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Method to analyse the contribution of material's sensitivity in buildings' environmental impact

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ABSTRACT

The assessment of environmental performances of building is now commonly based on a life cycle approach. The current studies comparing such performances highlight the problems related to uncertainties in the Life Cycle Assessment (LCA) results. The aim of this study is to identify the sensitivity and robustness of LCA models to uncertainties related to building materials in order to strengthen comparisons which can be done between building projects and secure the assessment of the building environmental performance calculation. However, in this study, all uncertainties are not covered and we restricted our calculation to uncertainties related to the use of building materials during the life cycle of the whole building. We have considered that the relative contribution of each material to the environmental impact of building is sensitive to three key points which are submitted to uncertainties: the service life of the building component; the environmental impact of this building component's production and the amount of material used in the building. The assessments of the uncertainties are treated at two levels: the material or element level and the building level. A statistical method, based on Taylor series expansion is developed to identify the most sensitive and uncertain parameters, with standpoint to strengthen comparison between projects. The first results are promising, although further work remains to be done to better quantify the uncertainties at the material scale.

1. Introduction

Buildings are the largest energy consumers and greenhouse gases emitters, both in the developed and developing countries (UNSTATS, 2010). In continental Europe, the energy used in buildings alone is responsible for up to 50% of carbon dioxide emissions (Capros et al., 2001; Levine et al., 2007). Urgent changes are therefore required relating to energy savings, production and application of materials, use of renewable resources, and to reuse and recycling of building materials. However, to be able to focus on the pertinent and most sensitive aspects of the building sector, it is fundamental to accurately quantify which part of the life cycle of which element is the main contributor to the environmental impacts. To do so, and since more than 30 years, scientific community have developed and validate life cycle assessment (LCA) methodology (Heijungs et al., 1992; Fink, 1997; Klöpffer, 2006; Sonnemann et al., 2003). The assessment includes the whole life-cycle of a product, process, or system encompassing the extraction and processing of raw materials, manufacturing, transportation and distribution, use, reuse, maintenance, recycling and final disposal. LCA has become a widely used methodology, because of its integrated way of treating the framework, impact assessment and data quality (Klöpffer, 2006). LCA methodology is based on ISO 14040 and consists of four distinct analytical steps: defining the goal and scope, creating the life-cycle inventory, assessing the impact and finally interpreting the results (ISO, 2006).

However, as LCA is more and more used as an analytical decision support tool (Fava et al., 1993; Werner and Scholz, 2002; Blengini and Di Carlo, 2010), it can be used to assist policy decision and the question of the reliability of its results becomes then pregnant. The

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sensitivity of results to hypothesis and data quality has long been discussed (e.g. Huijbregts, 1998; Basset-Mens and van der Werf, 2005; Lloyd and Ries, 2007; Wang and Shen, 2013). Concerning buildings, the reliability and robustness of results is even more complex than for the other industrial sectors due to their very long service life. It induces large question on how to assess the fact that:

- The energy during the use phase as well as its nature (and its associated environmental impact) will drastically change during the next 50 years (Grübler et al., 1999; de Vries et al., 2007; Tian and de Wilde, 2013).
- Some Building materials have a lower service life than the building itself (Kellenberger and Althaus, 2009) and their effective service life is influenced by many factors which can be classified between failure, dissatisfaction and change in consumer needs (Cooper, 2004). Failure is related to the degradation of the building elements and depends significantly on use condition (humidity, UV, temperature, etc...), dissatisfaction is mostly associated with styling changes, fashion trends and finally occupant needs may also change over time when occupants have children or become elderly for instance. All these factors will strongly affect the service life of building elements (Ashworth, 1996; Potting and Blok, 1995) and then, the amount of material needed for all the service life of the building.

Uncertainties in buildings are also controlled by the same type of uncertainties than for other industrial sectors: environmental database quality (Weidema and Wesnaes, 1996), technological variation between materials' production plant (Lewandowskaet et al., 2004; Reap et al., 2008; Gomes et al., 2013). A review of uncertainties in LCA can be found in Huijbregts (1998), Björklund (2002) and Imbeault-Tetreault (2010).

As a consequence, if we want to be able to assess the environmental impact of two building projects and be able to promote the choice of one rather the other, we need firstly to quantify these uncertainties and in a second step, identify the main contributions. In the present study, we will only study the uncertainties related to the building materials used during the life cycle of the building. For the moment, most of the LCA on buildings are comparing building designs without paying attention to the associated uncertainties. Others are using uncertainties associated with the pedigree matrix (Weidema and Wesnaes, 1996; Frischknecht and Rebitzer, 2005) which inform only on the quality of the environmental data but not on the service life uncertainty. A few studies have tried to address the mixed question of environmental data quality and service life for building elements but these studies were limited to one specific building's element (Aktas and Bilec, 2012). In our study the LCA of the building is calculated from the decomposition of the building in building material and component combination. The elements such are the windows, solar water heater etc., were preferred to be treated as building element and not decomposed in materials as their service life is defined at that scale. This choice can also be justified by SETAC who recommend paying attention to reference flows and not necessarily distinguish every materials (SETAC, 1999). The assessment of the uncertainties is treated at two levels: the material (or element) level and the building one. At the material level we want to identify which type of uncertainty has the most influence on the environmental performance of a material. We identified uncertainties concerning its production process, the quantity effectively used on site or its service life in the building. At the building scale we want to identify which material or element has the most influence on the environmental performance of the building.

To do so, a statistical method is used to identify the main parameters which contribute to the uncertainty of final results. The contribution analysis includes sensitivity and uncertainty analysis. Indeed a parameter which has a small sensitivity but a large uncertainty may be just as important as a parameter with a larger sensitivity but smaller uncertainty (Imbeault-Tetreault, 2010; Morgan et al., 1900). A description of the method is presented in the next section. Once the methodology is developed it is applied to one case study of two houses projects.

2. Method

Different methods have been proposed to evaluate data inaccuracy in LCA outcomes (SETAC, 2001). A review of uncertainty analysis methods can be found in Björklund (2002) and Leroy (2009). In this research we are developing a simplified analytical method based in Taylor series expansion. The other main alternative is the Monte Carlo simulation which is a numerical method that artificially allows the reconstruction of a random phenomenon simulating fictitious samples based on hypothesis on random variables. It is therefore necessary to define the probability density for the model inputs, assumed to be independent, which will be propagated to obtain the probability density of the output variable (Murtha, 2000). The Monte Carlo method is therefore time consuming and require realistic hypothesis on the distribution function.

The method we develop, based on analytical method derived from Taylor series expansion (Ciroth et al., 2004), is on the contrary easy to implement. We first propose a method for contribution analysis and then for uncertainty propagation and calculation.

2.1. General theory of contribution analysis

The contribution analysis includes sensitivity and uncertainty analysis.

2.1.1. Sensitivity analysis

The key purpose of sensitivity analysis is to identify which key data or assumptions significantly influence the result. This analysis allows simplifying data collection and analysis without compromising the robustness of a result and to identify crucial data that must be thoroughly investigated (Annex 31, 2005).

Sensitivity analysis can be described as follow:

Supposing an output variable z which depends on n inputs variables $x_1, x_2, \ldots x_i, \ldots x_n$ and their dependence which is expressed by a function f:

$$z = f(x_1, x_2, \ldots x_i, \ldots x_n) \tag{1}$$

Therefore, for a single nominal scenario, for which the different input variables have a given value $X^0 = (x_1^0, x_2^0, \ldots x_i^0, \ldots x_n^0)$ (each might be the mean, median or the mode values), the corresponding nominal output value is then defined as:

$$Z^0 = f\left(X^0\right) \tag{2}$$

(Morgan et al., 1900) has defined the normalised sensitivity coefficient known as elasticity coefficient by the equation:

$$U_z(x_i) = \left[\frac{\partial f}{\partial x_i}\right]_{X^0} \times \frac{x_i^0}{z^0} \tag{3}$$

Equation (3) can be used to calculate the relative change of the output result for a nominal variation in the input x_i. For instance, if we consider an equation such as $z = x_1^2 \times x_2$. For a scenario $X^0 = (x_1^0,\ x_2^0)$ and an output value $z^0 = x_1^{0^2} \times x_2^0$, the sensitivity coefficients for the two inputs (x_1, x_2) have the value: $U_z(x_1) = 2$ and $U_z(x_2) = 1$. It means that for a change in input variable x_1 of 1% the