COMPARATIVE LIFE-CYCLE ASSESSMENT OF A SINGLE-FAMILY HOUSE: LIGHT STEEL FRAME AND TIMBER FRAME

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ABSTRACT

From a sustainability point of view, timber and light steel framing may represent practicable alternatives to concrete structures, due to its lighter weight when comparing with concrete or other common structural systems. This paper presents a "cradle-to-grave" life-cycle assessment for a single-family house built in Kiruna (Sweden), comparing two structural systems: timber frame and light steel framing. Environmental and economical performance was assessed for a 50-year life-span. Environmental assessment showed that steel-frame represents a 41% higher impact on Human Health and 6% higher on Acidification. Economical assessment showed that the life-cycle cost increases 2% for the light-steel option, being the future costs with energy 6% higher than the timber-frame solution.

1. INTRODUCTION

Wooden construction is empirically known for its sustainability. When performing a life-cycle analysis (LCA) of wooden buildings, it must be considered that trees store carbon dioxide in their tissues, in amounts that will only be released by decay or combustion of wood. This wood feature is highlighted on long lifespan wood-based products, among which are the main construction industry materials [1]. Forestry industry has social and economic importance in many regions of the world. Besides that, it also contributes to control soil erosion, helps to regulate the climate and has a decisive role in efficient water cycle and on biodiversity of wildlife and flora [2]. Moreover, wood is a material that requires a relatively low processing power to be prepared for building industry, unlike most building materials [3]. On the other hand, it can be assumed that the transformation process of wood produces virtually no waste, since all the production residues can be used for production of wood-based products or fuel, decreasing the demand for fossil fuels [3]. Although wooden constructions need maintenance throughout its lifetime, the common wooden building systems allow partial replacement of modules or damaged elements, without compromising the entire structure. The use of wood also contributes to the energy efficiency of buildings, since it is a material with low thermal conductivity. When dismantling a wooden building, the recovered wood can be directly reused in another building, used as raw material for wood-based products, or simply used as biofuel. On landfill, wood is biodegradable and does not constitute any kind of environmental threat, although both combustion and decomposition of wood cause the release of the stored CO_2 back to the atmosphere [4]. However, wood is a combustible material. For that reason, some European countries don't allow its deposition on landfill. In these cases, wood residues have necessarily to be burned as biofuel or reprocessed in new products manufacturing [6]. Countries like Sweden, that restrain the landfill of wood, use its residues to generate district heat and electricity, reuse it directly as solid wood, use it as raw material to the production of particleboard, or pulp it to form paper products [6]. This study aims to assess the advantages of using timber-frame, comparing with light-steel frame structural system, to small-scale buildings, like single-family urban houses.

2. LCA APPLIED TO TIMBER BUILDINGS

LCA methodology, as prescript by ISO 14040 standard [5], is not particularly directed to buildings assessment. It was designed to assess the sustainability of general products throughout its lifetime, at first in an environmental perspective, but more recently also in social and economical perspectives [6].

One can find some applications of that methodology to timber buildings, like [6] who compared three different structural materials for the same house (timber, concrete and light steel framing), concluding that the timber solution achieved a better score for all the categories under analysis. Buchanan [4] and Sathre [3] show that timber buildings take greater advantage in the low energy processes required to its manufacture, than on the carbon storage itself, considering the whole life-cycle. Borjesson & Gustavsson [7] compared greenhouse gas emissions between timber and concrete solutions for a Swedish building, concluding that the timber option decreases Greenhouse Gas (GHG) emissions from 2 to 3 times, assuming that wood waste and logging residues are used to replace fossil fuels. More recently, Nassén [7] compares the use of concrete versus wood in buildings, from the energy system perspective, concluding that is not clear that the use of wood is a cost-effective option for carbon mitigation, recommending further studies on this subject.

This paper presents a "cradle-to-grave" life-cycle assessment for a single-family house built in Kiruna (Sweden), comparing two structural systems: timber frame and light steel framing. Environmental and economical performance was assessed for a 50-year life-span.

3. CASE STUDY

A single-family 180 square-meter house, built to provide shelter to 4 people during a 50-year period was considered in this study. The building's area is divided in two floors and all the façades are external, as far as the house is isolated on the building site. It was assumed that the house is located in Kiruna, Sweden, with its main facade turned south. Figure 1 presents the plain views of the floors and the four lateral views.

The climate in Kiruna is typically polar, with persistent winds, freezing temperatures throughout the year that reach -30ºC, with great duration of night periods during the heating season. The incident solar radiation is very low during the months of October to February and throughout the month of December.

The cooling Season in Kiruna gives the opportunity to obtain significant solar gains in buildings, because the days during the month of June starting at 3 a.m. and end at 20 p.m. (17 hours of sunlight), although the incident energy is low due to the high latitude. The maximum peak temperature registered in Kiruna has been around 23°C in June, however, the maximum hourly average is only 15.4°C during July.

The temperatures of the ground are extremely low and negative for about 7 months of the year, which emphasizes the importance of heat losses trough construction elements in contact with the ground, to the buildings thermal performance.

3.1. METHODOLOGY

The building products assessment was based on *BEES (Building for Environmental and Economic Sustainability)* database [8], developed by *North-American National Institute of Standards and Technology*. This software complies with the IS0 14040 standard for life-cycle environmental assessment [4] and the *ASTM – International Standard life-cycle cost* for economic assessment [9]. The impacts considered in the environmental assessment are Global Warming Potential, Acidification Potential, Eutrophication Potential, Fossil Fuel Depletion, Indoor Air Quality, Habitat Alteration, Human Health, Smog Formation Potential and Ozone Depletion Potential. Results were normalized according to Normalization Values assumed on *BEES*, which values are presented on Table 1.

The energetic balance was performed on *DesignBuilder* software [10], using the *EnergyPlus* dynamic simulation engine [11]. Based on a three-dimensional modeling of the spaces that make up the building, systematic analysis of climatic parameters, construction solutions, HVAC systems and its estimated time of operation were defined, aiming towards the fidelity of the results for the imposed conditions. On the other hand, the energy consumption with lighting and domestic appliances was excluded from the analysis.

Climatic data resulting from the research project 1015 ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) [12], was used in the study compiled into *EnergyPlus* [11] type files obtained from IWEC database (International Weather for Energy Calculations).

Calculations of the heat transfer coefficients were made in accordance with EN ISO 10211 [13]. The studied house is located in the city of Kiruna included in the district Norrbottens (Norrbottens Län) being classified as belonging to the climate zone I, which is the most rigorous in the heating season, but is also one where it is legally allowed a greater energy consumption with HVAC systems. The legal limit for the building is 150 kWh/m^2/year based on the Swedish BFS 2011:6 BBR18 [14], considering a mixed energetic type use.

In order to simplify the overall thermal simulation performed in DesignBuilder [10], average heat transfer coefficients were determined, which can represent through its multiplication by the element area, the total energy loss observed the element that presents heterogeneities, whether individual or linear. To determine this average values THERM software [15] was used, which complies with the calculation methodology prescribed in EN ISO 10211 [13]. The heterogeneities present in the main building blocks, correspond to the structural elements within the walls and slabs which have a linear layout. Cellulose fiber boards were used as insulation. The thermal conductivity coefficient was taken equal to λR = 0040 W/mK.

Given the energetic mix profile in Kiruna, where electricity production has a strong renewable component, electricity was considered for water heating and the use of District Heating (public heating supply network) was considered for heating.

Economical assessment was performed using the *BEES* database for the materials considered. BEES includes the initial cost of the material and potential maintenance costs that can be predicted for each material. *BEES* database doesn't consider the on site assembling cost of the building. Furthermore, the energy was also expressed as a "future cost", in order to get the final economical balance for each structural option under assessment. A 4% discount rate was applied to future costs, according to the formula:

$$X_{NPV} = \sum (Cn \times q) = \sum_{n=1}^{p} \frac{Cn}{(1+d)^n}$$

Where:
XNPV – net present value
n – number of years
Cn – cost in year *n*
q – discount factor
d – real discount rate
p – period of time considered

3.2. GOAL AND SCOPE DEFINITION

A single-family house used by 4 people in a 50-year period was defined as the functional unit. The aim of this study is to compare two different light-weight structural systems available to this kind of building: light steel frame and timber frame. For this reason, inventory is detailed for the building shell and main construction options, only excluding some features that are not related to the structural system, like window frames and general fixtures. Although foundations may be related to the structural system, as far as they are less demanding for light-weight structure buildings (timber and light steel frame are both light weight structural systems), foundations were not included in this study. The system boundaries, according to BEES database [8], includes raw materials acquisition, transport to the factory, manufacture, transport to the building site, construction process, whole life-span maintenance and end-of-life scenario, on a "cradle-to-grave" approach, for all the materials considered in the inventory.

Energetic assessment includes heating and water heating, excluding all the other energy consumption.

3.3. LIFE-CYCLE INVENTORY ANALYSIS

Ground-floor corresponds to a 100.8 square-meter area (see Figure 1), with 4 different material layers, from bottom to top: aluminum siding (8 mm), generic cellulose insulation (400 mm), two OSB panels and a layer of natural cork parquet as finishing. The structure is made of framing lumber in the first version under study and light steel on the second version (Figure 2).

First floor slab, dividing the two interior floors, corresponds to 59.58 m^2, which section has 4 different layers, from bottom to top: generic gypsum as finishing on the ground floor ceiling, generic cellulose insulation with 0,15m thickness, two layers of OSB panels, and finally, a natural cork parquet as finishing to the first floor ground. As in the rest of the building, structure is made of framing lumber on the timber option, and light steel, on the alternative solution under assessment(Figure 3).

First floor slab, dividing the interior space on first floor from the outside on the ground level, corresponds to a 21.06 square-meter area. The designed section repeats the solution formulated to the ground floor slab (Figure 2).

The roof slab (80.64 m^2), due to the building site climate, has large thermal insulation requirements. The assumed solution has 7 material layers, from bottom to top: generic gypsum board to the interior ceiling finish, generic cellulose insulation with 0,25m thickness, two layers of OSB panels, another cellulose insulation layer with 0,16m thickness, an OSB panel on top, to be covered with prime coatings utilithane, with generic fiber cement shingles on top (Figure 4).

The house presents a 20,16 m^2 terrace on the first floor (see Figure 1), dividing the outside above from an interior space below. Its section is similar to the roof section, except on the top, that is covered with a "floating" cedar deck (Figure 5).

External walls correspond to a large share of the whole building materials, an area of 66.40 m^2 of demanding outer shell, to meet Kiruna climate needs. Composition is as follows, from the inside to the outside: generic gypsum as interior finishing, generic cellulose insulation (0.10 m thickness), one layer of OSB panels, cellulose insulation filling the air gap between the structure (0.14 m thickness), one OSB panel layer, sealing with prime coatings utilithane and cedar siding to the external finishing (Figure 6).

Internal walls correspond to a total area of 110 sq meter. According to the building's constructive framework, these are light weight walls, composed by a framing lumber or light steel structure, with the air gap filled with cellulose insulation, limited on both sides with generic gypsum board (Figure 7).

3.4. LIFE-CYCLE IMPACT ASSESSMENT

3.4.1. Environmental Impacts

In this section, the life-cycle assessments of the different impacts are reported for both structural solutions studied (timber and steel frames). Results reporting the environmental impacts are presented in Table 2 and aiming a better analysis of the different impact categories of the house, graphs are used (Figure 7). The environmental impacts presented include all the materials considered in the inventory analysis, in a cradle-to-grave approach, as well as the impacts related to the production of the energy necessary to the 50 years use-phase. Energy quantity considered in the environmental impact assessment is according to the energetic balance assessment for both solutions under study, which results are presented in Table 4.

3.4.2. Economical impacts

Economical performance of both solutions under study was assessed according to the procedure described on the "Methodology" section. The total sum includes material acquisition and maintenance, as well as energy costs for the 50-year use phase. Results are presented on Table 4.

3.5. DISCUSSION

On the environmental balance, the timber frame building achieved more favourable results, caused by a better performance on three impact categories: Global Warming Potential (2% higher impacts on the steel option), Fossil Fuel Depletion (1% higher for steel) and Human Health (41% higher potential impacts for steel), from the nine categories considered. When it comes to the economic performance, the differences between the two options under study are not significant, even considering the maintenance costs for the use phase. The only remarkable difference is for the energy consumption costs (50 years, considering a discount rate of 4%), that favours the timber option. Therefore, the life-cycle cost balance indicates 2% advantage for the timber house (128.455,44$), comparing with the light steel framing house (131.124,22$). This is due to the better thermal performance of the wood: thermal losses of the light steel house are 6% higher than the timber house ones. Timber house consumes an average 124 kWh/m^2 primary energy a year, while light steel frame house consumes 132 kWh/m^2 primary energy a year.

4. CONCLUSIONS

Although results for both alternatives remain very close, as a balance we can conclude that the timber house has a more favourable performance both from an environmental and economical point of view. Potential negative effects on Human Health are clearly decreased on the timber-frame option, comparing with the light-steel frame. Also the energy requirements are smaller when a timber frame is considered, due to wood better thermal performance when compared with steel.

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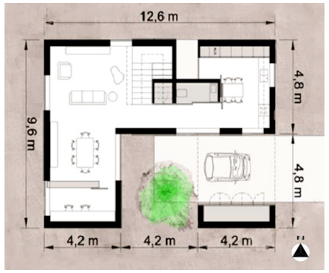
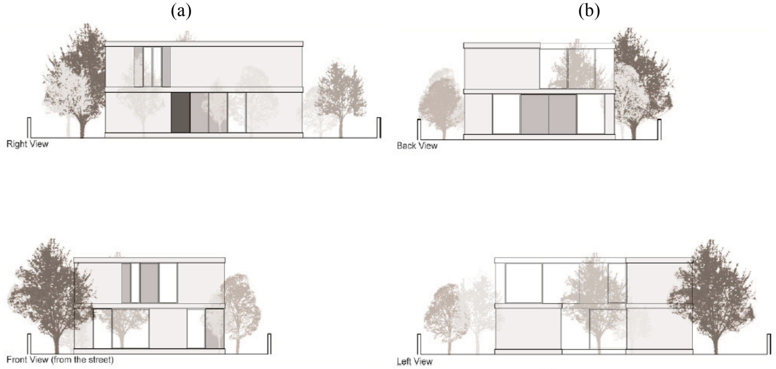


(a)

(b)



(c)

Figure 1 – Single family-house used as case study. Plan view of the ground floor (a) and first floor and the four lateral views

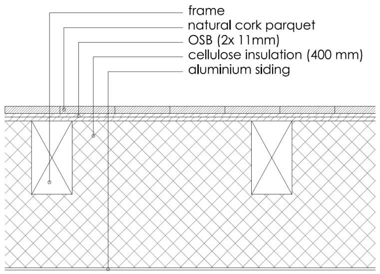


Figure 2 – Ground-floor section, First-floor slab (interior/exterior) section

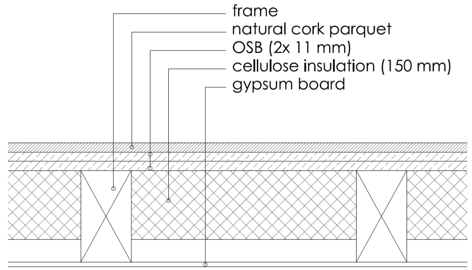


Figure 3 – First-floor slab (interior/ interior) section

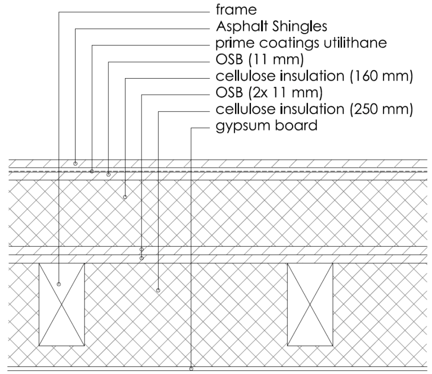


Figure 4 – Roof slab (interior/ exterior) section

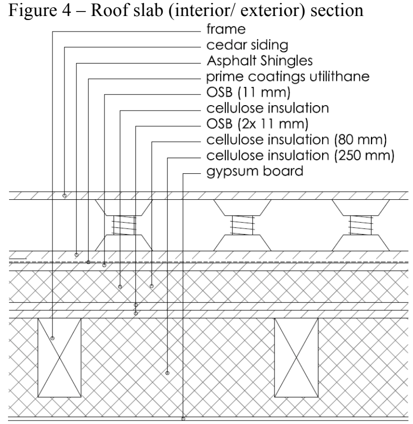


Figure 5 – Terrace section (exterior/interior)

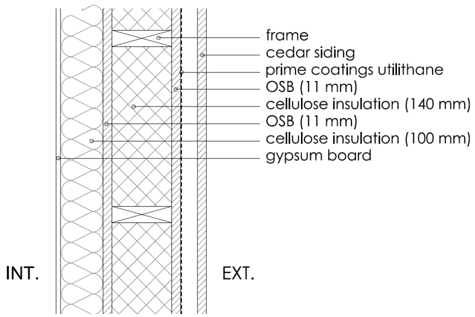


Figure 6 – External walls section

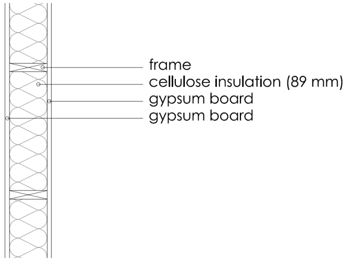


Figure 6 – Internal walls section

Table 2 – Environmental balance for each category under study

Impact	Normalization Value
GLOBAL WARMING POTENTIAL	25 582 640.09 g CO2 equivalents/year/capita
ACIDIFICATION POTENTIAL	7 800 200 000.00 millimoles H+ equivalents/year/capita
EUTROPHICATION POTENTIAL	19 214.20 g N equivalents/year/capita
FOSSIL FUEL DEPLETION	35 309.00 MJ surplus energy/year/capita
INDOOR AIR QUALITY	35 108.09 g TVOCs/year/capita
HABITAT ALTERATION	0.00335 T&E count/acre/capita
HUMAN HEALTH	274 557 555.37 g C7H8 equivalents/year/capita
SMOG FORMATION POTENTIAL	151 500.03 g NOX equivalents/year/capita
OZONE DEPLETION POTENTIAL	340.19 g CFC-11 equivalents/year/capita

Table 3 – Environmental balance for each Impact Category under study

	timber-frame	light-steel frame
GLOBAL WARMING POTENTIAL	1,31e+01	1,34e+01
ACIDIFICATION POTENTIAL	3,97e-09	4,23e-09
EUTROPHICATION POTENTIAL	2,57e+01	2,57e+01
FOSSIL FUEL DEPLETION	1,80e+01	1,82e+01
INDOOR AIR QUALITY	0,00e+00	0,00e+00
HABITAT ALTERATION	0,00e+00	0,00e+00
HUMAN HEALTH	5,41e+01	9,23e+01
SMOG FORMATION POTENTIAL	4,10e+01	4,10e+01
OZONE DEPLETION POTENTIAL	6,77e-01	6,77e-01

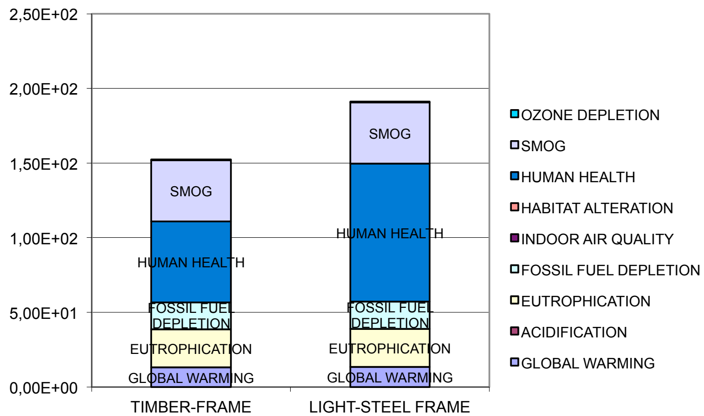


Figure 7 – Environmental impacts comparison: timber-frame and light-steel frame buildings under assessment

Table 4 – Economical balance for both alternatives under assessment

	timber-frame	light-steel frame
FIRST COST	$ 90.040,53	$ 90.480,53
FUTURE COSTS (maintenace)	$ 1.611,66	$ 1.599,43
FUTURE COSTS (energy)	$ 36.803,25	$ 39.044,26
LIFE-CYCLE COST	$ 128.455,44	$ 131.124,22

Table 4 – Energetic balance assessment

Structural solution	Total (per year)	Electricity (water heating) (kWh)	District Heating (kWh)
Timber frame	Energy Balance	666.7	12376
	Conversion Factor	3.167	1.024
	Primary Energy	2111	12673
		Primary Energy	*Legal Limit*
	Total (per year)	14784 kWh	17875.5 kWh
	Per square-meter	124 kWh/m^2	150 kWh/m^2
Steel frame	Energy Balance	666.7	13316
	Conversion Factor	3.167	1.024
	Primary Energy	2111	13635
		Primary Energy	*Legal Limit*
	Total (per year)	15747 kWh	17875.5 kWh
	Per square-meter	132 kWh/m^2	150 kWh/m^2