooth	0,130	650	1300
Plaster	Rough	0,800	1500	1046
Plaster board	Smooth	0,250	875	1000
Rockwool	Medium Rough	0,040	70	735
Wood	Medium Smooth	0.18	658	2005
XPS	Medium Rough	0,037	32	1550
		Thickness (mm)	**Thermal Resistance (m^3.ºC/W)**	
Vertical Air Gap		25-300	0.18	
Horizontal Air Gap		30-300	0.16	

4.5.2 Other considerations

The dynamic simulation considered some of the requirements referred on the Portuguese Regulation for the Energy Performance of Housing Buildings [4]. The main objectives of this regulation are to guarantee heat and cooling requirements for thermal comfort based on temperature set points and assuring minimum ventilation requirements for air quality. Here, the use of natural ventilation should also contribute to maintain thermal comfort and reduce the energy use [31]. The following reference parameters for simulation were considered:

- Interior comfort set points – 18ºC for winter and 25ºC for summer;
- Air change rate per hour due to air leakage of 0,4 h^{-1}; under average operating conditions to guarantee indoor air quality;
- It was defined a fictional heating system by the *IdealLoadsAirSystem* input. It is used when it is wished to study the performance of a building without modelling a full HVAC system [32]. It was considered that this system operates only during occupation hours;
- In order to evaluate the internal gains due to occupancy, it was set a metabolic rate of 80W/person during the night and 120W/person during the day;
- It was considered an illuminance level of 100 lux that corresponds to 4W/m^2, during occupation hours between 17:00 and 23:00;
- An additional gain of 4W/m^2 from other electric equipment during occupation hours was set.

4.5.3 Climate

The simulations were carried out using a climate file of Bragança, Portugal. This choice was due to the fact that this is the most severe climate area existing in Portugal. The latitude of Bragança is 41º 48’ N, the longitude is 6º 46’ W, the average altitude is 692 meters (2270 feet) above sea level and the exterior temperatures vary from 36.2ºC to -6ºC. The climate file used in the analysis is available for download from the United States Department of Energy site [33].

4.5.4 Pattern of occupancy

All models were analysed using the same pattern of occupancy, shown in Table 12 for each compartments during weekdays (WD) and weekends (WE). These were based on the UK NCM (National calculation methodology – occupancy pattern for fractions) and on the Portuguese average occupancy of 1,8 persons per dwelling unit [9].

Table 12: Pattern of occupancy considered for the dwelling unit

	Bedrooms		**Living Room**		**Kitchen**		**Bathrooms**	
Hours	**WD**	**WE**	**WD**	**WE**	**WD**	**WE**	**WD**	**WE**
1	1	1	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0
4	1	1	0	0	0	0	0	0
5	1	1	0	0	0	0	0	0

6	1	1	0	0	0	0	0	0
7	1	1	0	0	0	0	0	0
8	0,5	1	0	0	0,5	0	0,5	0
9	0,5	0,5	0	0	0,5	0	0,5	0
10	0	0,25	0	0	0	0,5	0	0,5
11	0	0	0	0,1	0	0,5	0	0,5
12	0	0	0	0,1	0	0	0	0
13	0	0	0	0,1	0	0	0	0
14	0	0	0	0,1	0	0,5	0	0
15	0	0	0	0,1	0	0	0	0
16	0	0	0	0,1	0	0	0	0
17	0	0	0	0,1	0	0	0	0
18	0	0	0	0,25	0,5	0	0	0
19	0	0	0,75	0,25	0,5	0	0	0
20	0	0	0,75	0,25	0	0	0,1	0,1
21	0	0	0,75	0,25	0	0	0,1	0,1
22	0,25	0	0,75	0,25	0	0	0	0
23	0,5	0	0,5	0,75	0	0	0	0
24	1	0	0	0,5	0	0	0	0

4.5.5 Simulation Results

The mean air temperature for one compartment (bedroom 1) in each of the different analysed solutions was simulated. These first simulations did not consider the HVAC system. Since it is not accurate to conclude the variation of conditions in a year by choosing randomly a few days or weeks, it was selected the typical summer and winter weeks (Figures 31 and 32, respectively) that represents the average conditions for these seasons.

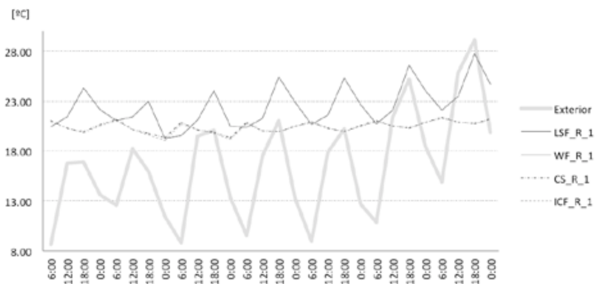

Fig. 31: Typical summer week thermal simulations for bedroom 1 from the analysed solutions

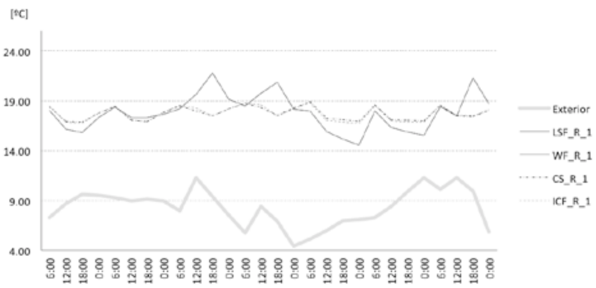

Fig. 32: Typical winter week thermal simulations for bedroom 1 from the analysed solutions

The building's energy consumption associated with the thermal comfort can be obtained by the heating and cooling needs for the winter and summer seasons, respectively. They represent a large proportion of the building's energy use through the year, even if necessary levels depend of occupancy rates, types of activity and equipment loads. But it is also important that the efficiency and capabilities of the system can influence the following results [31]. Also, the energy use and cost can clearly be controlled by the use of suitable insulation in exterior walls and roof of the building, where most of the thermal exchanges happen [34].

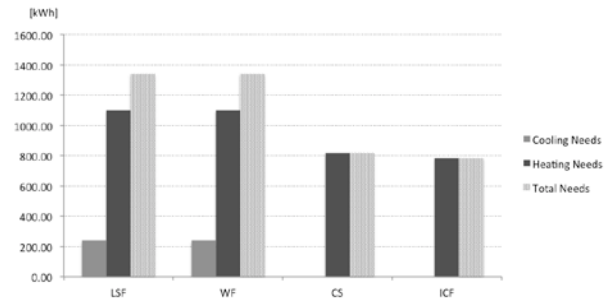

Fig. 33: Cooling and heating needs of the analysed solutions

Considering an electricity cost average for housing buildings of 0.2081€/kWh.year [35], it is possible to estimate the total economic cost of the analysed solutions (Table 13).

Table 13: Estimated economic costs of a dwelling with the analysed solutions

	Building Construction (€)	**Total Energy needs in 50 years (€)**	**Total costs (€)**
LSF	53.682,23	13.948,50	67.630,73
WF	42.386,61	13.948,51	56.335,12
CS	30.855,30	8.517,87	39.373,17
ICF	23.634,97	8.163,65	31.798,62

4.6 Statistical analysis

In order to better understand the variation of the results to the different constructive solutions a statistical analysis was done.

4.6.1 Non-structural partition walls

In the following table is presented the average, standard deviation and coefficient of variation for the construction time and environmental impacts.

Table 14: Statistical analysis to the construction time and environmental impacts of the non-structural partition walls

Solutions	Constr. Time (days)	Environmental impacts		
		GWP	AP	POCP
CS	9,2	3,01E+03	6,80E+00	4,54E-01
LSF	15,5	5,78E+02	2,40E+00	1,48E-01
WF	13,4	6,26E+01	1,16E+00	5,80E-02
Average	12,7	1,22E+03	3,45E+00	2,20E-01
Standard deviation	3,21	1,58E+03	2,96E+00	2,08E-01
Coefficient of variation	25%	129%	86%	94%

The average construction time of the non-structural partition walls is 12.7 days with a low coefficient of variation - 25%, in comparing to a very high variation of environmental impact to the different parameters tested, more than 85%.

The same statistical analysis is also presented in following table for the cost without and with transport.

Table 15: Statistical analysis to the economic aspects of the non-structural partition walls

Solutions	Economic without transport (€)	Number of heavy vehicles	500 km	4000 km	16000 km
CS	3 983,15 €	0,59	4 327,25 €	6 105,95 €	12 204,35 €
LSF	7 333,20	0,11	7 396,11 €	7 721,31 €	8 836,27 €
WF	6 576,25 €	0,11	6 640,02 €	6 969,63 €	8 099,75 €
Average	5 964,20 €	0,27	6 121,13 €	6 932,30 €	9 713,46 €
Standard deviation	1 756,89 €	0,28	1 598,88 €	808,32 €	2 188,39 €
Coefficient of variation	29%	103%	26%	12%	23%

On average the cost in Portugal is 5964,20€ and there is a cost variation of 29% among the constructive solutions studied. Regarding the number of vehicles used for transport the solutions there is a great variation, more than 100%, and the national average of heavy vehicles is 0,27. For distances of 500 km and 16000km the cost variation exceeds 20%, but for a distance of 4000 km the cost variance is 12% with an average cost of 6932,20 €.

4.6.2 Structural walls

In the following table is presented the average, standard deviation and coefficient of variation in terms of construction time and environmental impacts.

Table 16: Statistical analysis to the construction time and environmental impacts of the structural walls

Solutions	Constr. Time (days)	Environmental impacts		
		GWP	AP	POCP
CS	87,5	1,55E+04	5,84E+02	6,59E+01
LSF	20,8	-7,10E+02	2,43E+01	2,00E+00
WF	19,5	-8,15E+03	1,49E+01	1,52E+00
ICF	50,9	1,41E+04	7,46E+02	8,75E+01
Average	44,7	5,20E+03	3,42E+02	3,92E+01
Standard deviation	32,0	1,15E+04	3,78E+02	4,42E+01
Coefficient of variation	72%	222%	111%	113%

For the construction of the structural walls are needed on average 44,7 days, and the coefficient of variation to the four constructive solutions is 72%. There is a great variation in all parameters of environmental impact studied (greater than 100%), justified by the different values obtained at each constructive solution.

The same statistical analysis is also presented in following table for the cost without and with transport.

Table 17: Statistical analysis to the economic aspects of the structural walls

Solutions	Economic without transport (€)	Number of heavy vehicles	500 km	4000 km	16000 km
CS	17 636,48 €	3,3	19 551,52 €	29 450,65 €	63 390,50 €
LSF	28 243,37 €	0,4	28 459,98 €	29 579,65 €	33 418,54 €
WF	21 913,56 €	0,4	22 129,41 €	23 245,18 €	27 070,68 €
ICF	10 416,15 €	2,6	11 922,56 €	19 709,39 €	46 407,08 €
Average	19 552,39 €	1,68	20 515,87 €	25 496,22 €	42 571,70 €
Standard deviation	7 488,88 €	1,53	6 843,18 €	4 860,27 €	16 043,63 €
Coefficient of variation	38%	91%	33%	19%	38%

The average cost of the solutions to structural wall in Portugal is 19552,39 €, and there is a 38% variation in the cost of construction. The CS and ICF solutions require greater number of heavy vehicles for transport, 3.3 and 2.6, respectively. The cost variation for the distances 500 km and 16000 km is much higher than for 4000 km.

4.6.3 Slabs

In the following table is presented the average, standard deviation and coefficient of variation in terms of construction time and environmental impacts.

Table 18: Statistical analysis to the construction time and environmental impacts of the slabs

Solutions	Constr. Time (days)	Environmental impacts		
		GWP	AP	POCP
CS	29,2	9,16E+03	2,43E+01	4,91E+00
LSF	15,5	1,21E+03	2,23E+01	1,96E+00
WF	17,5	-6,65E+03	1,66E+01	1,74E+00
Average	20,7	1,24E+03	2,11E+01	2,87E+00
Standard deviation	7,37	7,90E+03	3,98E+00	1,77E+00
Coefficient of variation	36%	639%	19%	62%

For the slabs were only studied three constructive solutions. In Portugal is necessary on average 20.70 days to build a slab with 144 m^2. The coefficient of variation of the construction time of the three slabs is 36%. The environmental impact GWP has a coefficient of variation greater than 600%, justified by LSF and WF solutions use materials from renewable sources, such as wood. In others parameters - AP and POCP - the variation is not significant, 19% and 62%, respectively.

The same statistical analysis is also presented in following table for the cost without and with transport.

Table 19: Statistical analysis to the economic aspects of the slabs

Solutions	Economic without transport (€)	Number of heavy vehicles	500 km	4000 km	16000 km
CS	9 235,67 €	1,9	10 341,88 €	16 060,00 €	35 665,02 €
LSF	18 105,66 €	0,4	18 308,10 €	19 354,52 €	22 942,28 €
WF	13 996,80 €	0,4	14 219,98 €	15 373,66 €	19 329,11 €
Average	13 779,38 €	0,89	14 289,99 €	16 929,40 €	25 978,80 €
Standard deviation	4 438,99 €	0,90	3 983,57 €	2 128,08 €	8 580,84 €
Coefficient of variation	32%	101%	28%	13%	33%

The average cost for a slab with 144 m^2 is 13779,38 €, i.e. 95,69 €/m^2, and coefficient of variation of the solutions studied is 32%. Are required on average 0.89 heavy vehicles for the transport and the coefficient of variation is greater than 100%, justified by the weight difference between the conventional solution and the lightweight solutions, i.e. LSF and WF. The variation of cost for the distance 4000 km is reduced - 13%, and for the remaining distances, 500 km and 16000 km, the coefficient of variation is 28% and 33%, respectively.

4.6.4 Global

The partition walls, structural walls and slabs were analysed individually. However it is also important to consider the global construction time, overall cost and global environmental impact for the four constructive solutions studied.

In the following table is presented the average, standard deviation and coefficient of variation for the construction time and environmental impacts.

Table 20: Statistical analysis to the construction time and environmental impacts of the global solutions

Solutions	Constr. Time (days)	Environmental impacts		
		GWP	AP	POCP
CS	119,0	2,77E+04	6,15E+02	7,13E+01
LSF	36,0	1,08E+03	4,90E+01	4,11E+00
WF	37,0	-1,47E+04	3,27E+01	3,32E+00
ICF	79	2,63E+04	7,77E+02	9,29E+01
Average	67,8	1,01E+04	3,68E+02	4,29E+01
Standard deviation	39,61	20581,31	384,10	46,09
Coefficient of variation	58%	204%	104%	107%

The average construction time of a dwelling with 144 m^2 is 67.8 days, with a coefficient of variation higher than 58%. The variation of the environmental impact to all parameters studied is greater than 100%.

A similar statistical analysis is also presented in following table for the cost without and with transport.

Table 21: Statistical analysis to the economic aspects of the global solutions

Solutions	Economic without transport (€)	Number of heavy vehicles	500 km	4000 km	16000 km
CS	30.855,30 €	4,5	34.220,65 €	51.616,61 €	111.259,87 €
LSF	53.682,23 €	0,7	54.164,19 €	56.655,49 €	65.197,09 €
WF	42.486,61 €	0,8	42.989,41 €	45.588,47 €	54.499,54 €
ICF	23.634,97 €	3,4	26.591,69 €	41.875,34 €	94.276,45 €
Average	37.664,78 €	2,35	39.491,48 €	48.933,98 €	81.308,24 €
Standard deviation	13.203,70 €	1,90	11.856,22 €	6.527,76 €	26.099,49 €
Coefficient of variation	35%	81%	30%	13%	32%

The average cost without transportation is 37,664.78 € and the variation among the four constructive solutions is 35%. The constructive solutions ICF and CS require a greater number of vehicles to be transported, 4.5 and 3.4, respectively.

5 Conclusions

This study analysed different constructive solutions in four parameters: construction time, economic costs, environmental impact and energy performance. There was no solution proved to be effective in the three parameters. The construction time for the LSF and WF solutions stands out as the most effective, allows to build the house presented in the study in less than 40 days.

Solutions using concrete, such as the conventional and the ICF present longer construction times, as these require concrete to be cured.

In terms of construction cost, heavy solutions are less expensive when compared to LSF and WF solution, being the smallest the ICF solution, with 157€/m^2.

The total cost of construction results from the sum of the cost of construction and materials, plus the cost of transporting materials. The greater the weight and volume of constructive solution the higher is the cost of transport.

Despite that conventional and ICF solutions require greater number of vehicles compared to LSF and WF solutions, these only cease to be competitive for distances greater than 2000km for the conventional solution and distances exceeding 8000km for the ICF solution because the cost of construction is well below the LSF and WF solutions.

The comparison between solutions shows that the solution with the best environmental indicators is the WF solution, which presents an average of 50% reduction on the environmental parameters evaluated in relation to the conventional solution.

The poor environmental performance during construction of conventional system and heavy ICF is mainly associated with the large amount of steel and concrete used. However, these solutions present a better thermal performance, with reduced costs related to comfort maintenance.

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