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TECHNICAL NOTE

LIFE CYCLE OPTIMIZATION OF A LIGHTWEIGHT STEEL BUILDING: EFFECT OF DIFFERENT INSULATING LAYERS, GLAZING TYPE AND WINDOW SHADING

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Abstract: In recent years, life cycle assessment has become an important tool for determining the environmental impact of materials and products. It is also useful in analysing the impact of a building structure has over the course of its life cycle which includes production of materials, transport, construction, operation, end of life. This paper is intended to provide a life cycle analysis of a building located in Coimbra, Portugal. To achieve the effect of different insulation layers, glazing type and window shading, two different solutions were analysed. In order to compute the thermal transmittance U-values for the walls and roofs, Therm5 software was used, so as to account for the effect of thermal bridges induced by the steel framework. These values were then introduced in the building model, which was designed in the software DesignBuilder, in order to compute the thermal behaviour of the building. Finally, the values of the energy consumption for a period of 50 years were introduced in the life cycle analysis made in the GaBi software. This allowed estimating the impact of both solutions and providing conclusions as to which is the best solution.

Keywords: *Sustainability, life cycle optimization, environmental impact, energy consumption*

1.0 Introduction

Building structures represent a huge investment in terms of materials and energy and they lead to significant environmental impacts. Nowadays' society is getting more and more concerned by the impacts of the human on its environment. In a world where resources are becoming scarce and societies are realizing that the conveniences of modern life have a serious impact on the environment, it is becoming more important to analyze engineering designs and find ways to reduce humankind's environmental burden (Sartori & Hestnes, 2007). Towards the challenges of sustainable development and durability, we need to evaluate the environmental impacts of our decisions and develop structured ways to think about the environment. Businesses, policy-makers, public authorities, industries need to have environmental tools that help them during the decision-making process to choose the most environmentally-friendly alternative (Finnveden & Nilsson, 2005). Buildings consume approximately 40% of all the energy we use. Considering the total energy consumption throughout the whole life cycle of a building, the energy performance and energy supply is an important issue in the concern about climate changes, security of supply and reduced global energy consumption (Cole *et al.*, 1996). The worldwide CO2 emission mitigation efforts, the growing energy resource shortage and the fact that buildings are responsible for a large share of the world's primary energy use drives research towards new building concepts (Jönsson *et al.*, 1998) . The initial cost of can be higher than the cost of a conventional building because low energy consumption is attained by more energy efficient solutions and constructions (walls, roof, floors, windows, heating and ventilation system), and utilization of green technologies (solar panels, solar cells, heat pumps, etc.). However, these added costs are offset by savings in primary energy, and by production of renewable energy. It is therefore important to calculate the total costs and savings during the design phase (construction costs) and the operation phase (running costs) (Venkatarama & Jagadish, 2003). People spend 90% of their time indoors, but less than 30% of the building mass contributes to or provides a healthy indoor climate. Humans need comfortable conditions including thermal conditions, fresh air and daylight when they are indoors. These factors have a positive effect on our health and well-being as well as our ability to perform (Prek, 2004). Although the challenges we face are global, the local environment which always has unique features must be considered carefully.

The design takes into consideration a life cycle assessment evaluation, local building traditions and local construction materials, waste, water and infrastructure. The materials used have a minimum impact on the environment and the use of reusable materials (Citherle *et al*., 2000). The aim of this article is the life cycle optimization of a light-weight steel house and the optimization of the constructive solutions takes into consideration the following conditions: Minimization of the operational energy of the house over its life cycle; Minimization of life cycle environmental impacts; and Minimization of life cycle costs.

2.0 General Description of the Location and the Building

In this work it is considered that the building is situated in Coimbra, Portugal. The main dimensions of the building in plane are (12.30*9.30) m^2, each floor is approximately 2.65 m high and the slope of the roof is 0°. The dwelling orientation (main facade) is south. The structural skeleton is made of light-gauge C150 shaped profiles spaced 600 mm and the thickness of the profiles is 1.5 mm. The height of the profiles governed the thickness of the exterior walls. The partition walls are made of C90 profiles at 600 mm. The slabs of the building are defined by C200 spaced 600 mm in order to verify serviceability limit conditions. The contour beams of the structural skeleton are defined by 2C250 shaped profiles and 4U155 or 3U155 in order to have flexural resistance in both planes. The walls are considered to be stiffed with Oriented Strand Board (OSB) panels of 18 mm thickness located on both sides of the structural walls. The design of the floors is based on the principle of the resistance defined by the OSB panels. These buildings have a total internal net space of 130 m^2. The ground floor is composed by a living-dining room, a kitchen, one bathroom, corridor/stairs and an opened garage. The first floor has 3 bedrooms, 2 bathrooms and corridor/stairs.

Figure 1: Ground floor and 1st floor plan

In case of climate, Coimbra has a warm Mediterranean, dry-summer subtropical climate that is mild with dry, warm summers and moderate seasonality. The mean temperature is 15.7 degrees Celsius (60.3 degrees Fahrenheit). Average monthly temperatures vary by 11.8 °C (21.2°F). This indicates that the continentally type is oceanic, subtype truly oceanic. In the winter time records indicate temperatures by day reach 14.7°C (58.5°F) on average falling to 6.2°C (43.2°F) overnight. In spring time temperatures climb reaching 19.7°C (67.4°F) generally in the afternoon with overnight lows of 8.9°C (48°F). During summer average high temperatures are 27.6°C (81.6°F) and average low temperatures are 14.6°C (58.3°F). *(Source: http://www.coimbra.climatemps.com)*

3. 0 Determination of Thermal Transmittance (U-Value)

For the determination of the U-values of the exterior walls, interior partition walls and roofs, THERM software is used in order to more accurately compute the influence of the light steel frames. For the exterior walls and roof two solutions were analyzed. The description of those layers and their respective thicknesses for the two solutions are explained below.

The difference between the two solutions consists in the thickness of the layer of mineral wool, which constitutes the insulation layer for these elements. In solution 1, the mineral wool layer is 60mm thick, and there is a layer of air with 90mm, whereas in solution 2, the mineral wool layer is thickened, in order to occupy the space of the layer of air, thus resulting in an insulation thickness of 150mm.

In terms of the interior partition walls, only one solution is considered, since it is considered that these elements carry no significant influence in the global thermal behavior of the building.

For the roofs, two different solutions are also considered, with two different insulation thicknesses. For solution 1, a thickness of mineral wool of 100mm is considered, along with a layer of air with 100mm, whereas for solution 2, a thickness of insulation of 200mm is considered. In Figure 2, the layer configurations for solutions 1 and 2 for the roofs are presented.

The geometry of the above described elements was drawn and later imported to the THERM software, where the materials were assigned to their respective layers, thus enabling to perform the calculation of the U-values.

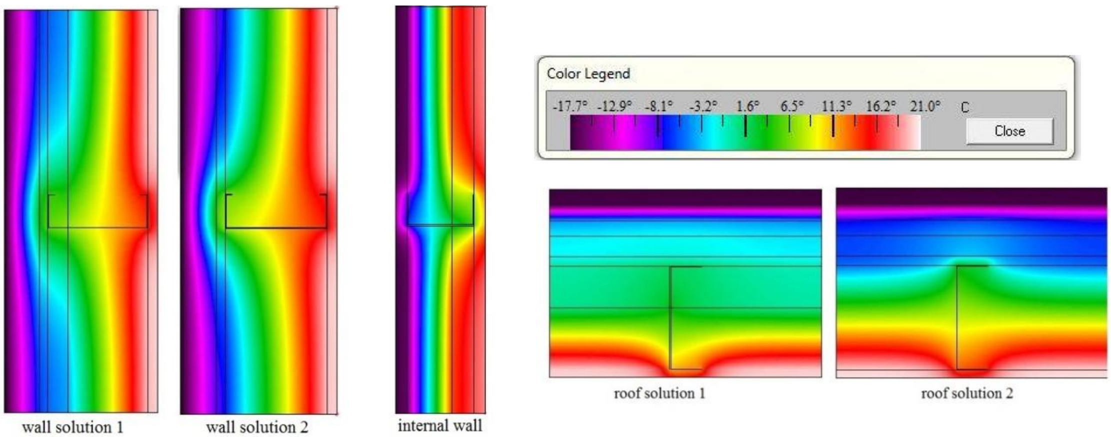

Figure 2: Temperature variation through wall and roof from Therm-5

The values obtained for the U-values in Therm5 software are presented in Table 1.

Table 1: U-values from Therm-5

Element	U-value
-	W/m^2K
External wall - Solution 1	0.3876
External wall - Solution 2	0.2629
Internal Partition Wool	0.7696
Roof - Solution 1	0.3874
Roof - Solution 2	0.2551

4.0 Determination of the Annual Energy Consumption

For the determination of the annual energy consumption of the building, the software DesignBuilder is used, so as to account for the global thermal behavior of the building. The thermal behavior was simulated by attributing to the relevant construction elements the respective U-values, previously computed in the Therm5 software and presented in **Error! Reference source not found.**. For this analysis, it is also assumed that the building is located in Portugal, and that the main façade is facing east. In order to determine the influence of each option with regard to the thermal behavior, two scenarios are defined and compared in terms of energy consumption. The considered scenarios are presented in Table 2.

Table 2: Scenario description for thermal behaviour analysis

Scenario	1	2
Description	Solution 1 for external walls Solution 1 for roofs 1.0m overhangs Double clear 6mm/13mm air glazing (U = 2.761 W/m^{2}K)	Solution 2 for external walls Solution 2 for roofs Outside window medium opaque shade roll Triple Low Emissivity glazing (U = 0.786 W/m^{2}K)

For the cooling mode, a CoP of 3 is assumed for the HVAC system, alongside with temperature set point 25ºC, and set back temperature of 50ºC. In terms of the heating mode, a CoP of 4 for the HVAC system is taken for calculations, as well as a set point temperature of 20ºC and a setback temperature of 15ºC. The scenarios are firstly calculated on DesignBuilder, and compared in terms of energy consumption for the summer and winter design weeks, assuming a passive thermal behaviour, i.e., without HVAC cooling or heating. In Figure 3(a) and 3(b), an assessment of the comfort level is presented for scenarios 1 and 2 for the design winter week and summer week respectively.

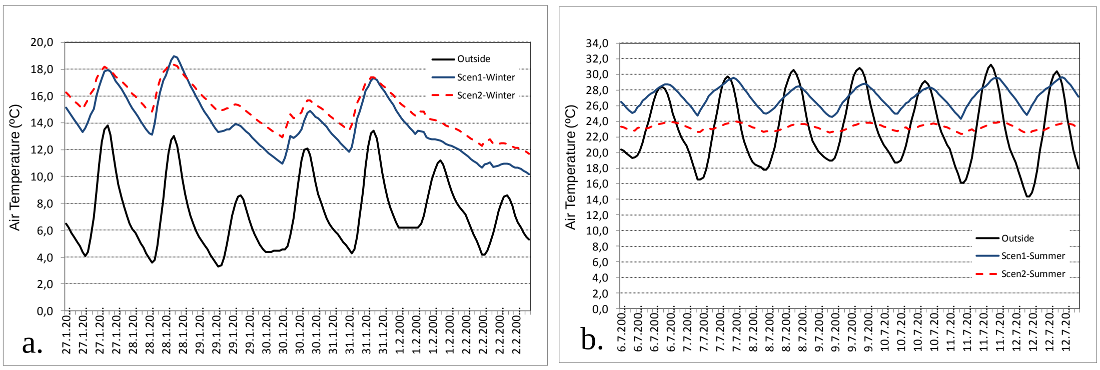

Figure 3: Inside temperatures for the design winter and summer weeks for scenarios 1&2

It can be seen from Figure 3, for the winter week, the inside temperatures are in general higher for scenario 2, which indicates a greater level of comfort for the users. The inside temperatures for the summer design week for scenarios 1 and 2 are presented in Figure 3(b). And for the summer week, the inside temperatures are in general lower for scenario 2, and present also smaller thermal amplitudes, which constitute a measure of comfort for the users. An annual simulation is also performed for both scenarios, in order to determine the differences in energy consumption. The obtained values for each scenario are presented in Table 3.

Table 3: Annual energy consumption for scenarios 1 and 2

Scenario	Annual energy consumption (kWh)		
	cooling mode	heating mode	Total
1	714	4629	5343
2	32	3821	3853

This indicates that when considering just the building energy performance, solution 2 is clearly better. However, to ascertain as to full impacts of this solution, a life cycle analysis must be performed on both solutions.

5.0 Life Cycle Analysis

In order to perform a life cycle analysis of the light weight steel house, several stages of the global process are modeled in the software GaBi. The global process was divided three simple phases: Construction, Operation and Demolition.

5.1 Construction

For the Construction phase, the relevant materials for the construction of the house are taken into account and quantified. The quantities considered for the analysis are the ones shown in Table 4.

Table 4: Material quantities

Material	Steel in sections	Steel in rebar	Concrete	EPS	Linoleum	Gypsum plaster	OSB	Rock wool
Quantity (kg)	5112	-	-	30	798	4356	4637	2020

These described materials constitute are the inputs for the construction process in life cycle analysis. The modeling for the Construction phase in GaBi is displayed in Figure 4.

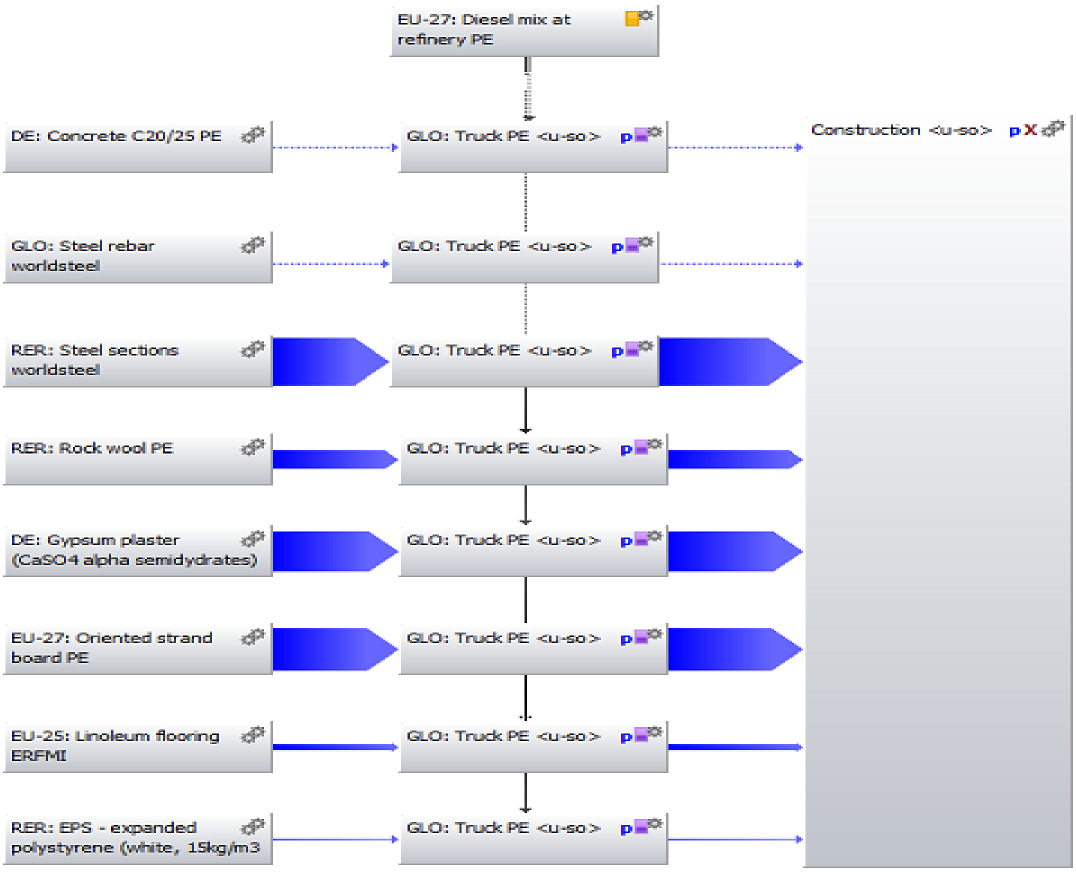

Figure 4: Construction phase with transportation in software GaBi.

Beside materials constitute in the inputs for the construction process, the transportation impacts were also considered for the analysis. This is done by introducing flows which correspond to the transportation of the several materials to the construction site, and by considering the expenditure and impacts of fuel for said transportation. From the construction process, a new parameter *Const_Output* is introduced, in order to simulate the output of this phase, which will in turn be the input for the next phase. This parameter is composed of the sum of all the above described materials that went into the construction of the house.

5.2 Operation

For the Operation phase, in a simplified way, a total of three inputs were considered for the process. These are the paint needed for the maintenance of the house along its lifetime, the electricity for current consumption along the house's lifetime and the parameter *Const_Output* from the construction phase. The electricity input considered for this stage corresponds to the energy needs for a period of 50 years. This is calculated from the annual consumption rate value which was calculated previously on the DesignBuilder software. As for the paint input, it represents the expenditure in maintenance of the building over its lifetime. The value for the amount of paint was calculated by estimating the amount of paint needed to paint the exterior of the house once every ten years. As outputs for the Operation process, only the parameter *Const_Output* was considered.

5.3 Demolition

For the Demolition phase, one input was considered for the process, which is the output parameter of operation phase *Const_Output*. For this part of the analysis, it is considered that all the materials with the exception of the steel in sections would go to the landfill. The steel in sections would be subject to a recycling process.

5.4 Life Cycle Analysis

The whole lifecycle of the house is considered throughout a model that links the previously described Construction, Operation and Demolition phases. The output of each phase constitutes the input for the following phase. The process is shown in the Figure 5.

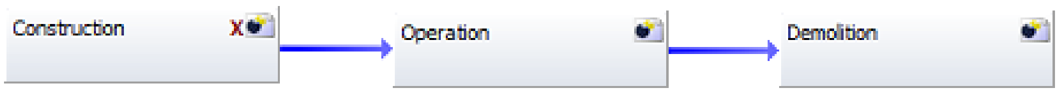

Figure 5: Model for the Life Cycle of the Building

5.5 Scenario Impact Comparison

In order to compare the impacts caused by the two scenarios considered, a life cycle analysis was performed to quantify the emissions and resource expenditure. The data for the two scenarios is presented in Table 1, in energy consumption given for the heating model.

Table 1: Life cycle impacts for scenarios 1 and 2

Description	Scenario 1	Scenario 2
Resources (kg)	1.82E8	1.51E8
Emissions to air (kg)	2.31E6	1.93E6
Emissions to fresh water (kg)	1.84E8	1.52E8
Emissions to sea water (kg)	1.35E4	1.12E4
Emissions to agricultural soil (kg)	0.00894	0.00778
Emissions to industrial soil (kg)	64.6	64.4

The values presented in the Table 5 show that for all categories, the scenario 2 presents lower environmental impacts, which are due to the lower energy consumption. It can be thus concluded that this is the most sustainable design solution for the building.

6.0 Conclusion

About the two scenarios in comparison, the second scenario has the most favorable environment performance as expected. It happened because of the increased rock wool layers on walls and floors for the second solution in order to improve the structural solution. This is also because of not using any overhang in window for sun shading and using triple layer glazing with low u-value for less heat transfer. The energy consumption was reduced from the scenario 1 to scenario 2 in all the parameters: Resources (kg), Emissions to air (kg), Emissions to fresh water (kg), Emissions to sea water (kg), Emissions to agricultural soil (kg) and Emissions to industrial soil (kg). So, the scenario 2 is the better in all the all aspect of sustainability. Finally the environmental impact of a building through its lifetime is related with the type of material used in insulation, window shading and glazing type. So while designing a building, everyone should make a parametric study of different construction material in life cycle analysis to determine the best solution having less environmental impact.

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