Environmental impact and comparative economic analysis among different building constructive systems used in Portugal

FRANCISCO OLIVEIRA[1a], PAULO MENDONÇA[2b], JOÃO PEDRO COUTO[1c], AIRES CAMÕES[1d]
[1]School of Engineering, [2]School of Architecture
University of Minho
Azurém Campus, P - 4800-058 Guimarães
PORTUGAL
[a]francisco.oliveira.afo@gmail.com, [b]mendonca@arquitectura.uminho.pt, [c]jpc@civil.uminho.pt, [d]aires@civil.uminho.pt

Abstract: - The choice between different materials and constructive systems can influence significantly the environmental impact and cost of construction. In this context, four constructive systems used in Portugal were studied: one conventional - composed by brick walls and steel reinforced post and beam concrete slabs; 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 typical 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 sector of construction has great importance for economy, being responsible for the generation of capital and employment. However, it is also a sector that is associated with significant environmental impacts. 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 Portugal in terms of economic costs, considering the cost of materials, shipping cost and labor cost. The four structural systems studied were defined for a current typology of a single family housing dwelling: conventional (hollow brick and concrete post and beam); light steel framing (LSF); wood frame (WF); insulation concrete form (ICF). All systems were analyzed without finishing materials, as these were assumed as equal.

The analyzed 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 [1].

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

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

2 Description of the case-study

According to statistic data, the type T3 dwelling is the most frequent typology in Portugal (about 57%) [2]. This type of housing is usually suitable for a household consisting of 3 to 4 people and has a area of 144m^2 resultant from the association of 4 square shaped modules of 6 x 6m.

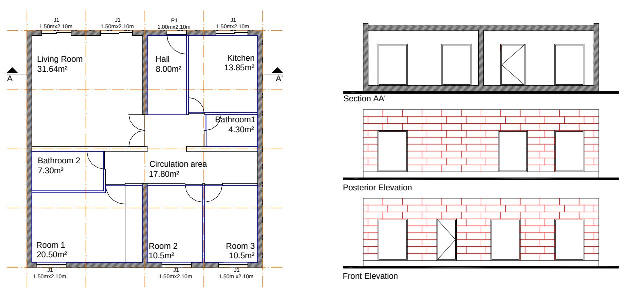

Fig. 1: Reference typology used for the case study.

3 Procedures in the structural design

The conventional, LSF, WF and ICF systems were analyzed in relation to its ultimate limit state and service limit state resistances, considering a similar behaviour to a shear wall. The calculation was performed using modal dynamic analysis and the determination of the response of the structure 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 [3].

According to Eurocode [4], 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.

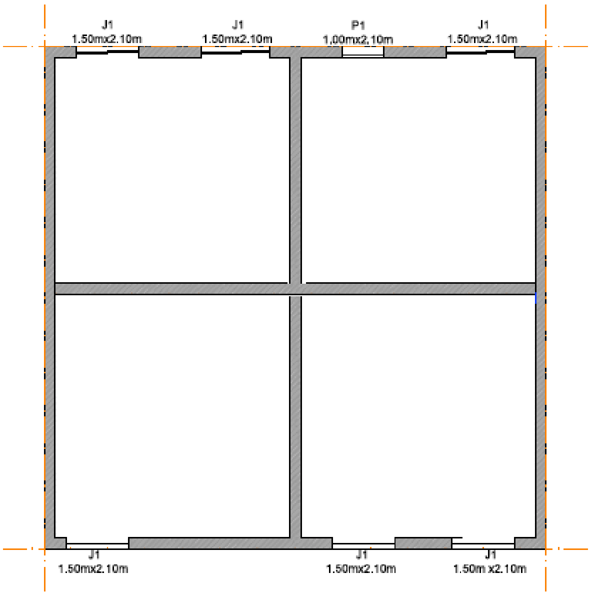

Fig. 2: Structural plant

The whole procedure of structural design and verification of safety was conducted considering the Eurocode [3] [4].

In LSF, WF and ICF systems, the walls have capacity to support efforts, so in reference typology used for the case study it was considered five resistant walls as shown in Fig.2 In conventional constructive solution, masonry walls don’t have carrying capacity, so it was needed to include columns and beams to support the loads.

4 Presentation of constructive solutions analyzed

The structural solutions analyzed are made up of walls and/or other vertical resistant elements and slabs. The conventional structural solution is composed by a steel reinforced concrete post and beam system. This include external double walls of hollow brick (15cm + 11cm) with extruded polystyrene insulation inside the air gap (Fig.3A) and roof in girder-slabs with ceramic flooring block interjoist (Fig.3E).

The structural solution LSF uses cold-formed steel profiles in structural walls and slabs (Figs.3B and 3F, respectively) and OSB boards mechanically fixed to the steel profiles. As insulation material is usually used rock wool with a density of 70kg/m^3.

The WF solution only differs from LSF in the use of wooden elements instead of steel profiles (Figs.3C and 3G).

In the ICF structural system (Fig.3D), there is no specific type of slab associated, however, it was chosen a conventional slab type (Fig.3E) in order to ensure the thermal inertia of the housing and also represents the option with lower cost

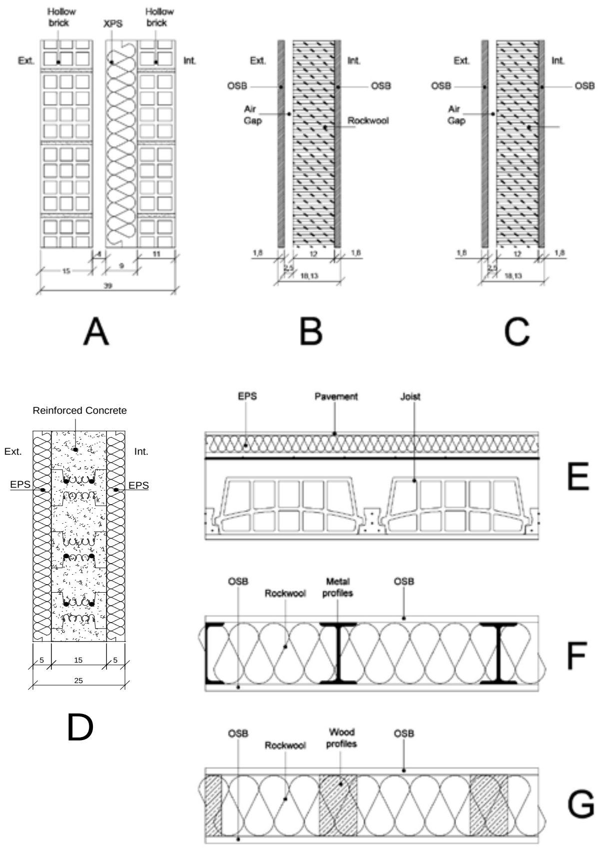

Fig. 3: Constructive solutions section detail.

The secondary partitions do not need to have structural capacity or thermal properties, so these differ from exterior walls and the structural walls that separate the 6x6m modules.

So, for each kind of constructive solution a corresponding diving wall was chosen. The conventional solution was calculated using the

ISBN: 978-960-474-391-9

hollow brick wall (11 cm) (Fig.4A). The LSF solution uses a partition wall with steel profiles and plasterboard (Fig.4B). The WF solution (Fig.4C) also uses plasterboard as the LSF however the metal profile are replaced by wood. The ICF solution was calculated both with hollow brick (11cm) as well as plasterboard with steel profiles.

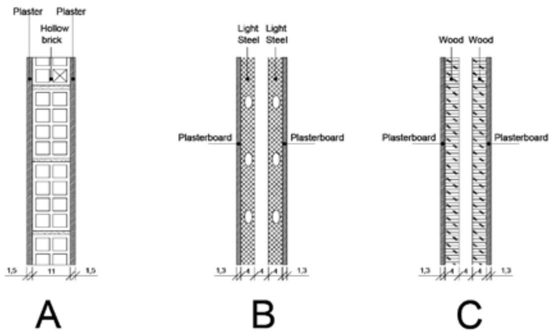

Fig. 4: Constructive solutions dividing wall

For allowing a comparison in equal circumstances, the same overall heat transfer coefficient (U-value) was fixed for all solutions.

This value was chosen by considering the Portuguese regulation demands for 2015 and beyond, who sets maximum permitted U-values for the vertical and horizontal opaque elements for the different climatic zones, in this case it was considered the most demanding in winter, the I3 [1].

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 1.

Table 1: Thickness of insulation and heat transfer coefficient

	Vertical elements (Walls)		**Horizontal elements (Slabs)**	
	Insul.	U ($W/m^2.ºC$)	Insul.	U ($W/m^2.ºC$)
Conventional	XPS 90mm	0,30	XPS 120	0,24
LSF	RW 110mm	0,30	MW 130mm	0,25
WF	RW 110mm	0,29	MW 130mm	0,25
ICF	EPS 200 100mm	0,30	XPS 120	0,24

5 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, regarding construction time, economy and environmental impact.

5.1 Construction time

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 solutions [5,6].

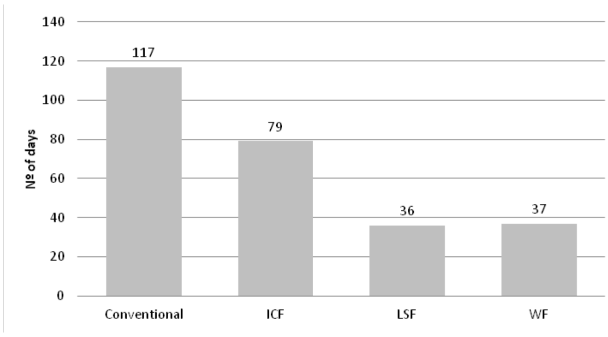

Fig. 5: Construction time of the solutions

As it is possible to observe in Fig.5 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.

5.2 Economic analyses

The economic cost of dwelling results from the sum of various costs of materials, cost of labor, and cost of equipment needed to support the construction.

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

To compare all solutions was assumed that all materials are transported by road with heavy vehicles. Thereby, it is necessary considered the maximum capacity that can be carried by each heavy vehicle; in this case it was considered that each heavy vehicle carrying a maximum bulk of 67m3 and a weight of 26.500 kg.

According to National Road Carriers Association of Public Goods Portuguese [7], the reference price per km for the first half of 2014 for the transport 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).

Table 2 and Table 3 present the total weight and bulk of each material for each constructive solution as well as the respective cost construction [5,6,8].

Table 2: Quantities (kg and m^3) and cost construction for ICF and conventional solution

Materials	**Conventional**		**ICF**	
	Bulk (m^3)	**Weight (kg)**	**Bulk (m^3)**	**Weight (kg)**
Concrete	22,5	49522,0	26,9	59287,5
Steel	1,9	1983,0	3,7	3793,8
Girder-slabs	2,1	5225,5	2,1	5225,5
Joist	22,1	12181,0	22,1	12181,0
XPS	29,1	945,9	17,3	561,6
Mortar	10,3	20567,7	3,7	7418,6
Brick 30x20x11	29,9	17662,3	12,2	239,4
Brick 30x20x15	20,1	11615,8		
Eps 200			26,1	940,6
Sum	138,0	119703,2	114,1	89648,0
Cost Sum (€)	30 855,30 €		22 634,97 €	
Cost (€/m^2)	214,27 €		157,10 €	

Table 3: Quantities (kg and m^3) and cost construction for LSF and WF

Materials	**LSF**		**WF**	
	Bulk (m^3)	**Weight (kg)**	**Bulk (m^3)**	**Weight (kg)**
Profiled steel	7,9	7406,6		
OSB	5,4	4404,6	5,4	4404,6
Rockwool (70kg/m^3)	33,1	2239,2	33,2	2239,3
Lumber			10,9	9229,7
Plasterboard	1,4	1995,8	1,4	1995,8
Sum	47,8	16046,2	50,9	17869,4
Cost Sum (€)	53 682,23 €		42 486,61 €	
Cost (€/m^2)	372,79 €		295,06 €	

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, it was determined the number of vehicles required to transport each constructive solution (Fig. 6).

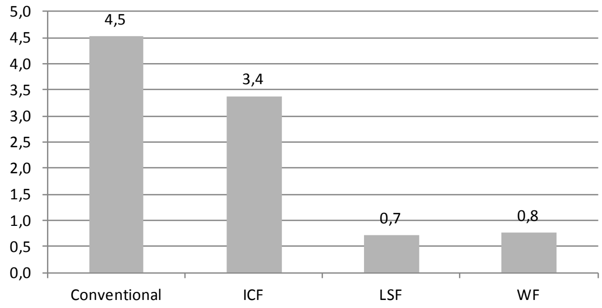

Fig. 6: Number of heavy vehicles need for transportation construtive solutions

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, Total cost represents the sum of the cost construction with cost of transport. The following figure represents the variability of the sum of the cost construction with cost of transport in function of transport distance (km) for each constructive solution.

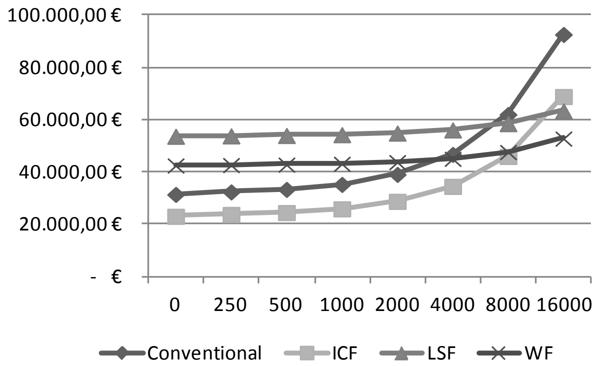

Fig. 7: Sum of the cost construction with cost of transport

By analyzing the graph you can see that the ICF solution is economically competitive with up to a maximum distance of 8000km from the factory to the building site, after which the WF solution has a lower cost.

The heavy solutions require a greater number of vehicles for transportation, so there is a greater variation in transport costs when the distance increases comparatively to LSF and WF solutions.

ISBN: 978-960-474-391-9

5.3 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) [7]. For this study, GWP (Fig.8A), AP (Fig.8B) and POCP (Fig.8c) values in gr of construction material were converted into total kg in the 144m^2 gross areas of the case study dwelling.

Fig. 8 presents the environmental assessment indicators comparison graphs for the constructive systems analyzed.

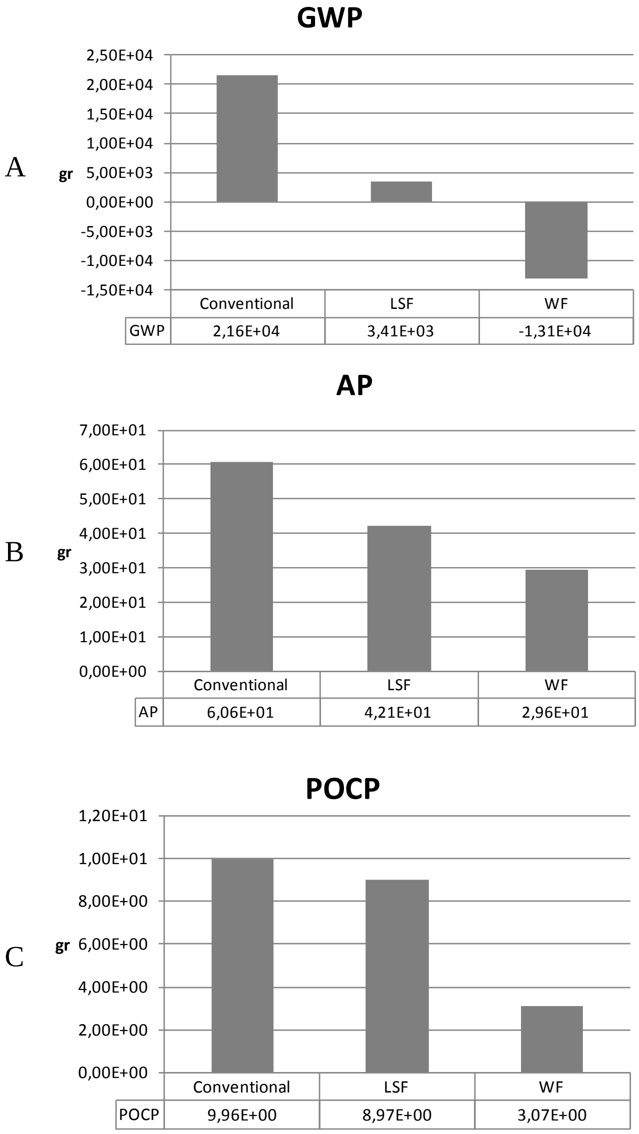

Fig. 8: Environmental assessment indicators

As it would be expected, the WF wall solution is the best solution at the environmental level, being even 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.

6 Conclusion

This study analyzed different constructive solutions in three parameters: construction time, economic costs and environmental impact. There was no solution which proved to be effective in the three parameters. The construction time for the LSF and WF solutions stand out as the most effective, allowing 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 requires concrete to be cured.

In terms of construction cost, heavy solutions are less expensive 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 of conventional systems and heavy ICF is mainly associated with the large amount of steel and concrete used. However, one must not forget that these solutions contain steel that can be 100% recycled, therefore, in an analysis of life cycle from cradle to gate the result could be more positive for these solutions.

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ISBN: 978-960-474-391-9

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ISSN: 2227-4359
ISBN: 978-960-474-391-9

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Published by WSEAS Press
www.wseas.org

All papers of the present volume were peer reviewed by no less that two independent reviewers. Acceptance was granted when both reviewers' recommendations were positive.

ISSN: 2227-4359
ISBN: 978-960-474-391-9