Life-cycle assessment of a single-family timber house

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ABSTRACT: This paper aims to produce a “cradle-to-cradle” life-cycle assessment for a single-family timber house, prefabricated in northern Portugal, to be assembled in Paris area, France. The three-story building has concrete foundations and basement. Above ground level, all the structure is made of solid wood and OSB panels, with gypsum board finishing on the inside and red cedar wood on the outside. All the thermal insulation is made of rockwool. The tool used for the life-cycle assessment was GaBi software and extensive databases from several sources, including data supported directly from the building manufacturer. In addition, a sensitivity analysis is performed in order to identify the most influent parameters in the life cycle analysis.

1 INTRODUCTION

Wooden construction is empirically known for its sustainability. Nevertheless, the potential associated with its life-cycle is not completely explored. The life-cycle analysis (LCA) of wooden buildings must, necessarily, consider that trees store carbon dioxide in their tissues, in amounts that will only be released by decay or combustion of wood, which only happens at the end of life of the material.

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 (Marques, 2008). Moreover, wood is a material that requires a relatively low processing power to be prepared for building industry, unlike most common materials. On the other hand, it can be assumed that the transformation process of wood produces virtually no waste, since all the "waste" can be used for production of wood-based products or fuel, decreasing the demand for fossil fuels.

Although wooden constructions need maintenance throughout its lifetime, the common wooden building systems allows 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 wood can be directly reused in another building, used as raw material for wood-based products, or simply used as fuel. In the worst case scenario, going to 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 (Buchanan & Levine, 1999).

2 LCA APPLIED TO TIMBER BUILDINGS

LCA methodology, as prescript by ISO 14040 standards, is not particularly directed to buildings assessment. Nevertheless, one can find some applications of that methodology to timber buildings, like Perez-Garcia (et al., 2005) 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 (1999) shows 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 (2000) compared greenhouse gas emissions between timber and concrete solutions for a Swedish building, concluding that the timber option decreases GHG emissions from 2 to 3 times, considering that wood waste and logging residues are used to replace fossil fuels. On the other hand, Nassén (et al., 2012) compares the use of concrete vs. 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.

3 CASE STUDY

In order to analyse the environmental impacts of a timber building, a case study was selected to perform a life-cycle assessment.

3.1*Goal and scope definition*

A single-family prefabricated timber house was defined as the functional unit. The building was assumed to be prefabricated in Vila Nova de Cerveira (Portugal) and assembled in the periphery of Paris (France), inserted on a narrow plot, following a very common urban architecture, considering that any other material rather than wood could be used instead. In other words, if the house was to be built with concrete or steel structure, its shape would virtually be the same.

The system boundaries for this study include all the elements that characterize this kind of construction except the elements that are not dependant from the structural system adopted for the building, for instance: window frames, floor finishes, bathroom and kitchen fixtures. Although foundations and basement depend of the structural system, being less demanding as the construction is lighter (like what happens when replacing concrete by wood), these elements were also excluded in this study, for practicability reasons. In other words, the elements included in this study are the structure (above ground level) and the exterior walls, as represented in figure 1. Energy use for erecting, operating and maintenance of the building was not included in this study.

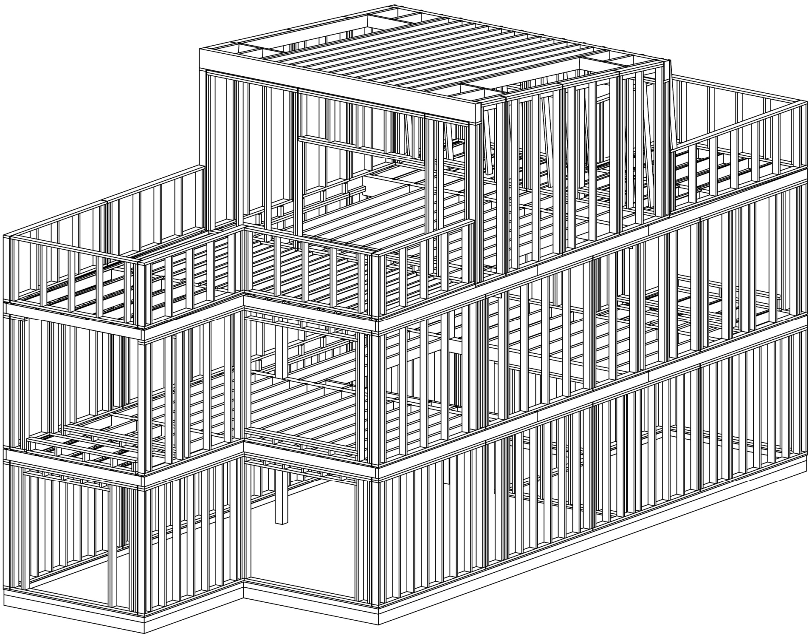

Figure 1 - Structural frame of the timber house

The impact categories considered in this LCA are according with the “CML2001 – Dec.07” methodology, namely: Abiotic Depletion (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP 100 years), Ozone Layer Depletion (ODP, steady state) and Photochemical Ozone Creation (POCP).

Inventory data was provided by the manufacturer and by the databases included in the software GaBi (2007). The given data is reliable and accurate.

3.2 *Life-cycle inventory analysis*

The life-cycle of the timber house is divided into 5 different phases. The construction of the foundations and basement represent the first one. Even thought a timber structure is lighter than a concrete one, requiring less and simpler foundations, this stage was not considered in this study. It was assumed that foundations and basement would be similar for most of the building systems available, therefore not being a specific feature of using timber.

The second phase corresponds to the prefabrication process of the house, prepared in the factory, and based on the definition of the timber elements required to build the house. All structural elements are produced in factory, and then transported to the building site, where they are assembled using, essentially, stainless steel connections. Both prefabrication and assembling processes are relatively low-tech, as far as they use very simple tools and require small amounts of energy to be completed. The tools used are mostly the electric saw and the screwdriver. For this reason, even a small wood-workshop can manage to produce a timber house like this one. As the energy amounts required are hard to measure and not very significant, its consumption will be dismissed from this study.

The third phase considered is the *in situ* assembling of the prefabricated elements. As mentioned before, this phase requires a very simple process: only a forklift or a small crane is used to put the pieces on place. Then, the structural elements are connected to each other using stainless steel joints and screws.

The fourth phase corresponds to the operation and maintenance of the building, during the 50 years defined as life span. The simulation of the energy amounts required during this phase overcomes the goals of this study, therefore it was excluded. The maintenance processes and materials are excluded for simplification reasons. However, for the 50-year life span, there is no significant demand for maintenance of the house. According to the manufacturer, the Canadian red-cedar used in the façade is extremely weather resistant, dismissing any maintenance process.

The fifth and last phase of the building’s life cycle is its dismantlement, after the 50-years use phase. When dismantling a building, one can hardly separate all the materials for recycling. It’s expected to have some of them mixed or damaged in a way that makes them going to landfill. Nässén (2012) points that “estimates of feasible recycling rates for building materials differ considerably in the literature”. This author assumes a recycling rate of 80% for wood, which we find a reasonable value. The same study (Nässén 2012) concludes that these rates don’t produce significant variations in the results, as long as recycling is assumed to occur “100 years into the future when CO_2 emissions of the surrounding energy systems are assumed to be low”.

The flow diagram of the timber house life cycle is represented in Figure 2.

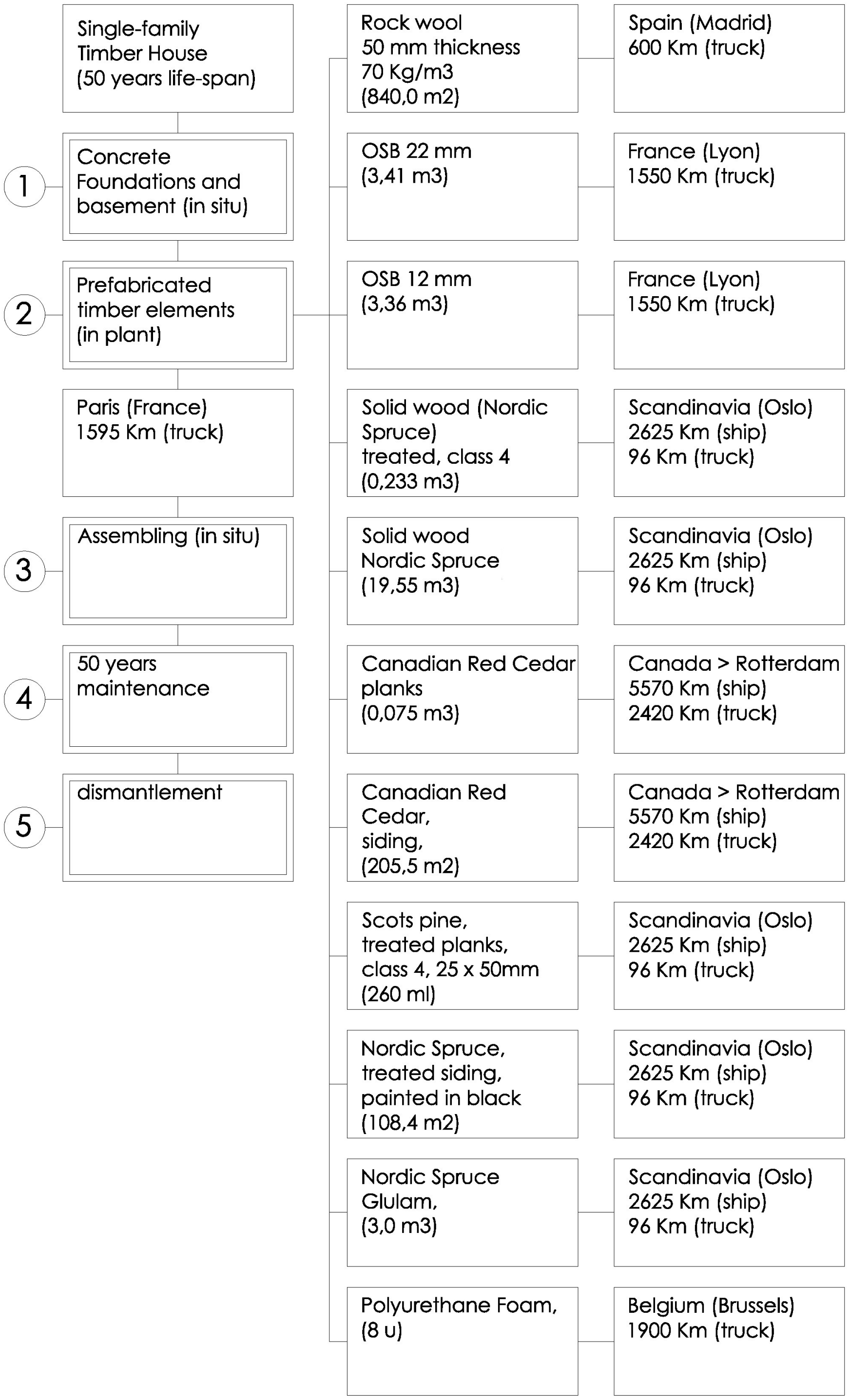

Figure 2 - Diagram of the house life-cycle, with reference to raw material quantities and transport distances

Three different end-of-life scenarios were studied. In the first one, for solid wood, we considered an average 80% separated and recycled as raw material for wood products. For wood products and treated wood existing in the house, that 80% are recycled for bio-fuel. The assumption for steel screws and big steel parts is that 80% of them are recycled, but the other 20% go to landfill mixed with other waste. Steel pins are more difficult to separate from the wood, so we considered 80% of those not being recycled.

Table 1 - Inventory of materials for the first end-of-life scenario (Scenario 1)

Recycling: wood products (kg)	Production of bio-fuel (kg)	Wood waste on landfill (kg)	Other solid residues on landfill (kg)	Recycling: steel products (kg)	Recycling: PVC (kg)
8825,544	5048,08	3468,406	2965,8	253,081	3,636

The second end-of life scenario assumes that all the wood, steel and PVC products are separated when dismantling the building, being fully conducted to recycling or reuse. As in the first end-of-life scenario, untreated wood is recycled into wood products, while treated wood and general wood products are used as bio-fuel.

Table 2 - Inventory of materials for the second end-of-life scenario (Scenario 2)

Recycling: wood products (kg)	Production of bio-fuel (kg)	Wood waste on landfill (kg)	Other solid residues on landfill (kg)	Recycling: steel products (kg)	Recycling: PVC (kg)
11031,93	6310,1	0	2940	277,945	4,572

The third end-of-life scenario dismisses every recycling or reuse processes. It actually considers the whole building as “waste” after the 50 years use, without any material separation.

Table 3 - Inventory of materials for the third end-of-life scenario (Scenario 3)

solid residues on landfill (kg)
20588

3.3 *Sensitivity analysis*

With the aim to analyse the sensitivity of the environmental impacts related to the different variables involved, several scenarios have been assumed considering some variations on the reference model. The defined scenarios are presented in table 4.

Table 4 - Summary of the analysed variables

Brief description		End-of-life
V1	Base version, According to inventory (figure 2)	Scenario 1
V2	Base version, but substituting OSB panels by plywood panels	Scenario 1
V3	Base version, but removing transport of prefabricated house from Portugal to France (assuming the house was to be prefabricated and built in the same location)	Scenario 1
V4	Base version, but assuming 100% recycling of wood and steel products	Scenario 2
V5	Base version, but assuming 0% recycling (100% landfill)	Scenario 3
V6	Base version, but removing transport for wood supply and transport of the prefabricated house from Portugal to France (assuming the house is prefabricated only with locally produced timber, and built near the prefabrication factory)	Scenario 1

4 LIFE-CYCLE IMPACT ASSESSMENT

Impact assessment of the timber house life-cycle was performed under the impact categories defined on “CML2001 – Dec.07”, using the normalization factors listed on table 5.

Table 5 - Normalization factors for the impact categories considered

Quantity	Equivalences	Unit	Factor
Abiotic Depletion (ADP)	1,69E+10	kg Sb-Equiv.	5,92E-11
Acidification Potential (AP)	1,68E+10	kg SO2-Equiv.	5,95E-11
Eutrophication Potential (EP)	1,85E+10	kg Phosphate-Equiv.	5,41E-11
Global Warming Potential (GWP 100 years)	5,21E+12	kg CO2-Equiv.	1,92E-13
Ozone Layer Depletion Potential (ODP, steady state)	7,70E+06	kg R11-Equiv.	1,30E-07
Photochem. Ozone Creation Potential (POCP)	2,66E+09	kg Ethene-Equiv.	3,76E-10

The results for the default version of the building life cycle are listed on table 6, divided into the three phases developed on the LCA model: prefabrication (including raw materials acquisition and transport to the factory), transport of the prefabricated pieces to the construction site (from Portugal to France) and, finally, the end-of-life scenario.

Table 6 - LCA results for V1

Impact Categories	units	**Total**	Prefabrication	Transport	End of life
Abiotic Depletion (ADP)	kg Sb-Equiv.	**3,31E-07**	3,29E-07	1,82E-09	2,31E-10
Acidification Potential (AP)	kg SO2-Equiv.	**9,16E-07**	9,15E-07	1,61E-09	1,58E-10
Eutrophication Potential (EP)	kg Phosphate-Equiv.	**8,41E-08**	8,38E-08	2,54E-10	4,31E-11
Global Warming Potential (GWP 100 years)	kg CO2-Equiv.	**-4,47E-07**	-4,48E-07	8,85E-10	1,38E-10
Ozone Layer Depletion Potential (ODP, steady state)	kg R11-Equiv.	**2,01E-09**	2,01E-09	9,90E-13	-1,43E-12
Photochem. Ozone Creation Potential (POCP)	kg Ethene-Equiv.	**3,83E-07**	3,82E-07	8,22E-10	1,39E-10

Comparing the impacts of the different life-cycle phases defined in the timber house LCA, one can conclude that the large majority of the impacts are associated with the “Prefabrication” phase (99,38% for the Abiotic Depletion potential), corresponding only 0,07% of the Abiotic Depletion Impact to the End-of-life phase and 0,55% to the transport of the prefabricated house from the factory to the construction site. For all the other Impact Categories analysed in this study, the proportion between different life-cycle phases is even less expressive.

The sensitivity analysis provided the results listed on Table 7. The variations are not very significant between the scenarios defined in this study, because each variation represents a small fraction of the whole process.

Table 7 - Variation of results from the sensitivity analysis performed

	V1	V2	V3	V4	V5	V6
Abiotic Depletion (ADP)	**3,31E-07**	-0,14%	-0,14%	0,00%	+0,10%	-0,72%
Acidification Potential (AP)	**9,16E-07**	+0,01%	+0,01%	0,00%	+0,04%	-0,35%
Eutrophication Potential (EP)	**8,41E-08**	-0,02%	-0,02%	0,00%	+2,34%	-0,51%
Global Warming Potential (GWP 100 years)	**-4,47E-07**	+0,04%	+0,04%	0,00%	+0,61%	+0,26%
Ozone Layer Depletion Potential (ODP, steady state)	**2,01E-09**	-0,56%	-0,56%	-0,01%	+0,36%	-0,06%
Photochem. Ozone Creation Potential (POCP)	**3,83E-07**	+0,03%	+0,03%	0,00%	+0,31%	-0,37%

Comparing the results of the sensitivity analysis performed, one can conclude that the variation that produces a higher decrease in the environmental impacts is the elimination of the transportation. Only eliminating the need of transport from the factory to the construction site (V3) does not produce a significant decrease in most of the categories. Nevertheless, combining it with the elimination of the transport of raw materials to the factory, produces a remarkable decrease in the global environmental impact (V6). In fact, wood products are supplied by overseas sources like Canada and Scandinavia countries, which means a long distance to be covered by large amounts of materials, both by cargo ship and by truck. This could be avoided if a local source of timber and wood products would be used, highlighting the need to increase the development of local economies for economic, social and environmental reasons.

Removing the recycling process from the life-cycle (V5) produces remarkable environmental impacts increase for almost all the indicators. The difference between Version 1 and Version 4 is negligible. This means that the additional effort in recycling the totality of the materials, comparing with an average 80% recycling, does not produce a noticeable impact.

According to the observed pattern, t~~T~~he variation that produces a higher decrease in “Abiotic Depletion” indicator is the elimination of transport both for raw materials and for the delivery of prefabricated building on the construction site (V6). It can be also noticed that the elimination of recycling process (V5) increases the potential for Abiotic Depletion.

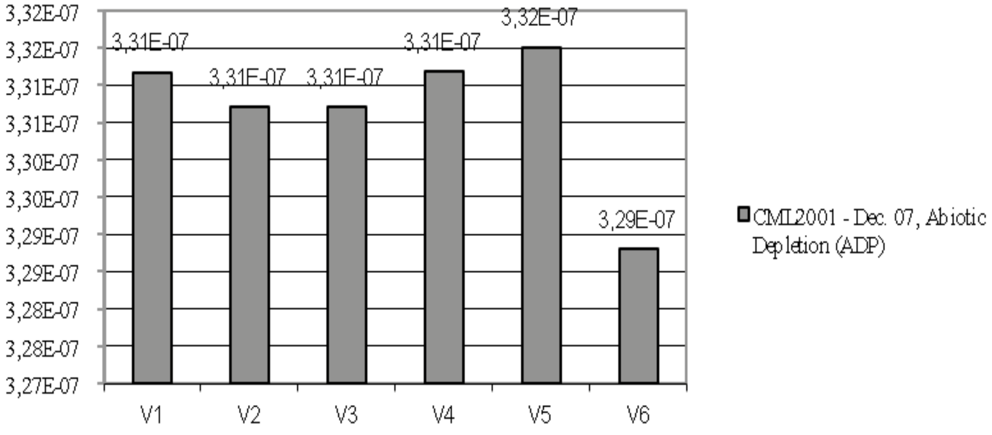

Figure 3 - Summary of “Abiotic Depletion” Impact Category for all the versions considered (kg Sb-Equiv.)

Acidification Potential only suffers a significant variation in the scenario where the transport of large amounts of materials is suppressed (V6). For all the other scenarios under study, the values for this impact category remain very close to each other (Figure 4~~Figure 4~~).

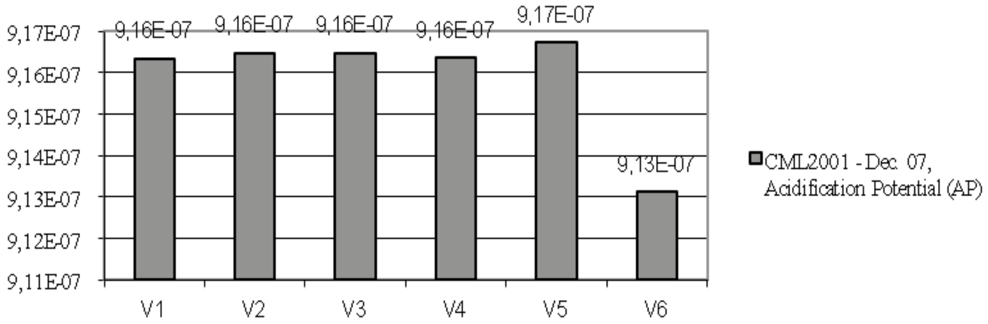

Figure 4 - Summary of “Acidification Potential” Impact Category for all the versions considered (kg SO2-Equiv.)

In the performed LCA, Eutrophication Potential seems to be closely related to the deposition of waste in landfill (V5). This may be due to the hazardous gases released on the decomposition processes of the various landfilled materials. For all the other scenarios under study, the environmental impact “Eutrophication Potential” remains barely unchanged.

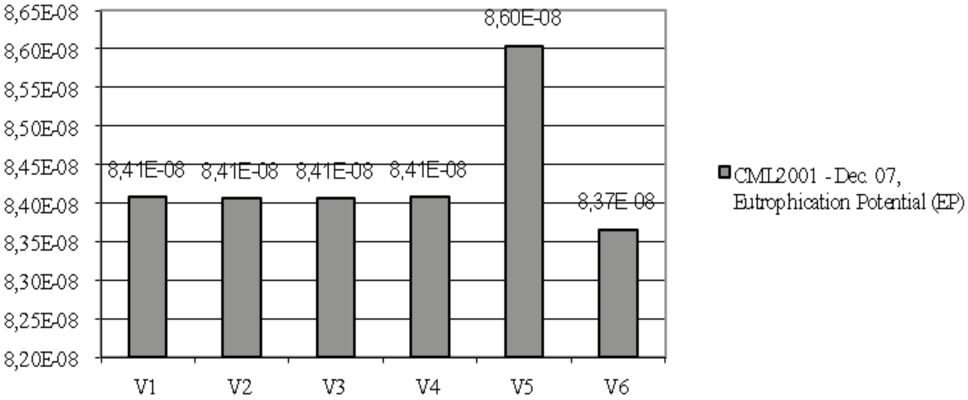

Figure 5 - Summary of “Eutrophication Potential” Impact Category for all the versions considered (kg Phosphate-Equiv.)

Global Warming Potential indicator gets negative results for all the assumed versions of the timber house. This is due to the wood ability to store carbon, creating temporary “carbon pools”, which may result in a negative carbon balance within its life-cycle (Perez-Garcia et al., 2005). For the success of this process, forest management assumes a very relevant role. In fact, most of the carbon fixing occurs during the trees fast growing process, which represents mostly the first 100 years of their life. After that period, in order to increase the carbon storage, it is encouraged to cut down the tree, giving place for a new one to grow (Joseph & Tretsiakove-McNally, 2010).

Carbon storage on Version 5 is partially offset by the end-of-life scenario defined. In this version, no recycling or reuse is considered, which may lead to an increase of the Global Warming Potential of the solution. In any case, even though all the materials are landfilled in this version, the global life-cycle also gets negative values when it comes to this indicator.

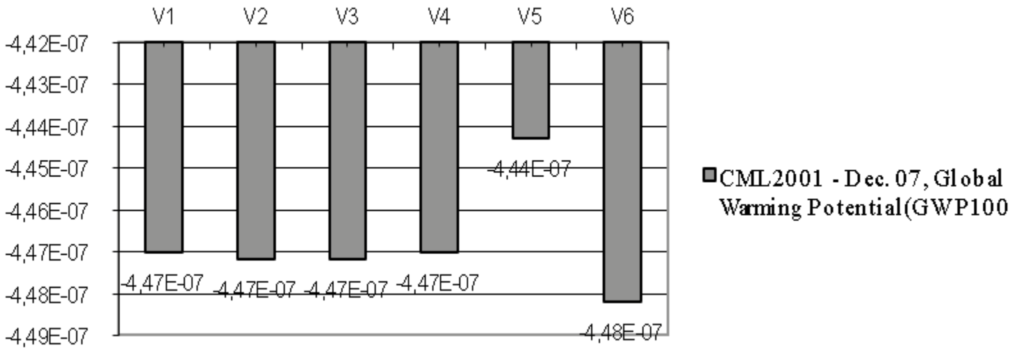

Figure 6 - Summary of “Global Warming Potential” Impact Category for all the versions considered (kg CO2-Equiv.)

Ozone Layer Depletion is a bigger threat when it comes to Version 5, which considers no recycling at all. This impact category gets the lower values for Versions 2 and 3, for different reasons.

On Version 2, this can only be due to the replacing of OSB by plywood panels. Although plywood gets a more favourable result for this impact category, probably due to its manufacturing processes, this advantage it’s not a pattern for all the categories considered. The option between one of these wood products demands further study of different parameters.

In what concerns to Version 3 of the model, the lower values for Ozone Layer Depletion (comparing with the default version) are due to the decrease of transport, which means less demand for fuel consumption and associated emissions.

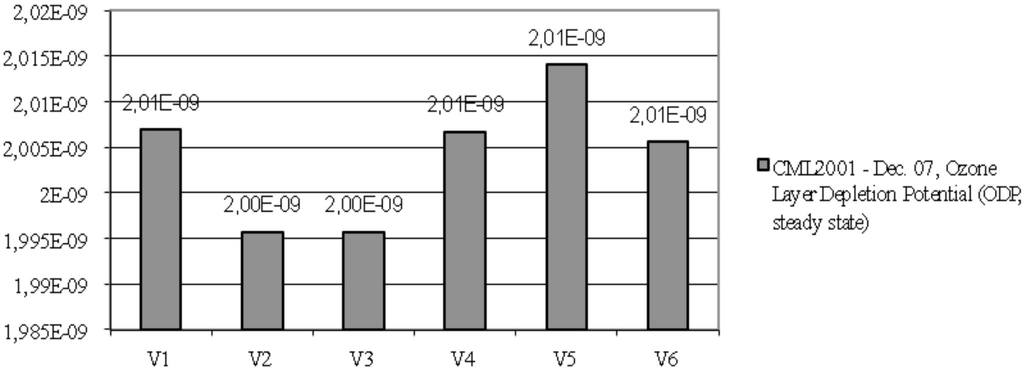

Figure 7 - Summary of “Ozone Layer Depletion” Impact Category for all the versions considered (kg R11-Equiv.)

“Photochemical Ozone Creation Potential” gets its higher values for Version 5 and its lower values for Version 6. It’s a pattern between all the categories that Version 5 gets the “worst” results, considering that lower environmental impacts are “better”. As stated before, this is due to the amount of solid waste on landfill on the house end-of-life, which affects the air and soil quality. Version 6 dismisses the need for long-distance transport, which leads to less fuel consumption and therefore lower emissions.

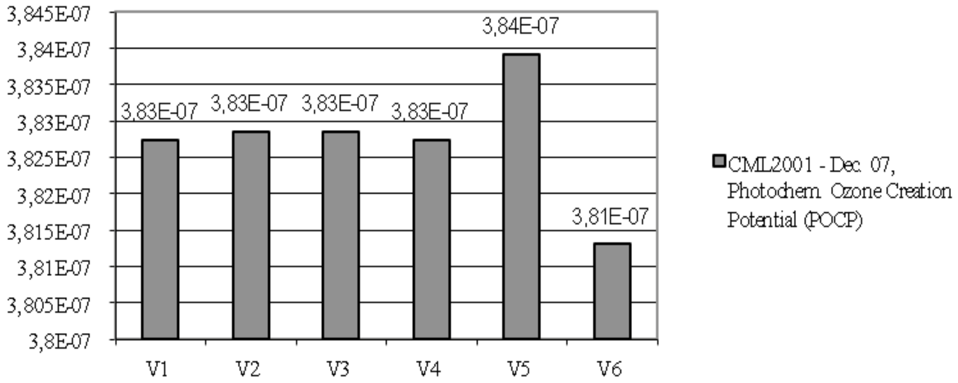

Figure 8 - Summary of “Photochemical Ozone Creation Potential” Impact Category for all the versions considered (kg Ethene-Equiv.).

5 CONCLUSIONS

The results of this study highlight the need to decrease the transportation distances, ~~favoring~~favouring the use of local sources and manufacturers, for an environmental-friendly construction. Recycling plays an important role as a mean to decrease the environmental impacts of the building’s end-of-life.

It has been stated that wood is a suitable construction product when it comes to reduce the Global Warming Potential, due to its ability to store carbon on its tissues. This ability can lead to a negative carbon balance which, combined with a zero-energy building policy, results in a highly sustainable construction in the whole life-cycle.

REFERENCES

Buchanan, A., & Levine, S. (1999). Wood based building materials and atmospheric carbon emissions. *Environmental Science & Policy* (2), 427-437.

Borjesson, P., & Gustavsson, L. (2000). Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. *Energy Policy* (28), 575-588.

GaBi 4: Software and data base for Life Cycle Engineering, PE INTERNATIONAL GmbH, April 2007

Nassén, J., Hedenus, F., Karlsson, S., & Holmberg, J. (2012). Concrete vs. wood in buildings - An energy system approach. *Building and Environment* (51), 361-369.

Marques, L. (2008). *O papel da madeira na sustentabilidade da construção.* Porto: Dissertação de Mestrado em Engenharia Civil, Especialização em Construções Civis.

Perez-Garcia, J., Lippke, B., Briggs, D., Wilson, J., Bowyer, J., & Meil, J. (2005). The environmental performance of renewable building materials in the context of residential construction. *Wood and Fiber Science* (37), 3-17.