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HOW TO USE LCA TO ASSESS MATERIALS AS ECO-DESIGN PARAMETERS IN CONSTRUCTION PROJECTS? – APPENDIXES – EXAMPLES OF BIO-BASED MATERIALS

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S1. BIO-BASED MATERIALS FOR CONSTRUCTION

Although there is no existing official definition, it is commonly admitted that bio-based materials are materials issued from potentially renewable resources, i.e. from vegetal or animal origin.

There is over a hundred listed bio-based materials for use in buildings. One can cite hemp, flax, cellulose, straw, cotton, cork, coconut, sugar beet, wood, casein, corn, jute, kenaf, marine biomass, grass, sisal or henequen, ramie, abaca, broom, kapok, raffia, bamboo, reeds, rushes, silk, sugar, wax, citrus distillates, pine needles, feathers, sheep wool, etc. [1]. The expected ecological and health assets of bio-based materials are: a neutral carbon balance-sheet, the use of renewable resources, biodegradation after service life, recycling, reuse or incineration, the use of local fields which enables to avoid transport, to have a low grey energy, waste and agricultural co-products valorization.

In the following text, the list is limited to the most used materials in France and the ones that seem the most promising in terms of industrial development: wood, hemp, flax, straw, cork, and cellulose.

Depending on their usage in buildings, three categories of products can be distinguished, corresponding to their technological functions. Table 1 synthesizes different usage categories, bio-based materials associated with these usage categories, environmental studies dedicated to these materials, and the technological maturity of the different usages and associated standards and patents.

Usage categories have been defined as thermal insulation and/or acoustic, supporting structures and other usages.

- thermal insulation and/or acoustic:

For the insulation function, there is a large number of materials made out of plant fibers associated with a synthetic or bio-based polymer binder. Fibers are first treated and combined with polymers binders (up to 25%) ensuring materials cohesion. Synthetic-based binders products are found on the market as wool rolls or rigid or semi-rigid panels. Bio-based binder products are still at a development stage.

Insulators can be also found as compacted straw blocks without additives, in accordance with the construction rules [3].

Finally, insulators bio-based materials can also be found as aggregates and, to a lesser extent, as plant fibers combined with inorganic binder containing lime or clay. These mixed materials, commonly called “vegetal-concrete”, are already used in construction [4] while those with plant fibers are still in research [5].

For all these products, initial characteristics are now well understood [2] but their ageing processes are not well known and rarely studied. Some authors investigated the degradation of natural fibers in an alkali medium [6], vegetal concrete mechanical strength decrease after aging [7][8][9]. Nevertheless, complementary studies would be needed to evaluate life time duration of their function inside their surrounding environment.

- Supporting structures:

This usage category includes wood, straw blocks and self-supporting blocks based on hemp. Wood is already on the market, while the two others are still at research stage [10][11].

- Multi-functional construction elements:

Materials such as synthetic matrix composites or partially bio-based composites reinforced with plant fibers can have various applications: windows profiles [12], cladding, noise barriers, decking... Some of these multifunctional materials are in research and development phases whereas others are already in the marketing stage.

Table 1: bio-based materials in the construction

Usage category	Materials	Technological maturity	Standards	Environmental evaluation
Insulation	Vegetal wool	Commercialized	- European technical agreement (ex: n°ATE-05/0037 for hemp wool) [15] - EN 13168 [16]	EEHD* NF P 01-010 Ex: hemp / flax [21]; wood wool [22][23]
	Straw balls	Self-construction	- Professional standards of construction in France (applied in 2012) [3]	
	Concrete containing vegetal aggregates	Commercialized	- Hemp aggregates: [17] - Wood aggregates: EN 14 474 [18]	LCA study Hemp aggregates [24]
	Concrete containing vegetal fibers	Research [13]		
Supporting structures	Wood	Commercialized	- NF EN 594 [19], 596 [20]: timber structures	EEHD* NF P 01-010 [25][26]
	Straw balls	Research [10]		
	Precast hemp based supporting blocks	Research [14]		
Construction elements	Vegetal fibers reinforced composites	Commercialized/ in development	No regulation	LCA study [27]

* Extract of Environmental and Health Declaration

S2. MATERIALS INTRINSIC PROPERTIES

Examples of potential technological functions of materials

Table 1 in main article details materials properties that are generally required for construction materials.

Thermal properties enable the interpretation of the material's reactions due to temperature variations. *The thermal conductivity (λ)* corresponds to the heat flow per square meter, through a meter thick material for a temperature difference of one degree between the two faces of this material. *The thermal resistance (R)* indicates the resistance of a material to heat transfer for a given thickness. *The specific heat capacity (Cp)* (or mass heat capacity) is the amount of energy to supply by heat exchange to raise the temperature of one kilogram of the material of one Kelvin.

Hygrometric properties reflect the material behavior in contact with water. *Resistance factor to the diffusion of steam* (μ) expresses the resistance of a material against the spread of steam depending on its thickness. It is determined by a coefficient steam diffusion resistance. *Steam permeability* is the amount of steam which diffuses through a square meter in one hour. It is determined by steam transmission coefficient.

Acoustic properties of a given material are assessed through two quantities. *Sound absorption index* (α_w) corresponds to the ratio between the acoustic energy absorbed by the material and the incident sound energy. *Sound reduction index* (R) is used to assess the sound insulation of the materials. It is the ratio between sound intensity measured before the wall and after the wall.

The mechanical properties are characterized by three quantities. *Compressive strength* (R_c) is the maximum allowed stress of a material subjected to a crushing load. In a compression test, the compressive strength is equal to the quotient of the maximum load by the initial area of the section of the test piece. *Flexural strength* (R_f) is the maximum fiber strain of a test piece just before cracking or breaking in a bending test. For the materials which do not crack, the result is expressed as the elasticity limit in bending instead of the bending resistance. *Elasticity modulus* (E) is the speed of the deformation variation in function of the strain that is to say the slope of the linear portion of a stress-strain curve. The tangent elasticity modulus is the slope of the curve at any point. The secant elasticity modulus is equal to the stress divided by the strain in any point. It is also called “stress-strain ratio”.

Fire behavior is characterized by classes. Materials are classified into seven categories according to their combustible/flammable and inflammable properties. There are also two sub classifications: the first one concerning the smoke emission and the other the production of flaming drops or particles. The different categories are divided as it follows: two categories A1 combustible and A2 poorly combustible; four combustible categories corresponding to an increasing order of flammability: B, C, D and E; a F category corresponding to a product which has not been classified or failed to be classified in category E (it is ranked NC).

Examples of potential health and ecological functions of bio-based materials

In addition to their technological interests, bio-based materials are generally expected to offer environmental benefits. However, raw materials are combined with other products to expand some of their properties. Indeed, an oil fraction (10 to 20% of polymer) can be added to plant fibers to ensure the insulating wools cohesion for example. Flames retardants containing phosphorus, phosphates, chlorine, borates, etc., can also be added to bio-based materials to improve their fire resistance, their humidity sensibility and biological attacks [28]. Fibers are treated against the development of mould, moth and termites. From the perspective of health impacts, the presence of these additives, put bio-based materials at the same level with other materials regarding the various tests they must pass. According to Déoux [29], it is necessary to integrate its health effects in environmental analysis at each stage of its life cycle: production, implementation, service life, aging and end of life. Thus evaluating the ecological functions in situ seems indispensable. However, potential function can be explored by various tests on materials. Thereafter examples of toxicity tests are presented.

- Lethal Dose, 50 % Kill (LD50): amount of material which kills 50 % of laboratory animals, expressed in mg of poison per kg of animal weight. Example: aspirin: LD50 = 1750 mg/kg: 100 kg person will have 50 % chance of death consuming 175 grams;
- Lethal Concentration, 50 % Kill (LC50): concentration of material in ppm per volume that kills 50 % of laboratory animals during exposure period;
- Lethal Dose, Low (LD_{LO}): smallest dose ever reported to have caused a fatality
- Lethal Concentration, Low (LC_{LO}): smallest concentration ever reported to have caused a fatality.

S3. EXAMPLES OF IN SITU INDEPENDENT FUNCTIONS FOR BIO-BASED MATERIALS

In situ independent technological functions of construction bio-based materials

At the building end-of-life, deconstructed materials undergo different elimination scenarios: recycling (in open or closed loop), incineration or landfill. The **recyclability** of bio-based materials is firstly a technological function, although it can fulfil an ecological interest. A set of standards regulate the use of recycled aggregates, according to various parameters such as their granularity [35], their hardness [36], their cleanness [37][37], their sulfate content [38].

In situ independent ecological functions of construction bio-based materials

At the building end-of-life, deconstructed materials undergo different elimination scenarios: recycling (in open or closed loop), incineration or landfill. Today, bio-based materials are treated with different products in order to enhance some of their properties (resistance to ignition...). The non-bio-based nature of these admixtures means that these materials are eliminated the same way as regular materials. End of life scenarios (Table 3) should be accounted in life-cycle assessment. Different tests, standards, models, and databases, are devoted to assess environmental impacts of these end-of-life scenarios. Recyclability of wastes is mostly a technological function (see previous paragraph). Waste bio-based materials that cannot be recycled or reused are incinerated or stored in landfill sites. They can thus be carbon stocks or an expected carbon neutral renewable energy source.

The neutral carbon balance is an expected functionality that is evaluated by calculating emitted carbon from agricultural and manufacturing processes. It is included in the LCA by including production processes in the technological system and by a global warming potential indicator.

The use of renewable resources can be accounted as a resource depletion indicator. In terms of resource-oriented life cycle analysis, there is no doubt that exergetic life cycle analysis (ELCA) shows strong potential [30][31][32][33][34]. This approach relies on two concepts: life cycle analysis and exergy. The latter is a thermodynamic concept: it expresses the potential to perform work that is embodied in an energy or material, be it a resource, a material or a waste stream.

Table 3: end of life scenarios

Main scenarios		Processes to add as additional elements of the technological system	Specific models
Recycling	close loop	Deconstruction processes Treatment process Transports	
	open loop	Treatment process Transports	
Incineration		Transports Combustion process Treatment of air emissions Energy production	Combustion emissions
Landfill		Transports Impermeabilisation and/or coverage of stocks Biogas production Biodegradability	Leaching emissions Biodegradation kinetics

S4. EXAMPLES OF IN SITU CONSTANT FUNCTIONS FOR BIO-BASED MATERIALS

In situ constant technological functions of construction bio-based materials

Thermic, acoustic, hygrometric or aeraulic behavior are the most studied functions of materials inside construction elements or buildings [39-43]. As an example, Figure 1 shows direct relationship between insulating material thickness and inside temperature of a building. At the scale of a construction element or a constructed object, any thermic or hygrometric study must account for a reference environment [44], and climate has proven to be a sensitive parameter [45].

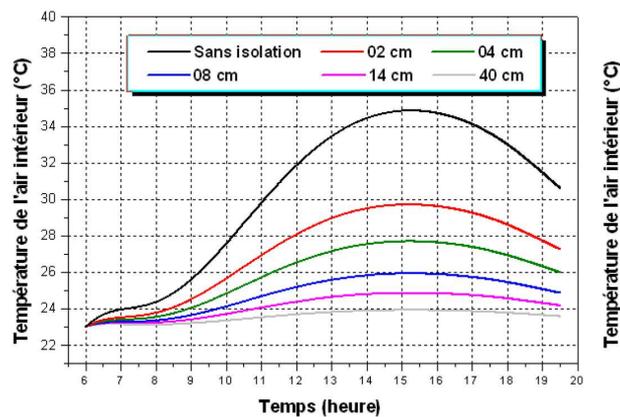


Figure 1: Relationship between insulating material thickness and inside ambient temperature (example taken from [42]).

In situ constant ecological functions of construction bio-based materials

Biodegradation process is often used in natural-waste treatments. The so-called biodegradable materials are converted in carbon dioxide and/or methane, water and biomass. A material is considered as biodegradable, when it can undergo a total biodegradation.

However, in anaerobic medium, i.e. without oxygen, biodegradability is compromised: materials often don't get altered because of the absence of oxygen necessary for aerobic micro-organisms, anaerobic process occurs producing biogas (methane), an energy source if captured. Its combustion will emit carbon dioxide, a greenhouse effect gas as well, but since that carbon was originally present in the atmosphere (fixed in plants by photosynthesis), we can consider that this energy source is neutral towards the greenhouse effect.

Thus **biodegradability** or **carbon neutral renewable energy** can be considered as constant ecological functions of bio-based materials.

S5. EXAMPLES OF IN SITU DYNAMIC TECHNOLOGICAL AND ECOLOGICAL FUNCTIONS FOR BIO-BASED MATERIALS

In situ dynamic technological functions of construction bio-based materials

The durability of the functions held by a material in place is linked to a set of constraints imposed by the environment.

The lack of feedback and testing protocols specific to bio-based materials make the assessment of their durability in a construction difficult.

Models to predict lifetime are based on the analysis of accelerated aging tests. These tests are performed under more aggressive conditions than the conditions of use. These models are not specific to the functionality of the material or the system but are rather developed or adapted according to the studied material and the stresses associated with its application. However, two generic models are commonly used: the Arrhenius one and the "acceleration factor" one. The Arrhenius model is based on the equivalence of time versus temperature. The accelerated aging is simulated by increasing the reaction rates related to aging of the material, assuming that no change in degradation mechanisms occurs during long-term use of the material. The "acceleration factor" model presupposes, using appropriate accelerated aging conditions that the kinetic curves of natural and accelerated aging are homothetic, so that it would be possible to determine the factor of acceleration between the "natural" lifetime and the accelerated one.

The lifetime prediction is also complicated by the fact that the materials could be exposed to different aging mechanisms according to their application. The materials can be exposed to physical aging phenomena (absorption, diffusion, swelling, extraction) or to chemical aging phenomena (thermo-chemical, photo-chemical, in the reaction medium, biochemical) but also to mechanical aging phenomena, such as creep relaxation or fatigue

In the case of innovative materials such as bio-based materials, there is no feedback. Then, the conventional LCA study can be completed with indicators of durability of the various functions or with estimations of lifetimes dependent on the reference environment, without being able to define detailed service life scenarios.

In situ dynamic ecological functions of construction bio-based materials

The ageing mechanisms have themselves an influence on the environmental and health impacts of the material in place: volatile organic compounds emissions (VOC), behavior in response to humidity, resistance to microorganisms, safety of substances used to preserve the sustainability of the properties (for example antifungal treatments) are characteristics to know to estimate the health impacts of any material used.

S6. EXAMPLE OF OTHER FUNCTIONS FOR BIO-BASED MATERIALS

In the case of bio-based materials, the use of local deposits avoids transport and valorization of waste, and agricultural by-products could avoid some environmental impacts but also to reduce the food source of livestock. These aspects, with economic and

environmental consequences can be evaluated in the form of additional scenarios to a given technological system (consequential LCA).

S7. SYNTHESIS OF EXAMPLES GIVEN FOR FUNCTIONS OF BIO-BASED MATERIALS

	Potential functions	In situ functions		
		<i>Independent behavior</i>	<i>Constant behavior</i>	<i>Dynamic behavior</i>
Technological functions	Thermic or acoustic insulation Hygrometric properties Mechanical properties Fire behavior	Recyclability	Insulation efficiency Bearing capacity	Durability of insulation efficiency Durability of bearing capacity Durability of hygrometric regulation Reusability
Ecological or health function	Toxicity	End of life scenarios: - Renewability of material and energy resources - Carbon stock or carbon neutral balance	End of life scenarios: - Biodegradability - Biogas production	Materials alteration and inside air emissions
Other functions		Effect on agricultural wastes Effect on global food resources and occupied surfaces Effect on transports by using local resources		

S8. APPENDIX REFERENCES

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