How to use LCA to assess materials as eco-design parameters in construction projects?

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Abstract

Eco-design aims at improving the production process of a single product and eco-design practitioners often consider environmental performances of a product as a part of its initial functionalities. Only the use of LCA can quantify environmental performances. Because of its comparative nature, using LCA for eco-design requires comparing a new solution to an existing one. In the construction sector, materials are often considered as an eco-design variant. The use of a construction material is undeniably linked to its intrinsic properties but the link between these properties and its functions is not always obvious because several physical scales are nested (materials, in construction elements, in constructed objects). Using LCA in that frame means to compare various materials on the basis of identical fulfilled functions. The purpose of this article is to suggest a generic approach for using LCA to eco-design materials for construction. This approach takes into account the multi-functionality of materials, the "nested scales" of products, and the lack of knowledge at the early stages of design. The proposed approach might be the most convenient accompanying approach that should occur all along the design process from the material to the constructed object.

1. INTRODUCTION

Life Cycle Assessment (LCA) is the most suitable method to compare environmental (i.e. health and ecological) performances of technological solutions (products or services). According to Wenzel and Hauschild [1], a product's environmental impacts can be considered when the product is designed and inappropriate solutions and technologies can be avoided from the start. To that end, eco-design aims at improving the production process of a single product and eco-design practitioners often consider environmental performances of a product as a part of its initial functionalities. There are several methods to quantify environmental performances. However, LCA is one of the best and is an accepted method both in industry and science. Because of its comparative nature, using LCA for eco-design requires comparing a new solution to an existing one.

In the construction sector, materials are often considered as an eco-design variant as a construction element or in a constructed object (building or infrastructure). Using LCA in that frame conducts requires comparing various materials and the LCA comparison is based on the concept of identical functions fulfilled by compared products or services. The reason for this principle is ethical: it is only fair to compare products or services that fulfil comparable functions. These compared functions are defined by a functional unit (FU). The choice of the FU is important because it will determine whether products are comparable, and identify elements to include or exclude from the LCA technological system.

The use of a construction material is undeniably linked to its intrinsic properties (i.e. thermal or acoustic insulation, bearing capacity, skid resistance, health or ecological innocuousness…) but the link between these properties and its functions (the word function literally means the role of something in an ensemble) in a construction element or in a constructed object is not always obvious because several physical scales are nested:

- a *material* is a component of a construction element (i.e. glass, wood, stone, steel…);
- a *construction element* designates a product as an assembly of several materials, and as a part of a *constructed object*;
- and a *constructed object* is the construction itself (i.e. a building or an infrastructure);

Ortiz et al. [2] have already discussed the comparability of buildings using LCA according to their numerous functionalities; comparing materials themselves obviously conducts to the same issue. Furthermore, the information level required for LCA appears important, whereas it is not always available at the early phases of design [3].

The multifunctional issue in LCA has already been treated in the allocation step [4], or on the question of results standardisation for decision making, as for construction products [5], (which is a wider question than just a LCA particularity). However, this issue has rarely been considered at the first stage of the method, when defining the FU. According to the literature, FUs are generally oversimplified and insufficiently defined [6], [7]. It has been proposed to define a functional profile representing the functional characteristics of a product in the early phase of design [8], but in that case, environmental performances are seen as functional properties of products in eco-design whereas they are result figures in LCA. Collado-Ruiz and Ostad-Ahmad-Ghorabi (2010) recently introduced the so-called "fuon" concept [9] in order to standardise the choice of the FU in LCA used in eco-design. This concept proposes to define set of required functions independently from the physical object itself. According to them, a function must always be quantifiable, in several manners: a physical magnitude, a logical condition, or a subjective scale [9]. They also specify that some functions are more important (called “main functions”) whereas others are less important (called “secondary functions”). However, the fuon concept does not consider the nested scales of products, although it appears to be suitable for this purpose.

The purpose of this article is to suggest a generic approach for using LCA to eco-design materials for construction. This approach must take into account the multi-functionality of materials in consistency with the fuons concept [9], the nested scales of products, and must deal with the lack of knowledge at the early stages of design [3].

The first part of this article deals with the functions of a material as multi-scale (material*: potential functions*, construction element or the constructed object: *in situ functions)*, multi-stakes and environmental behaviour issues (*independent, constant, dynamic)*, and suggests a manner to characterise functions as an outcome. In the second part, generic principles are suggested to choose main functions in accordance with LCA requirements, and the way to use LCA in a progressive and iterative process all along the construction phase. Some examples applied to bio-based materials used for buildings are presented in the Appendixes. The conclusion summarised the main principles of the proposed approach and discusses with its compatibility with the fuons concept.

2. CHARACTERISING FUNCTIONS OF MATERIALS IN CONSTRUCTION

If in LCA for eco-design, a function must always be quantifiable [9], the manner to perform this quantification will first depend on the considered scale of the product, but also on the stake and on the surrounding environment.

2.1 The nested scales issue and the surrounding environment

As said in the introduction, the choice to use a certain type of material in a construction is linked to its intrinsic properties. For a given material used in a building, five intrinsic properties are generally investigated: thermal, hygrometric; acoustic, mechanical and burning behaviour. Each property can be characterised by commonly measured values (Table 1). The detailed descriptions of cited properties are given in the Appendixes (S2).

Table 1: Examples of intrinsic properties of materials used in buildings and common characterisation values

Kinds of materials properties	Common characterisation values	Units
Thermal	Thermal conductivity (λ)	W/(m.K)
	Thermal resistance (R)	m².K/W
	Massic thermal capacity (Cp)	J/(kg.K)
Hygrothermal	Resistance factor to water vapour (μ)	m
Acoustic	Sound absorption index α_w	-
	Acoustic transmission loss index (R)	dB
Mechanical	Compressive strength (Rc)	N/mm² (MPa)
	Flexural strength (Rf)	N/mm² (MPa)
	Modulus of elasticity (E)	MPa
Burning behaviour	Categories	-

Intrinsic properties of materials are quantified but these values only reflect the potentialities of materials: they can be designated as *potential functions*. If these materials are considered at the upper scales, their intrinsic properties will not be sufficient to estimate the value of their functions inside the construction element or the constructed object. Functions of a material in a construction element or in constructed objects can depend on their surrounding environment. As an example, several materials are often combined in a construction element because of their complementary properties: a material with thermal insulation properties is associated with a structural material to fulfil the functions of a wall element. Another example is the design of a building with respect the architectural harmony of historical area, leading to the choice of a certain type of materials for construction elements.

Here the term *surrounding environment* is thus to be taken literally, i.e. "*what is around*". The terms *ecological* and *health* will be used in this article when meaning *ecosystem and human protection areas*.

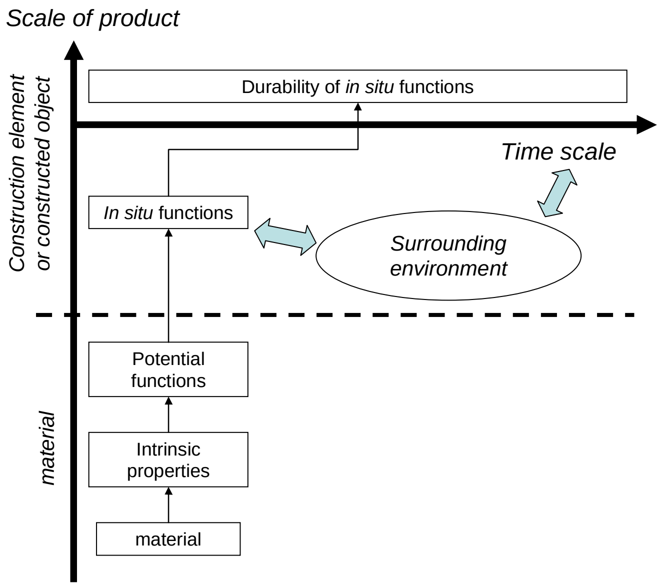

Figure 1: Interaction between nested scales, functions and surrounding environment

Given as an example in the Appendixes (S2), the thermal insulation due to a wall element does not only depend on the material's thermal properties, but also on its surrounding environment: the other materials of the construction elements, differences between inside and outside temperatures.

At the construction element or the constructed object scales, functions can be qualified as *in situ functions* and have different behaviours considering their surrounding environment as resumed in Figure 1. Furthermore, the function can be altered by the environment, i.e. the water impermeability of a roof element is altered by the occurrence of wind episodes or by ultraviolet radiations.

Considering both the surrounding environment and the time dimensions, an *in situ function* can have three types of *behaviour*, its value can be qualified as:

- *independent* of the surrounding environment (see example in Appendix S3);
- *constant* when depending on the environment but considered not variable with time (see Appendix S4)

- *dynamic* when depending on the environment and time (see Appendix S5).

These three types of behaviour reflect increasing levels of knowledge and modelling complexity.

2.2 The stake issue: the perimeter of functions

As explained in the introduction, in eco-design, new materials are considered to fulfil additional functions like health or ecological innocuousness (see Appendixes S2), or they can also be considered as biodegradable, recyclable or energy carriers at their end of life. Materials can also be used in eco-design according to their origin: renewable or non-renewable.

Construction elements can provide energy such as photovoltaic panels, or ensure natural luminosity, and thus reduce electrical energy demand in buildings. Wearing courses of road pavements are another example: in addition to their mechanical resistance, they can be designed to minimise noise annoyance or to improve security by their skid resistance.

Constructed objects can have ecological, historical, cultural or esthetical functions. An example of an ecological function is the use of specific paintings on buildings, containing titan dioxides that are expected to oxidize atmospheric pollutants (Volatile Organic Compounds and nitrogen oxides).

Thus, in addition to the scale and behaviour of functions in their surrounding environment, materials, construction elements or constructed objects can fulfil numerous and varied functions related to what can be called a *stake*. According to the perimeter of this stake, functions can be differentiated:

- *Technological functions* are those of which values can be controlled by measurable or scalable modifications of the studied product. Technological functions meet stakes that are exclusively related to quantifiable physical characteristics of the studied product. In eco-design, modifying voluntarily a target value of a technological function will necessary modify the physical characteristics of the product (component, mass, shape, size…). An example of technological function at the scale of a construction element is thermal resistance of a wall element: to increase it will conduct to change materials or to modify their thicknesses.
- *External functions* are those of which values can not be controlled by modifications of the studied product, because the perimeter of their stake is much wider than the perimeter of the product. As an example, the eco-designer aiming at improving environmental performances of a building can decide to use a bio-based material, because of an expected carbon neutral functionality. However the global decrease of carbon equivalent emissions is not certain because this stake depends on many other human activities. The carbon neutral functionality of a bio-based material is a function that is external to the product itself.

3. HOW TO DEAL WITH LCA FOR THE ECO-DESIGN OF CONSTRUCTION MATERIALS

3.1 An LCA iterative approach for eco-design

From previous parts of this article, it can be seen that choosing a material for eco-design leads to consider multi-functional, multi-scale and multi-stake issues in the LCA method. Figure 2 resumes a possible iterative articulation between LCA and eco-design. At step A, designers choose a set of action parameters on their product. Among these parameters, technological parameters represent a set of possible decisions (step B Figure 2). To evaluate environmental effects of these choices, technological scenarios can be defined (step D Figure 2) and compared using LCA (steps E to F Figure 2). The use of LCA tools (i.e. parameterized softwares, fuons [9]) allows simulation and detection of sensitive parameters (step G Figure 2). The set of effective parameters is chosen and retested at the upper scale with the same approach (step A Figure 2).

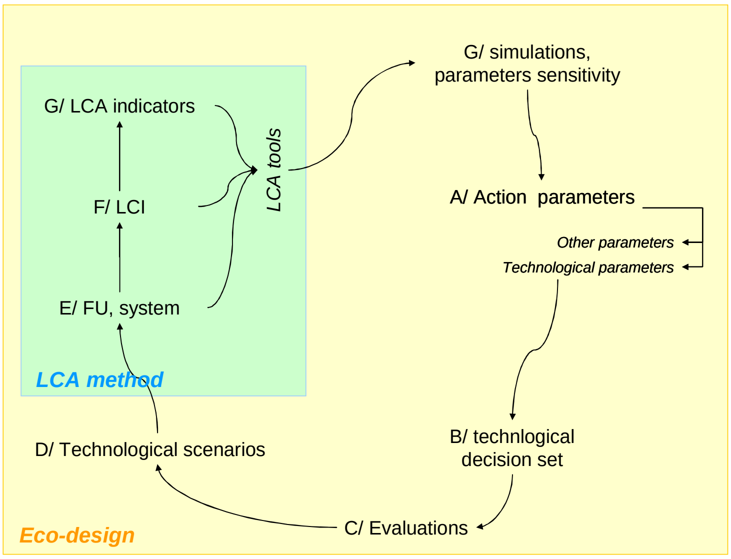

Figure 2: Iterative approach between LCA and eco-design

3.2 Description of basic rules for accounting of multiple functions

In the previous parts of this article, functions of materials have been characterised by a quantifiable value [9], a scale (potential or in situ), a behaviour towards its surrounding environment (independent, constant or dynamic), and a stake perimeter (technological or external). Suggested basic principles are given below:

1. a function has a quantifiable value in accordance with [9]
2. the functional unit should only account for technological functions;
3. health and ecological functions should be accounted using system extension, service or end of life scenarios and through indicators of impact categories;
4. economic or social functions should be accounted for by alternative scenarios using consequential LCA (see examples of economic and social functions in Appendixes S6).

Principles 2 and 3 rely on the basic purpose of LCA models: this method is dedicated to assess and compare effects of technological solutions on the environment: technological solutions are the questions to be analysed, whereas environmental stakes are the results.

Principle 4 is proposed because economic and social interactions with technological systems are important, but should be clearly stated as the studies' objectives and thus be considered as a specific scenario, i.e. they refer to economic and social modelling.

3.3 Construction materials and LCA for eco-design

Figure 2 proposed a generic articulation between LCA and eco-design, and the previous paragraph proposes generic principles to account for functions in LCA. The application to materials for construction can now be detailed. Figure 3 resumes the application of this approach to materials for construction. A synthesis of various functions fulfilled by bio-based materials is given in the Appendixes (S7).

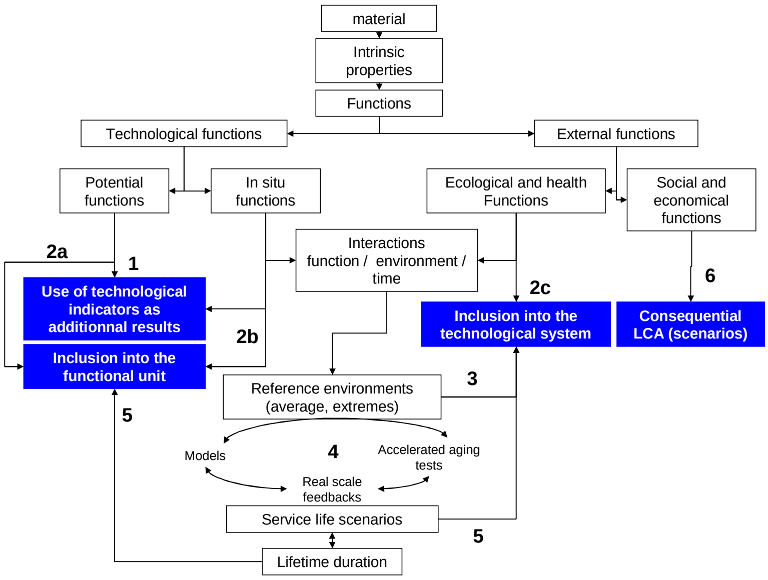

Figure 3: Generic approach to account for functions of materials in LCA studies

At the *first iteration* of Figure 2, construction materials are individually compared. Their technological potential functions have an independent behaviour towards the product's surrounding environment (see Figure 1): they can be included in the functional unit (n°1 Figure 3) or as additional results using technological indicators (n°2a Figure 3). This case will correspond to a "cradle to gate" system, with a functional unit related to a mass of material, with a chosen set of technological potential functions.

In *a second iteration* (Figure2), the scale is the one of a construction element composed of several materials (chosen according to the sensitivity assessment in the first iteration), with a chosen set of technological in situ functions. These functions are considered having an independent behaviour from the surrounding environment (n°2b Figure 3) and are treated the same as technological potential functions. This case will correspond to a "cradle to gate" system. External ecological and health functions are also considered having an independent behaviour (n°2c Figure 3) and are included in the technological system if they correspond to specific additional processes (i.e. end of life scenarios such as recycling or biodegradability) or are considered into LCA indicators results if they correspond to an LCA environmental impact category (i.e. decrease of non renewable resource consumption for bio-based materials).

In a *third iteration* (Figure 2), the scale is the one of a construction element composed of several materials and, if relevant, technological, ecological and health functions can be considered having a constant behaviour towards the product's surrounding environment (n°3 Figure2). Sensitivity (step G figure 2) to various reference (average and extreme) environment scenarios can be tested.

In a *fourth iteration*, the scale is the one of a construction element composed of several materials and, if relevant, functions can be considered having a dynamic behaviour towards the product's surrounding environment (n°4 Figure 3). Additional experimental studies and models can be required to generate service life scenarios. Sensitivity of these scenarios is tested. Models can generate lifetime duration in the functional unit (n°5 Figure 3).

In *further steps*, the scale of the constructed object can be reached, if the previous approach has been conducted for each construction element. Social and economic functions (n°6 Figure 3) can be tested with consequential LCA if social or economic factors can affect technological scenarios.

4. CONCLUSIONS

Comparing construction materials for eco-design raises complex methodological questions for using LCA. This paper highlights the interactions between value, behaviour, stakes of functions and the nested scales (materials nested in construction elements nested in constructed object). It proposes an iterative LCA approach for eco-design (Figure 2) using increasing degrees of complexity (Figure 3). The proposed approach is definitely an accompanying approach that should occur all along the design process from material scale to constructed object. The application of this approach "in the real world" is however delicate because actors are different all along the system: materials designers, architects, construction operators, users… Furthermore, it can appear as a time consuming activity for actors of which competencies are not focused on environmental assessment. It would require from these various actors to share identical methods, and to have access to suitable software tools. The "fuon" concept [9] seems a very promising concept that should help to harmonise the choice of functions and to provide results rapidly. Existing publications do not mention the nested scale issue, but the fuon structure appears suitable for that approach.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Wenzel H., Hauschild M., Alting L., 1997. *Environmental Assessment of products,* DTU, Denmark, *vol.1, 1997*

[2] Ortiz O., Castells F., Sonnemann G., 2009. Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials 23: 28-39*

[3] Millet D., Bistagnino L., Lanzavecchia C., Camous R., Poldma T. 2007. Does the potential of the use of LCA match the design team needs? *Journal of Cleaner Production 15: 335-346*

[4] Heijungs R., Guinée J.B., 2007. Allocation and 'what-if' scenarios in life cycle assessment of waste management systems. *Waste Manag. 27 (8): 997-1005*

[5] Alarcon A., Aguado A., Manga R., Josa A., 2011. A Value Function for Assessing Sustainability: Application to the Industrial Buildings. *Sustainability 3: 35-50*

[6] Hirtz J., Stone R.B., McAdams D.A., Szykman S., Wood K.L. 2002. A functional basis for engineering design: reconciling and evolving previous efforts. *Research in Engineering design 13:65-82*

[7] Stone R.B., Wood K.L. 2000. Development of a functional basis for design. *Journal of Mechanical design 122:359-70*

[8] Lagerstedt J. 2003. Functional and environmental factors in early phases of product development – Eco-functional matrix. *PhD thesis KTH, Stockholm, 156 p.*

[9] Collado-Ruiz D., Ostad-Ahmad-Ghorabi H. 2010. Fuon theory: standardizing functional units for product design. *Resources, conservation and recycling 54:683-691*