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Abstract: The present paper deals with a comparative Life Cycle Assessment study of two wall assemblies using natural insulating material: linen panels and straw. The Bilan Produit ® software, associated to the eco-invent database is used to quantify the environmental impacts of the analyzed walls. Obviously, some steps of the wall lifecycle have a small environmental footprint: the consumer use step provides little impacts, while the end of life step (post-consumer) allows a saving (diminution?) of impacts because of the “reusing” of (possibility to reuse) a part of the natural materials. On the other side, the raw material procurement and manufacturing steps are at the origin of the greatest impacts. The linen panel is a rather complex manufactured product, so that the order of height of the impacts is greatly superior to the one of the straw wall. To minimize the impacts (environmental footprint) of this step, local producers should be preferred. Both assemblies are finally compared to a conventional wall realized by using glass wool. According to the obtained results Straw is shown to be better for the environment than the linseed whatever the considered indicator. Besides, the wall with linen panels is finally more impacting for the environment than a conventional wall, so that the only alternative to the conventional insulation for the environmental point of view seems to be the straw.

Keywords: *life cycle assessment, energy, insulating materials, glass wool, linen, straw*

1. Introduction

Population on earth is nowadays around 7 billion inhabitants, and will probably reach 10 billions people in 2050 [1]. Consequently, building market is an industrial sector in permanent development all around the world.

However the companies of this sector must overcome major difficulties, due to the important energy consumptions and to the big quantities of raw materials which are employed to ensure ~~a~~ good hygro-thermal performance, correct acoustic properties, or other comfort facilities and economical performances. The passive buildings (i.e. buildings requiring not much energy than the one it produces) seem to be an appropiate solution permitting a decrease or at least a stabilization of climate change indicators.

It is obvious that one of the main requirements is that buildings must be correctly insulated since in numerous countries, the thermal regulation guides the consumers in insulating houses and buildings.

Unfortunately, the requirements and the legislation relative to the building's envelope performance vary from a country to the other; besides they are often very restrictive. The construction systems must therefore be adapted to each specific decision or to the design context. For example, in France, a recent thermal regulation impose for the new buildings to have a given sufficient insulating performance depending on the region [2].

On the other hand, if a correct insulating should save energy for heating and air conditioning, the real question is to evaluate its contribution to the total energy consumption. This question can only be answered if a “life cycle thinking” is adopted in the design. In fact, if a conventional insulating material is used (e.g. glass wool or rockwool), it is obvious to analyze if the energy consumption related to the production and/or the transportation of this material has not a greater impact than the one which could be saved by using this material. This question has been studied by different authors, and fortunately the use of such

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material seems to be beneficial for the environment, but only by considering strictly the energy consumption [3, 4].

The previous remark and point of view are not sufficient as arguments for the choice of the materials, since the global environment must be considered. It is inadequate and dangerous to consider only one indicator, namely the energy consumption, to evaluate the environmental impact of an insulating wall, for at least three reasons:

- The insulating material is never used alone and it is necessary to evaluate the contribution of all the elements used for the 'insulating installation'.

- The energy consumption is not necessary a bad thing for the environment, particularly regarding the fossil resources. For example, if the energy is produced by renewable resources, and even if it is always better to consume less energy from a local point of view, the global contribution is not affected by this type of energy consumption. Then the real indicator to be used should be the "Non-Renewable Energy Consumption" (the NREC indicator).

- Supplementary indidators must be used if the environmental impacts are to be evaluated. Reducing the Non-Renewable Energy Consumption (NREC) could in fact increase other impacts, and/or other global pollutions.

In fact, considering for example the insulating of a house, the global environmental impacts can only be adequate if a specific tool associated to a specific methodology, is used. Applied to a given product (reaching the wanted insulating performances for example), this methodology must have three essential properties:

- It must deal with a life cycle thinking, i.e. it must consider the differents steps of the life cycle of the product.
- It must consider all the elements of the product.
- It must evaluate few environmental criteria.

Such a methodology does exist, it is currently known under the denomination of Life Cycle Assessment (LCA).

The present paper deals with a comparative LCA study on different insulating exterior walls. The idea is to evaluate the interest and the environmental footprint of the use of natural insulating materials for buildings. In a first part, the LCA methodology is presented. It is then applied to evaluate the impact of different insulating walls, following exactly the different steps of the methodology. The obtained results are finally discussed.

2. LCA of the wall assemblies

2.1. Motivation of the study

As seen above, conventional insulating materials have been studied separately using the LCA methodology [3, 4], i.e. independently of the existence of the wall. This can be useful if a builder desires to choose environmentally friendly materials for a given wall; besides, it can be pertinent and sufficient if only the insulating material is to be changed, which is generally the case for conventional walls.

On the other side, different authors have studied the environmental impacts of wall assemblies [5, 6, 7]. The aim was generally the evaluation of several impacts, for example the global climate change indicator.

To the authors knowledge, very few studies have been conducted about wall assemblies constructed by using natural materials, particularly the straw. Besides, comparative studies are very rare, while a pertinent choice should be made using comparisons.

In the following section, the LCA tool is used to quantify and to compare the environmental impacts of three insulating walls, after a brief description of their physical characteristics and performances.

2.2. Wall assembly using straw bundles

The straw is a natural material which has always been used in the field of buildings. Formerly present in the form of cob for the wall, or thatch for the covering of roofs, it can also be used as straw bundles for the insulation of walls or roofs. The straw is locally produced by farmers. The characteristics of the bundles are defined in table 1.

Table 1
Main physical data for the straw

Straw properties	Values (unit)	
Size	35x50x100	(cm)
Thickness	35	(cm)
Thermal conductivity	λ = 0.065	(W/m.K)
Thermal resistance	5.4	(m².K/W)

There are numerous ways to use the straw in housing. The chosen technique was proposed by the GREB (Groupe de Recherches Ecologiques de la Batture) born in Canada, where the climate leaves no place to mediocre quality houses [8]. The wall assembly is composed of the following elements (see figure 1):

- The wood (brackets and beams) used for the load-bearing structure.
- The straw bundles.
- The nails or screws.
- The mortar.

More explainations about the size of the structure and the mortar-making, leading to the quantity of materials can be found in [9]:

- 30 straw bundles.
- 4 beams 5 m long and 16 beams 3 m long.
- 40 brackets 35 cm long.
- about 1 m^3 mortar.
- 240 nails or screws.
- 273 m string for the straw bundles.

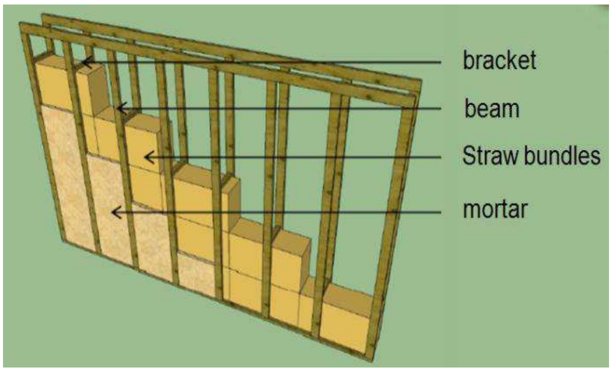

Figure 1. Scheme of the 'straw wall assembly' [9]

Let us notice that only the exterior side of the wall assembly is designed.

2.3. Wall assembly using linen panels

Linen is usually used in clothes manufacturing. The corresponding insulating material is made from the linen fibers which cannot be used in this industry because they are not long enough to be spinned. Linen presents numerous advantages within the framework of our study. First of all, linen is essentially cultivated in the regions of the North of France where the considered wall assembly is supposed to be built. Secondly, the linen culture does not require many operations and amendment, which is harmful for the environment.

In the present study, two natural insulating materials are compared. Consequently, the linen panel must have the same thermal resistance as the straw bundles described in the section 2.1. A simple calculation leads to a corresponding thickness of 21 cm for the panel. This thickness cannot be found on the market, so that a thickness of 20 cm has been used, which can be estimated as reasonable, with respect to the thermal resistance. The characteristics of the linen panels are presented in table 2.

Table 2
Main physical data for the linne panels

Straw properties	Values (unit)	
Size	135x60x20	(cm)
Thickness	20	(cm)
Thermal conductivity	λ = 0.039	(W/m.K)
Thermal resistance	~5.4	(m^2.K/W)

As specified previously, only the exterior side of the wall assembly is designed. The wall assembly is made of the following elements (see figure 2):

- The wood and OSB lumber.
- The linen panels.
- The nails or the screws.

More details about the size of the structure leading to the following quantity of materials can be found in [9]:

- 2 wood boards 5 m long.
- 8 wood boards 3 m long.
- 15 m^2 OSB lumber.
- 18 linen panels.
- About 200 nails and 150 staples.

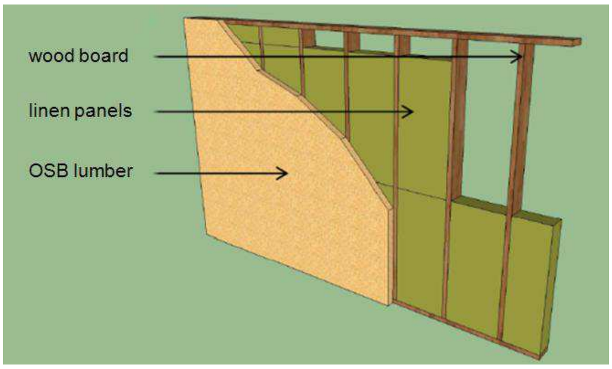

Figure 2. Scheme of the 'linen wall assembly' [9]

3. The Life Cycle Assessment Methodology

The Life Cycle Assessment (LCA) methodology is supposed to lead to the quantification of the environmental footprint for goods, services and processes, called *products* in the following. One of the attended objectives is to identify some main points allowing to do design choices permitting the diminution of the environmental impacts in one or several lifecycle steps. This approach is also called *life cycle analysis*, *ecobalance* or *cradle-to-grave-analysis*.

As previously indicated, a Life Cycle Assessment is the investigation and valuation of the environmental impacts of a given product. It is a variant of an input-output analysis, focusing on physical rather than monetary flows. LCA is both a multi-criteria and a multi-step study, and it has the particularity of being "goal-dependant". This means that the goal and scope definition of the study are not only important, but can be redefined during the entire study if necessary. In the same way, every phase of a LCA is linked with at least two others.

A framework for LCA has been standardised in the ISO 14040-44 series [10-11] by the International Organisation for Standardisation (ISO). As shown on figure 3, it consists in the following phases:

- **Goal and scope definition**: it defines the goal and intended use of the LCA, and scopes the assessment concerning system boundaries, function and flow, required data quality, technology and assessment parameters.
- **Life Cycle Inventory (LCI)**: this is an activity for collecting data on inputs (resources, such as the energy or the raw materials consumptions, and intermediate products) and outputs (emissions, wastes) for all the processes in the considered product system.
- **Life Cycle Impact~~y~~ Assessment (LCIA)**: it is the phase of the LCA where inventory data on inputs and outputs are translated into indicators about the product system's potential impacts on the environment, on human health, and on the availability of natural resources.
- **Interpretation**: this crucial step is the phase where the results of the LCI and the LCIA are interpreted according to the goal of the study and where sensitivity and uncertainty analysis can also be performed to qualify the results and the conclusions.

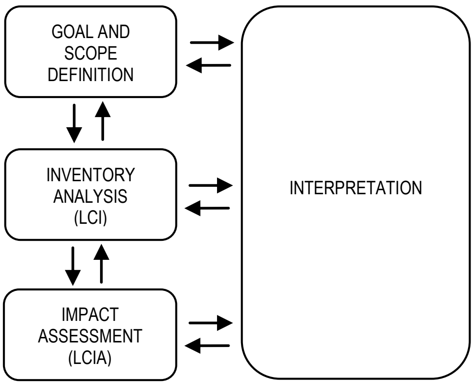

Figure 3. The different phases of a LCA study

Some of these phases are divided in several steps, particularly the first phase of the methodology (goal and scope definition) which must be made very precisely. In the following, the study will follow the four phases described above.

4. LCA methodology applied to insulating walls

4.1. Goal and scope definition

In the following the customers are defined, the main objective is precised, the function and the functional unit are clarified, the keys parameters are highlighted, and the system boundaries are fixed.

Our study is intended for every person (private person or builder) expecting to insolate a building or a house using natural materials, i.e. straw or linen.

Insulation made from straw bundles or linen panels are supposed to be ecological. The main objective of the present study is to quantify the environmental impacts of these two natural materials on a given wall. We can then define the goal of the study, which is to compare these two insolations materials (straw and linen) used on a given wall with a wood structure, of 15 m^2 area (3 meters high and 5 meters long)

According to the LCA methodology [10, 11], the function of the products must be correctly and precisely defined. Concerning insulation, a house said to be passive or a new building following the actual regulation [2] must reach a thermal transfer coefficient U of 0.15 $W/m^2.K$. Consequently, the thermal resistance 1/U must be approximately equal to 6.5 $m^2.K/W$. Let us notice that this value of the thermal resistance has been taken into account for the wall assemblies described in the section 2.

The chosen functional unit is to build an exterior wall assembly of 15 m^2 which has the following characteristics:

- The classical building objectives (for example in terms load-bearing structure) are reached.
- The thermal resistance of the final assembly is about 6.5 $m^2.K/W$.
- The lifetime of the assembly is 100 years.

Let us notice that this last value corresponds to the mean rate of renewal of the house park which is around 1% in France [12].

The key parameters are the linen and straw thicknesses leading to the wished thermal resistance, as well as the life expectancy of the various materials. The thicknesses are easily determined from the thermal conductivity of both types of insulating materials. Straw and linen are materials which reach 100 years old without any problem. Concerning the structure, it will be necessary to choose a wood which resists 100 years.

Concerning the boundaries of the study, let us remind that only the exterior side of the wall assembly is designed because a comparative study is projected. The final casing of the exterior is not taken into account, just as the inside casing (for example plaster plates and painting). The LCA of the different machines used to cultivate the cereals (for straw) or the linen are not considered in the present study, because the straw and the used linen fibre are in fact waste of the cultivation, as precised above. Tools and natural resources used for the building have not been taken into account, such as the water consumptions.

4.2. Life Cycle Inventory (LCI)

After the goal and scope definition, the different steps and elements of the analyzed products must be determined precisely. This phase of the LCA methodology [10, 11] must be made very carefully conducted. Some hypothesis can be made, for example neglecting some of the lifecycle steps or some of the evaluated impacts. The data used for this LCI are available in reference [9]. In the following, only the LCI concerning the wall assembly using straw is reported (see table 3).

The data corresponding to the LCI are associated to the classical four steps of the LCA methodology:

- **Step 1:** The raw material procurement and manufacturing, namely the ***Production***, takes into account the pollutions created by the use of raw materials to build the product.
- **Step 2:** The ***distribution*** phase takes into account the impacts generated during the transportation of the product towards the destination where it will be used.
- **Step 3:** In the present case, the ***consumer use*** phase is not considered because the maintenance (e.g. the wall painting or cleaning) is not included in the study.
- **Step 4**
  For the ***end of life*** phase (post-consumer use), mortar is supposed to be incinerated. Straw is assumed to be 50% buried and 50% recycled or composted (these values are means of the actual french treatment for such kind of waste).

Concerning the different quantities of fuel, chemical fertilizer, and weed killer used to cultivate cereals or linen, mean data have been estimated for the North of France directly from farmers [9]. Concerning the end of life of straw, some restrictive hypothesis have been made, as it is explained below (see the section 4.4.).

Table 3
Partial LCI data for the straw wall assembly

Step of life	Element	Material	Quantity	Unit	Comment
Production	String	Polyester fibers	0.5	Kg	273 m
	mortar	Lime	71.5	Kg	1 part
	mortar	Portland cement	109.45	Kg	1 part
	mortar	Sand	512	Kg	3 parts
	mortar	Common wood (hard)	0.115	m^3	4 parts of sawdust (specific weight 120 kg/ m^3)
	structure	Board made of common wood (soft)	0.263	m^3	Vosges spruce (specific weight 450 kg/ m^3)
	brackets	Board made of common wood (soft)	0.0336	m^3	Vosges spruce (specific weight 450 kg/ m^3)
	screws or nails	Current construction steel	2.4	Kg	240 nails
Distribution	Straw	Conventional vehicle with a trailer	50	pkm	5 round-trips with a trailer (local productor)
	Wood from seller to builder	Little truck (3.5 to 16 t)	3.55	t.km	Distance : 30 km Weight : 118.4 kg
	Little equipment	Conventional vehicle	20	p.km	
	Wood from forest to seller	32t truck	59.18	t.km	Distance : 500 km Weight : 118.4 kg

4.3. Life Cycle Impat Assessment (LCIA)

In order to quantify the environmental impacts, the Eco-invent 2.0 data-base [13] was used. The chosen indicators are referenced in table 4.

The resulting data of the LCIA calculation are not reported here, but are represented on figures 4 to 6.

The calculations were done using the Bilan Produit ® software [14]. The results are reported for a year, i.e. the calculated impact is divided by 100 (life time of each assembly).

Table 4
Chosen indicators for the environmental impacts

designation	Impact	Unit
NREC	Non-Renewable Energy Consumption	MJ eq.
RD	Resources Depletion	kg Sb eq.
GWP	100 year Global Warning Potential	kg CO_2 eq.
A	Acidification	kg SO_2 eq.
E	Eutrophication	kg $PO4^{2-}$ eq.
PP	Photochemical Pollution	kg C_2H_4 eq.
AT	Aquatic Toxicity	kg 1.4-DB eq.
HT	Human Ecotoxicity	kg 1.4-DB eq.

The environmental impacts are estimated using midpoint indicators associated with the CML 2001 evaluation method [15]. Since each indicator has a different unit, the impacts are normalized, according to the specifications of the normalized ISO procedures [10,11]. Each indicator is then expressed in *points*. A point represents the potential impact for a given indicator divided by the value of the same impact for a mean European people during a day.

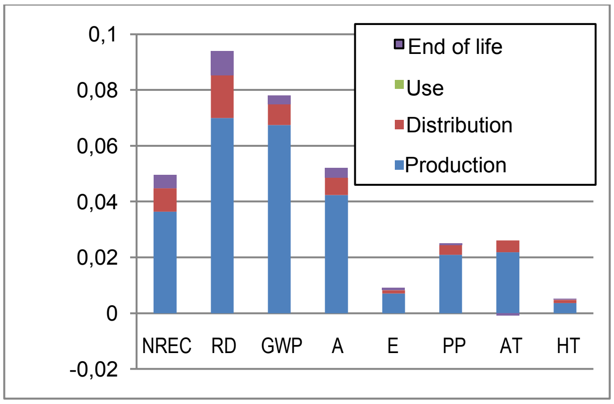

Figure 4. Environmal impacts by step of life for “straw wall”:

Figure 4 presents the environmental impacts of the wall assembly using straw described in part 2.2., for each step of lifecycle. Because of the end of life choice, some impacts are negative. This means that instead producing environmental impact, some design choices or end of life scenarii can avoid the production of pollution. The first conclusion which can be made by observing the results is that the production phase is by far the most important. More detailed conclusions will be made in the section 4.4.

The same calculation can be made for the wall assembly using linen panels, described in part 2.3. (figure 5).

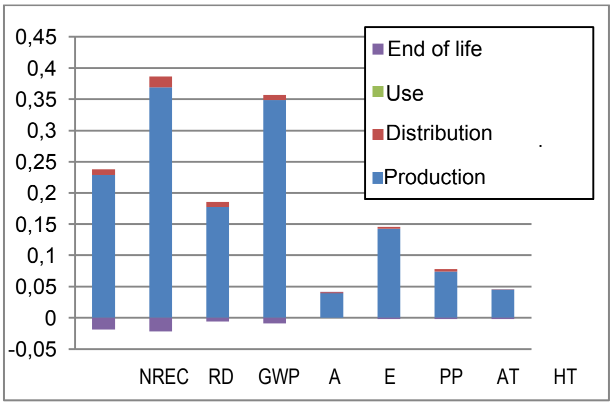

Figure 5. Environmal impacts by step of life for the “linen wall”

A detailed conclusion will be made in the interpretation phase of the LCA methodology (section 4.4., hereafter), but it worths to underline that:

- The production step remains the more impacting phase.
- The dominant impacts are globally the same for the straw bundles wall and for the wall assembly using linen panels.
- The mean impacts are around 4 times greater for the wall assembly using linen panels than for the “straw wall”.

4.4. Interpretation / results and discussion

The Interpretation is the last phase of the LCA methodology [10,11].

Figure 4 shows that for the “straw wall”, four impacts are dominant: Non Renewable Energy Consumption, Resources Depletion, Acidification and Aquatic Toxicity. This is mainly due to mortar, cement and sand [9]. As mean data for the end of life were not available for this material, straw has been assumed to have the same end of life than cotton canvas. It is clear that the end of life has a great influence on the global impacts. But the chosen end of life scenario (around 50% buried and 50% recycled) surevaluates the impacts, since straw could be totally composted. Anyway, the environmental impacts are inferior to the ones of the linen assembly whatever the considered indicator.

In the case of the linen panels assembly, the dominant environmental impacts are still the Non Renewable Energy Consumption, the Resources Depletion, the Global Warning Potential and the Acidification (figure 5). This is mainly due to the polyesther fibers used for the manufacturing of the panels and to the OSB boards [9].

We recall that the linen wall has 4 times stronger impact than straw, which is a local product the manufacturing of which is easy since it can be made by the farmer. Let us also remind that generally, straw is already a waste, especially if the farmer has no precise need of straw in his farm (for example if he just cultivates cereals for the seeds and has no animal in his farm).

But another question is to know if a wall assembly said to be natural is better for the environment than a conventional insulating wall using breeze block and glass wool. This comparison has also been made in the realized study. The results are reported on figure 6. The Environmental impacts are quantified for each step of life as previously done.

The main conclusion is that not only the wall assembly using linen panels is more impacting than the 'straw wall', as shown above, but it seems to generate more environmental impacts than a conventional wall, whatever the indicator. On the contrary, the "straw wall" is showed to be the less impacting insulating wall among the three considered assemblies.

However, each wall assembly, made with natural materials or not, has a score inferior to 1, whatever the indicator. This means that for the studied assemblies, the environmental impact is lower than the one generated by a mean European on a day.

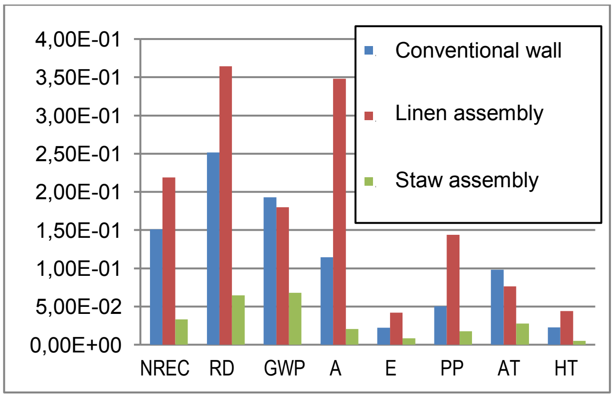

Figure 6. Comparison of three wall asssemblies

5. Conclusion

The present study deals with the use of the Life Cycle Assessment (LCA) methodology and tools to quantify the environmental impacts of two wall assemblies using natural materials : straw bundles and linen panels. The considered wall assemblies were first described from a physical and functional point of view. The LCA methodology has next been presented and applied to the previous introduced wall assemblies. the goal of the study was to compare two insulating materials (straw and linen) used on a given wall with a wood structure, of $15m^2$ area.

The obtained results show that the wall using straw bundles has a lower environmental impact than either the linen panels wall assembly or a conventinal wall, whatever the indicator. Of course, this study used some restrictive hypothesis which must be verified and tested in future works. Besides, the study has been simplified to allow a first comparison, and it must be continued, notably to quantify the influence of the different elements or steps in the life cycle of a wall assembly. However, the present results give encouraging elements for future study concerning the use of local and/or natural material for housing.

Acknowledgements

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