Improving the reliability of environmental assessments of buildings

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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 these uncertainties in order to strengthen comparisons that can be done between building projects. The ultimate objective would be to implement sensitivity analysis in ELODIE software which is the life cycle assessment of buildings tool developed by the "Centre Scientifique et Technique du Bâtiment" in France. Calculation of building LCA conveys uncertainties due to: the calculation model; the data used into calculation and the LCA user's level of practice. This study is only concerned by the uncertainties related to the data used for calculation and is restricted to the data used for building components at the building scale. 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 components; the environmental impact of this building component's production and the amount of material used in the building. In this study, statistical analysis allows to test the contribution of these three uncertainty parameters on the final impact for each building components at the building scale. Most sensitive parameters are identified. As a consequence, we are able to models buildings LCA throughout the main building materials as well as the potential variation of their impacts due to uncertainties on the three identified parameters. The first results are promising, although further work remains to be done to better quantify the uncertainties in the material scale.

Keywords: LCA of building, uncertainties, variability, contribution analysis.

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1. Introduction

Buildings are the largest energy consumers and greenhouse gases emitters, both in the developed and developing countries UNSTATS (2010). Li (2005) and Bribian (2010) cite that the building construction consumes approximately 40% of the total material use, 30-40% of the societies total energy demand, roughly 1/3 of the total CO2 emission. Urgent changes are therefore required relating to energy saving, production and application of materials, use of renewable resources, and to recycling and reuse 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, which part of the building industry, which part of the structural elements are the main contributors to environmental impacts and for which reason. 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). Life cycle assessment “cradle-to-grave” approach, that begins with the gathering of raw materials from the earth and ends at the points when all materials are returned to the earth, is used to quantify the environmental impacts of a product on the environment Saic (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). Applying LCA to buildings has been done since a long time Fava (2006), but the reliability and robustness of results is even more complex than for the other industry sectors due to their very long service life, environmental database quality Weidema et al (1996), technological variation between materials’ production plant Lewandowskaet et al (2004), Reap et al (2008). 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 order to be able to constrain the constructor or to inform the stakeholder on the specific points on which they need to pay attention. For the moment, most of the LCA on buildings are comparing building designs without paying attention to the associated uncertainties. Other 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, we want to assess these uncertainties at the two levels: the material level in order to identify which input parameter (lifetime, quantity or impact coefficient) has the most influence on the environmental performance of a material; and at the building scale to identify which material has the most influence on the environmental performance of building.

Furthermore, the objective of our study is to develop a method that can be easily used in order to use it at the project phase, when all the decisions have not been made and that stakeholders have to decide which project they want to fund and build. In that phase of the project, it is necessary to have a simple method that is able to highlight the main points of uncertainties in order that these aspects can be solved in a second phase of the project, and choose a project that will effectively be more environmentally friendly than the other one.

To do so, we proposed a methodology based on the statistical which is used to identify the most contributor parameters to the uncertainty of final results. The contribution analysis includes sensitivity and uncertainty analysis Imbeault-Tetreault (2010), as a parameter that has a small sensitivity but a large uncertainty may be just as important as a parameter with a larger sensitivity but smaller uncertainty Morgan et al (1990). Contribution analysis allows than to reach the goal of simplifying data collection and analysis without compromising the robustness of a result and to identify crucial data that must be thoroughly investigated. A general description of the method is resented in the next section before its application to buildings. Once the methodology described it is applied for the comparison of two single detached houses.

2. General theory of contribution analysis

The key purpose of sensitivity analysis is to identify the key data that have most influence on a result. But an input variable that has a small sensitivity but a large uncertainty may be just as important as a parameter with a larger sensitivity but smaller uncertainty Morgan et al (1990). Persuading a contribution analysis we must kept in consideration both analysis.

The contribution analysis which follows is mainly inspired by Ciroth *et al*. (2004), Morgan *et al*. (1990), Protassov (2002) and Taykir (2000). Consider a model represented as a function, f, with n uncertain inputs, and one output z.

$$z = f\left(x_1, x_2, \ldots x_i, \ldots x_n\right)$$

Proposing a Taylor series expansion of this function with respect to a chosen point $X^0 = \left(x_1^0, x_2^0, \ldots, x_i^0, \ldots x_n^0\right)$. If we can assume the independence of input parameters, the first order approximation of Taylor series expansion of function will be expressed:

$$\operatorname{var}(z) = \sum_{i=1}^{n} \operatorname{var}(x_i) \left(\frac{\partial f}{\partial x_i}\right)^2_{X^0} \qquad (1)$$

Where $\operatorname{var}(z)$ represent the variance of output and coefficients such as $\left(\frac{\partial f}{\partial x_i}\right)$ are referred to as sensitivity coefficients (Morgan 1990). The problem of determining the real value of a physical quantity (x_i) is inseparable by its uncertainties. The degree of uncertainty in each variable x_i can be expressed by its standard deviation σ_{x_i}.

$$\sigma_{x_i} = \sqrt{\operatorname{var}(x_i)} \qquad (2)$$

More simply the equation (5) has the form: $\operatorname{var}(z) \approx \sum_{i=1}^{c} \Delta x_i^2$ (3)

Where: $\Delta x_i = \sigma_{x_i} \left(\frac{\partial f}{\partial x_i}\right)_{X^0}$ (4)

The relative contribution of each input parameter in output result is identified by equation:

$$RC_{M1}(x_i) = \left(\frac{\Delta x_i^2}{\operatorname{var}(z)}\right) \times 100 \qquad (5)$$

A second method to identify the contribution of input data in output result is to study different scenarios of $f\left(x_i\right)$. In our case the output result is supposed to be a function of n input variables, so n scenarios will be performed.

First scenario is to fix all the input variable except one x_1 . Applying the Taylor series expansion in function will provide:

$$\operatorname{var}\left(z_1\right)=\operatorname{var}\left(x_1\right)\left(\frac{\partial f}{\partial x_1}\right)_{X^0}^2 \Rightarrow \sigma_{z_1}=\sigma_{x_1}\left(\frac{\partial f}{\partial x_1}\right)_{X^0}=\Delta x_1 \tag{6}$$

Applying the Taylor series expansion with all other variables will have:

$$\begin{gathered}
\operatorname{var}\left(z_2\right)=\operatorname{var}\left(x_2\right)\left(\frac{\partial f}{\partial x_2}\right)_{X^0}^2 \Rightarrow \sigma_{z_2}=\sigma_{x_2}\left(\frac{\partial f}{\partial x_2}\right)_{X^0}=\Delta x_2 \\
\vdots \\
\operatorname{var}\left(z_i\right)=\operatorname{var}\left(x_i\right)\left(\frac{\partial f}{\partial x_i}\right)_{X^0}^2 \Rightarrow \sigma_{z_i}=\sigma_{x_i}\left(\frac{\partial f}{\partial x_i}\right)_{X^0}=\Delta x_i \\
\vdots \\
\operatorname{var}\left(z_c\right)=\operatorname{var}\left(x_c\right)\left(\frac{\partial f}{\partial x_c}\right)_{X^0}^2 \Rightarrow \sigma_{z_c}=\sigma_{x_c}\left(\frac{\partial f}{\partial x_c}\right)_{X^0}=\Delta x_c
\end{gathered} \tag{7}$$

Uncertainty in the output result can then be calculated as a sum of the contribution of each input parameter's uncertainty in output result:

$$\Delta z=\sum_{i=1}^{c} \Delta x_i \tag{8}$$

The relative contribution of each input parameter in output result is calculated by equation:

$$RC_{M2}\left(x_i\right)=\frac{\Delta x_i}{\Delta z} \tag{9}$$

Both equation (5) and (9) can be used for identifying which input parameter has the most significant contribution to output result. The difference between methods is that the first method pushes up the input parameter with the higher contribution due to the square values. We underline that the hierarchy of the contribution inputs calculated with the two methods is the same.

3. Case study

In this case study we have applied the methodology presented above in order to compare two different projects of single-family detached house. The houses studies are fictifs and the are modelled by the Centre Scientifique et Technique du Bâtiment, France with a surface area of 100 m^2 and the lifetime of the house is considered to be equal to 50 years. One of the projects is a house with a reinforcing concrete structure (Project 1) and the second one is made with a wood structure (Project 2). The environmental performance of the building is commonly presented as a sum of the environmental performance of its building material plus the energy and water consumed during the use phase.

In the present paper, we will only consider the building materials used during all the service life of the building. Water and energy consumption during the use phase are not considered but could be implemented in a further extension of the method. Equation (10) is used for evaluation of environmental impacts over the life cycle of the building. I_g , the value of the impact of the category g for the building, is calculated as the sum of the contribution of the impact of each building material (i).

$$I_g = \sum_{i=1}^{c} I_{g,i} \qquad (10)$$

Where: c present the number of elements and material which the building is composed.

And the environmental performances of materials are calculated by the equation:

$$I_{f,i} = n_i \times k_{f,i} \times m_i \qquad (11)$$

Where: $n_i = \dfrac{LB}{LM_i}$ (12)

LB -> lifetime of building;

LM_i -> lifetime of material;

$k_{f,i}$ is the environmental impact for the impact category f of life cycle of one unit mass of the building material i;

m_i is the amount of material i used for the construction of the building

n_i is the number of use of the material i during the service life of the building;

As shown in equation (11), uncertainties come from the mass, the service life and the elementary environmental impact of each material. To take them into account, we have introduced uncertainties. The variations in mass of materials are associated with waste on construction site ADEME (2001) and differences between provisional maps and the reality (Expert judgement). According to expert’s judgements and ADEME (2001), uncertainties that are used vary from -5% to +10% of materials’ quantities. In the case of knowledge of the minimum, mean and maximum of a physical quantity the normal distribution or triangular distribution is preferred to be used. In our study the standard deviation is calculated supposing that the distribution law for the quantity taken off is a triangular one.

Service life of materials has been calculated through the use of different references Lair (2000), in order to define a mean value and a standard deviation for each material.

The impacts coefficients, the environmental products declaration (EPD) of French database INIES (2012) are used. It means that all the life cycle of the product is considered (production, transport, use, demolition and end of life) and that the impact categories are the one from the NF P 01-010 standard AFNOR (2004). These standards are close to CML methods Guinée *et al* (2002). The standard deviations in this case are calculated using these EPDs.

When the EPD doesn’t exist, environmental impacts have been calculated with Ecoinvent v2.2 database Kellenberger *et al* (2007). However, as Ecoinvent is a calculation from cradle to gate (production at plant), results need to be adapted to be compared to INIES. Previous studies have shown that this comparison was possible for most of the standard impact categories (GWP, acidification, energy) when some adaptations are made. For cradle-to-grave calculation, the other phases such as transport, use and en of life are added by talking a given percentage of the production phase. Actually, previous works have shown that it was possible, without deteriorating too much the results, to consider the other phases of the life cycle as a given percentage of the production phase Lasvaux (2010). Concerning the standard deviation, the pedigree matrix of the process associated with the production of material in the Ecoinvent database is used. In the only case of reinforcing concrete elements, a further uncertainly concerning the amount of steel is added. More detailed the means and standards deviations for lifetime, quantity taken off and indicators of global warming potential (GWP) and atmospheric acidification (AA) are presented in table 1.

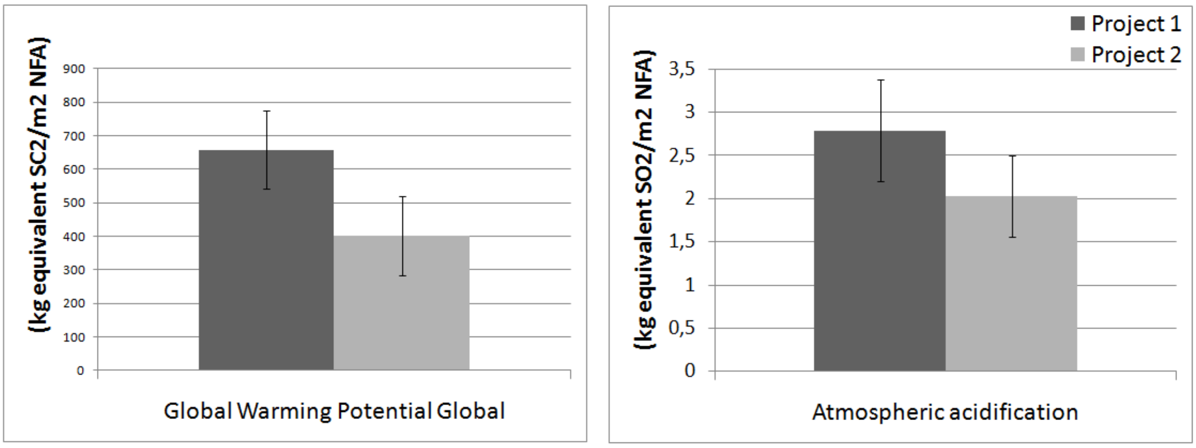
Table 1: Details of the technical data used for the life cycle inventory of both houses solutions

Projects Decomposition of projects		Project 1	Project 2	
Materials	Elements	Qty	Qty	Unit
Non-structural clay	Tiles	130	IDEM	m^2
Structural clay	Wall	25727		kg
Gravel	Access road an drainage	33448	IDEM	kg
Non-structural concrete	Mortal	1530		kg
	Sill	347		kg
	Blinding concrete	1.44	IDEM	m^3
	Concrete layer/grout	4.94	IDEM	m^3
Structural concrete	Basement wall	9657	IDEM	kg
Reinforcing concrete steel	Beam	3.216		m^3
	Column	0,9821		m^3
	Foundations	11.31	IDEM	m^3
	Stairs	0,4935		m^3
	Floor	8,276		m^3
	Slab	15	IDEM	m^3
Non-structural steel	Garage door	4.8	IDEM	m^2
	Uprights and rails	54.5	IDEM	kg
	Valves	27.5	IDEM	kg
Non-structural wood	External and internal doors	13.45	IDEM	m^2
	Cabinet for sink	0.065	IDEM	m^3
	Shutter		15.63	m^2
	Panelling		54.54	m^2
Structural wood	Truss construction	3.82	IDEM	m^3
	Beam		1.13	m^3
	Column		0.32	
	Stairs		0.2657	m^3
	Deck		6	m^3

	Wall		6.8015	m^3
Glass wool	Thermal and acoustical insulation		809	kg
Rock wool	Thermal and acoustical insulation	1211		kg
PVC	Shutter	15.63		m^2
	Pipelines	519.5		kg
	Panelling	54.54		m^2
Bitumen	Waterproofing	159.25	IDEM	m^2
Plaster	Product for false ceiling/ suspended ceiling/etc	4643	IDEM	kg
Polyurethane	Thermal and acoustical insulation	243.5	IDEM	kg
Photovoltaic panels	Water heater	4	IDEM	m^2
Window	PVC	15.61		m^2
	Bois		15.61	m^2
Paint	Paint	166.6		kg
	Varnish		115.2	kg
Electrical installation	Light-switch/ consumption/indicator/etc	1	IDEM	u
Porcelain	WC	2	IDEM	u
	Sink	2	IDEM	u
Acrylic	Bathtub	1	IDEM	u
Enamelled sandstone	Kitchen sink	1	IDEM	u
	Shower plate	1	IDEM	u
Porcelain stoneware	Paving	72.13	24	m^2
Zinc	Gutter system	10.6	IDEM	m^2

Once all uncertainties are defined, we can use the analytical uncertainty propagation method based in Taylor series expansion (equation (1)), for assessing the uncertainty for the GWP and AA indicators. In figure 1 are presented the value for an interval of 95%.

Figure 1: Environmental impact of the life cycle of two houses solutions



Two types of results can be seen depending on the impact category. For impact categories related to GWP the results show that the project with reinforcing concrete steel structure has greater environmental impacts than the wood structure and we can conclude that the second project is better than first one. However for the other impact categories, uncertainties variations so that the two projects don't have significant differences. In order to reduce the uncertainties and choose the best project, we propose to identify the contribution of the different material in order to evaluate where are the easiest and most efficient improvements which can be done to reduce this variation and have finally a significant difference between the two projects.

Table 2: Relative contribution of different materials to the building life cycle assessment for atmospheric acidification indicator

Project Materials	Project 1		Project Materials	Project 2
Rock wool	11,97%		PVC	16,10%
PVC	11,87%		Bitumen	15,55%
Bitumen	11,44%		Non-structural wood	10,27%
Non-structural wood	7,56%		Plaster	8,72%
Porcelain stoneware	7,08%		Glass wool	7,1%
Plaster	6,4%		Photovoltaic panels	5,62%
Paint	6,28%		Structural concrete	5,01%
Window	5,02%		Polyurethane	4,47%
Non-structural concrete	4,98%		Reinforcing concrete steel	4,14%
Photovoltaic panels	4,13%		Window	3,8%
Structural clay	3,98%		Non-structural steel	3,36%
Reinforcing concrete	3,82%		Porcelain stoneware	3,2%
Structural concrete	3,68%		Porcelain	3,13%
Polyurethane	3,29%		Zinc	2,58%
Porcelain	2,31%		Structural wood	2,22%
Zinc	1,89%		Non-structural clay	1,98%
Structural wood	1,63%		Varnish	0,99%
Non-structural clay	1,45%		Non-structural concrete	0,74%
Non-structural steel	0,44%		Acrylic	0,48%
Acrylic	0,36%		Enamelled sandstone	0,38%
Enamelled sandstone	0,28%		Gravel	0,15%
Gravel	0,11%		Electrical installation	0,01%
Electrical installation	0,01%			
TOTAL	100%			100%

At the building scale, table 2 shows clearly that insulation rock wool, PVC and bitumen are the three materials which have the greatest contribution to variability of the buildings' environmental impact. It is due at a combination of the amount of material used of its elementary impact and lifetime as well as its uncertainty. Application of contribution analysis in this material will give the values presented in table 3:

Table 3: Relative contribution of different inputs to the material life cycle assessment for atmospheric acidification indicator

	Lifetime	Impact coefficient	Quantity taken off
Rock wool	86%	07%	07%
PVC	83%	14%	03%
Bitumen	63%	34%%	03%

For the three materials the highest contribution to uncertainties comes from the lifetime. It could then be possible to try to improve the knowledge on service life. For instance, a control on site work could be done, just after the rock wool has been fixed in order to certify that it has been done correctly (vapour barriers, humidity control, etc…). Similar work could be done for bitumen where it could for instance be mandatory to avoid an exposition to UV or high temperature in order to preserve the bitumen qualities. Finally, PVC tubes could be installed in a way that they can easily be check and only partially removed so that the majority of PVC tubes can have a given lifetime expectation. The methodology proposed here is then a tool for stakeholders to quickly evaluate in a project which aspects will induce a large variability on the expected environmental performance and take the appropriate decision to reduce the uncertainties on the environmental impact. For instance, if it is possible through design and quality control to be sure that service life of rock wool will be higher than 30 years, the one of PVC higher than 25 years and the one of bitumen higher than 30 years, and then uncertainties are reduced and presented in table 4. The two projects are now significantly different.

Table 4: Environmental impact of two houses solution

Indicators / Project	Atmospheric acidification (kg equivalent CO_2/m^2 NFA)		
	Minimum	Mean	Maximum
Project 1	2.132	2.52	2.91
Project 2	1.436	1.74	2.04

4. Conclusion

Analytic uncertainties propagation, using Taylor series expansion has quickly and easily permitted to calculate the uncertainty of environmental indicators. Previous studies have been working with Monte Carlo analysis which is time consuming when addressing uncertainties of each material. The contribution analysis using the second method allows identifying the highest contribution factors to the variability of output at material and then at building scale. In that situation, the developed method provides a very easy tool, which will give the relative contribution of each material to the variability of the building. In our case, we define Rockwool, PVC and bitumen as major contributors due to uncertainties on their lifetime. It could then be possible to try to improve the knowledge on service life. For instance, a control on site work could be done, just after that the rock wool has been fixed in order to certify that it has been done correctly (vapour, barriers, humidity control etc). Similar work could be done for bitumen and PVC tubes. Once these certification and design controls have been implemented in the new project the comparison can be done again until it reached a position where the two projects are effectively significantly different. The relative contribution of environmental impact, lifetime and quantity taken off is essentially controlled by our hypothesis on the fact that structural material last as long as the house. This assumption where concrete, bricks or wood last as long as the house, could be discussed and probably improved. We think that the appropriate way of assessing this uncertainty would be to have uncertainty on the lifetime of the house rather than on the structural materials. Actually, it can be explained as the fact that if concrete is deteriorated through corrosion or that if bricks wall is fracture, it might reduce the lifetime of all the house, rather than just inducing the replacement of structural materials. This aspect should however be assessed in more details in further works. Thus, it is worthwhile to note that the methodology would be the same. Expect this strong assumption this fast identification is then a tool for stakeholder to constrain constructors or design offices to provide controls or design modification on specific aspect of the building throughout its service life. This first results presented here are encouraging as it has been shown that it is possible to choose which materials parameters has to be constrained in order to have significant difference between two projects that were initially to close to be distinguished. However further work is needed, in particular to improve the database on uncertainties at the material scale. Our study is actually based on an extensive bibliographic works; however variability on the environmental impact of materials' production as well on their effective service life needs to be better constrained to be able to apply our methodology to other case studies.

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