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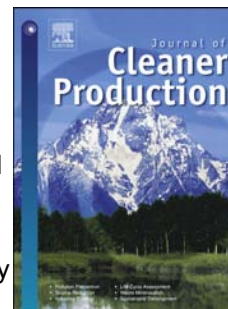
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1 **Method to analyse the contribution of material's sensitivity in buildings'**  
2 **environmental impact**

3

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16

17

18 **Keywords:** LCA, building, uncertainty, variability, contribution analysis.

19

20

21

22 **Abstract**

23 The assessment of environmental performances of building is now commonly based on a life  
24 cycle approach. The current studies comparing such performances highlight the problems  
25 related to uncertainties in the Life Cycle Assessment (LCA) results. The aim of this study is  
26 to identify the sensitivity and robustness of LCA models to uncertainties related to building  
27 materials in order to strengthen comparisons which can be done between building projects

28 and secure the assessment of the building environmental performance calculation. However,  
29 in this study, all uncertainties are not covered and we restricted our calculation to  
30 uncertainties related to the use of building materials during the life cycle of the whole  
31 building. We have considered that the relative contribution of each material to the  
32 environmental impact of building is sensitive to three key points which are submitted to  
33 uncertainties: the service life of the building component; the environmental impact of this  
34 building component's production and the amount of material used in the building. The  
35 assessments of the uncertainties are treated at two levels: the material or element level and the  
36 building level. A statistical method, based on Taylor series expansion is developed to identify  
37 the most sensitive and uncertain parameters, with standpoint to strengthen comparison  
38 between projects. The first results are promising, although further work remains to be done to  
39 better quantify the uncertainties at the material scale.

40

## 41 **1. Introduction**

42 Buildings are the largest energy consumers and greenhouse gases emitters, both in the  
43 developed and developing countries (UNSTATS, 2010). In continental Europe, the energy  
44 used in buildings alone is responsible for up to 50% of carbon dioxide emissions (Capros,  
45 2001; Levine et al., 2007). Urgent changes are therefore required relating to energy savings,  
46 production and application of materials, use of renewable resources, and to reuse and  
47 recycling of building materials. However, to be able to focus on the pertinent and most  
48 sensitive aspects of the building sector, it is fundamental to accurately quantify which part of  
49 the life cycle of which element is the main contributor to the environmental impacts. To do  
50 so, and since more than 30 years, scientific community have developed and validate life cycle  
51 assessment (LCA) methodology (Heijungs *et al.*, 1992; Fink, 1997; Klöpffer, 2006;

52 Sonnemann *et al.*, 2003). The assessment includes the whole life-cycle of a product, process,  
53 or system encompassing the extraction and processing of raw materials, manufacturing,  
54 transportation and distribution, use, reuse, maintenance, recycling and final disposal. LCA has  
55 become a widely used methodology, because of its integrated way of treating the framework,  
56 impact assessment and data quality (Klöpffer, 2006). LCA methodology is based on ISO  
57 14040 and consists of four distinct analytical steps: defining the goal and scope, creating the  
58 life-cycle inventory, assessing the impact and finally interpreting the results (ISO, 2006).

59 However, as LCA is more and more used as an analytical decision support tool (Fava *et al.*,  
60 1993; Werner and Scholz, 2002; Blengini and Di Carlo, 2010), it can be used to assist policy  
61 decision and the question of the reliability of its results becomes then pregnant. The  
62 sensitivity of results to hypothesis and data quality has long been discussed (e.g. Huijbregts,  
63 1998; Basset-Mens and van der Werf, 2005; Lloyd and Ries, 2007; Wand and Shen, 2013).  
64 Concerning buildings, the reliability and robustness of results is even more complex than for  
65 the other industrial sectors due to their very long service life. It induces large question on how  
66 to assess the fact that:

67 - The energy during the use phase as well as its nature (and its associated environmental  
68 impact) will drastically change during the next 50 years (Grübler *et al.*, 1999; de Vries *et al.*,  
69 2007; Tian and de Wilde, 2013).

70 - Some Building materials have a lower service life than the building itself (Kellenberger and  
71 Althaus, 2009) and their effective service life is influenced by many factors which can be  
72 classified between failure, dissatisfaction and change in consumer needs (Cooper, 2004).  
73 Failure is related to the degradation of the building elements and depends significantly on use  
74 condition (humidity, UV, temperature, etc...), dissatisfaction is mostly associated with styling  
75 changes, fashion trends and finally occupant needs may also change over time when  
76 occupants have children or become elderly for instance. All these factors will strongly affect

77 the service life of building elements (Ashworth, 1996; Potting and Blok, 1995) and then, the  
78 amount of material needed for all the service life of the building.

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

84 As a consequence, if we want to be able to assess the environmental impact of two building  
85 projects and be able to promote the choice of one rather the other, we need firstly to quantify  
86 these uncertainties and in a second step, identify the main contributions. In the present study,  
87 we will only study the uncertainties related to the building materials used during the life cycle  
88 of the building. For the moment, most of the LCA on buildings are comparing building  
89 designs without paying attention to the associated uncertainties. Others are using uncertainties  
90 associated with the pedigree matrix (Weidema and Wesnaes, 1996; Frischknecht and  
91 Rebitzer, 2005) which inform only on the quality of the environmental data but not on the  
92 service life uncertainty. A few studies have tried to address the mixed question of  
93 environmental data quality and service life for building elements but these studies were  
94 limited to one specific building's element (Aktas and Bilec, 2012). In our study the LCA of  
95 the building is calculated from the decomposition of the building in building material and  
96 component combination. The elements such are the windows, solar water heater etc., were  
97 preferred to be treated as building element and not decomposed in materials as their service  
98 life is defined at that scale. This choice can also be justified by SETAC who recommend  
99 paying attention to reference flows and not necessarily distinguish every materials (SETAC,  
100 1999). The assessment of the uncertainties is treated at two levels: the material (or element)  
101 level and the building one. At the material level we want to identify which type of uncertainty

102 has the most influence on the environmental performance of a material. We identified  
103 uncertainties concerning its production process, the quantity effectively used on site or its  
104 service life in the building. At the building scale we want to identify which material or  
105 element has the most influence on the environmental performance of the building.  
106 To do so, a statistical method is used to identify the main parameters which contribute to the  
107 uncertainty of final results. The contribution analysis includes sensitivity and uncertainty  
108 analysis. Indeed a parameter which has a small sensitivity but a large uncertainty may be just  
109 as important as a parameter with a larger sensitivity but smaller uncertainty (Imbeault-  
110 Tetreault, 2010; Morgan *et al.*, 1990)]. A description of the method is presented in the next  
111 section. Once the methodology is developed it is applied to one case study of two houses  
112 projects.

113

## 114 **2. Method**

115 Different methods have been proposed to evaluate data inaccuracy in LCA outcomes  
116 (SETAC, 2001). A review of uncertainty analysis methods can be found in (Björklund, 2002;  
117 Leroy, 2009). In this research we are developing a simplified analytical method based in  
118 Taylor series expansion. The other main alternative is the Monte Carlo simulation which is a  
119 numerical method that artificially allows the reconstruction of a random phenomenon  
120 simulating fictitious samples based on hypothesis on random variables. It is therefore  
121 necessary to define the probability density for the model inputs, assumed to be independent,  
122 which will be propagated to obtain the probability density of the output variable (Murtha,  
123 2000). The Monte Carlo method is therefore time consuming and require realistic hypothesis  
124 on the distribution function.

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

128

## 129 2.1. General theory of contribution analysis

130 The contribution analysis includes sensitivity and uncertainty analysis.

131

### 132 2.1.1. Sensitivity analysis

133 The key purpose of sensitivity analysis is to identify which key data or assumptions  
 134 significantly influence the result. This analysis allows simplifying data collection and analysis  
 135 without compromising the robustness of a result and to identify crucial data that must be  
 136 thoroughly investigated (Annex 31, 2004).

137 Sensitivity analysis can be described as follow:

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

$$140 \quad z = f(x_1, x_2, \dots, x_i, \dots, x_n) \quad (1)$$

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

$$144 \quad Z^0 = f(X^0) \quad (2)$$

145 (Morgan *et al.*, 1990) has defined the normalised sensitivity coefficient known as elasticity  
 146 coefficient by the equation:

$$147 \quad U_z(x_i) = \left[ \frac{\partial f}{\partial x_i} \right]_{x_i^0} \times \frac{x_i^0}{z^0} \quad (3)$$



148 Equation (3) can be used to calculate the relative change of the output result for a nominal  
 149 variation in the input  $x_i$ . For instance, if we consider an equation such as  $z = x_1^2 \times x_2$ . For a  
 150 scenario  $\mathbf{X}^0 = (x_1^0, x_2^0)$  and an output value  $z^0 = x_1^{0^2} \times x_2^0$ , the sensitivity coefficients for the  
 151 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  
 152 in input variable  $x_1$  of 1% the output varies by 2%, and for a change in input variable  $x_2$  of  
 153 1% the output varies by 1%.

154

### 155 2.1.2. Uncertainty analysis

156 A physical quantity can be expressed as  $x_i = x_{i,true} \pm \epsilon_{x_i}$ , where  $\epsilon_{x_i}$  represent the uncertainties  
 157 associated with a supposed exact value  $x_{i,true}$ , for which we have accepted the mean value  
 158  $x_{i,true} = x_{i,mean}$ . The degree of uncertainty for the variable  $x_i$  is usually expressed by its  
 159 standard deviation  $\sigma_{x_i}$  which is defined as the square root of the variance  $\text{var}(x_i)$ .

$$160 \sigma_{x_i} = \sqrt{\text{var}(x_i)} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - x_{i,mean})^2} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\epsilon_{x_i})^2} = \sigma_{\epsilon_{x_i}} \quad (4)$$

161

### 162 2.1.3. Contribution analysis

163 To perform a contribution analysis we must keep in consideration both analyses: sensitivity  
 164 and uncertainty. The contribution analysis which follows is mainly inspired by (Ciroth *et al.*  
 165 2004; Morgan *et al.*, 1990; Protassov, 2002; NASA, 2010; and Taykir, 2000). In the following  
 166 we present two methods of calculation of the relative contribution of inputs variables in  
 167 output result.

168 In the first method, we propose to use a power series expansion of the continuous function  
 169  $z = f(x_1, x_2, \dots, x_i, \dots, x_n)$  with respect to a chosen nominal scenario  $\mathbf{X}^0$ . The Taylor series  
 170 expansion provides a way to express deviations of output data from its nominal value  $z^0$  in

171 term of deviations of its input variables from their nominal values  $\mathbf{x}_i^0$ . If we can assume the  
 172 independence of input variables, the first order approximation of Taylor series expansion of  
 173 function will be expressed:

$$174 \quad \text{var}(\mathbf{z}) \approx \sum_{i=1}^n \text{var}(x_i) \left( \frac{\partial f}{\partial x_i} \right)_{\mathbf{x}^0}^2 \quad (5)$$

175 If  $\Delta x_i = \sigma_{x_i} \left| \left( \frac{\partial f}{\partial x_i} \right)_{\mathbf{x}^0} \right|$ , then equation (5) has the form:

$$176 \quad \text{var}(\mathbf{z}) \approx \sum_{i=1}^n \Delta x_i^2 \quad (6)$$

177 And the relative contribution of each input variable to the output result can be defined by  
 178 equation:

$$179 \quad RC_{M1}(x_i) = \frac{\Delta x_i^2}{\text{var}(\mathbf{z})} \times 100 \quad (7)$$

180 A second method to identify the contribution of inputs data to output result is to study  
 181 different scenarios of  $f(\mathbf{x}_i)$ . In our case the output result is supposed to be a function of  $n$   
 182 input parameter, so  $n$  scenarios will be performed.

183 In the first scenario, all the input variables are determined except one:  $x_1$ . Applying expansion  
 184 defined in equation (5) to this scenario will then provide:

$$185 \quad \text{var}(z_{[x_1]}) = \text{var}(x_1) \left( \frac{\partial f}{\partial x_1} \right)_{\mathbf{x}^0}^2 \quad (8)$$

186 which can be simplified as:

$$187 \quad \sigma_{z_{[x_1]}} = \sigma_{x_1} \left| \left( \frac{\partial f}{\partial x_1} \right)_{\mathbf{x}^0} \right| = \Delta x_1$$

188 Applying the Taylor series expansion with all other scenarios will have:

$$\begin{aligned}
 \Delta x_2 &= \sigma_{x_2} \left| \left( \frac{\partial f}{\partial x_2} \right)_{X^0} \right| \\
 \Delta x_3 &= \sigma_{x_3} \left| \left( \frac{\partial f}{\partial x_3} \right)_{X^0} \right| \\
 &\vdots \\
 \Delta x_1 &= \sigma_{x_1} \left| \left( \frac{\partial f}{\partial x_1} \right)_{X^0} \right| \\
 &\vdots \\
 \Delta x_n &= \sigma_{x_n} \left| \left( \frac{\partial f}{\partial x_n} \right)_{X^0} \right|
 \end{aligned} \tag{9}$$

190 Uncertainty in the output variable can then be calculated as a sum of the contribution of each  
 191 scenario:

$$\Delta z \approx \sum_{i=1}^n \sigma_{x_i} \left| \left( \frac{\partial f}{\partial x_i} \right)_{X^0} \right| \tag{10}$$

193 The relative contribution of each input parameter to the output result is calculated by  
 194 equation:

$$RC_{M2}(x_i) = \frac{\Delta x_i}{\Delta z} \times 100 \tag{11}$$

196 Both methods (equation (7) and (11)) can be used for identifying which input variable induces  
 197 the main variation in the output variable. The difference between the two methods is that the  
 198 first method (equation (7)) enhances the contribution of the input parameter with the higher  
 199 contribution due to the square values. In order to have a contribution analysis that allow  
 200 identifying a group of parameter and not only one, we prefer to use the second method. In the  
 201 practice it is easy to be demonstrated that the hierarchy of the inputs contribution in output  
 202 result is the same whatever the method used.

203

## 204 2.2. *Applied method for life cycle assessment of buildings*

205 In this section the method will be applied in Life Cycle Assessment of Building. From the EN  
 206 15978 standards (EN-15978, 2011), environmental performance of buildings can be presented  
 207 as a sum of the environmental performance of its building material plus the energy and water  
 208 consumed during the use phase. In the present paper, we only consider the building materials

209 used during the life cycle of the building. Further research should be done to understand how  
 210 water and energy consumption during the operation phase can be integrated in the method and how  
 211 to couple all uncertainties (Peuportier et al., 2013). For instance, it would be fundamental in a  
 212 broader study to associate uncertainties due to energy use during building operation and the  
 213 uncertainty on the degradation potential of building materials. This is however, beyond the scope of  
 214 this study which is restricted the uncertainties in embedded energy in building materials.. In this  
 215 study, we consider that the contribution of materials/elements in environmental performances  
 216 of building ( $I_f$ ) can be calculated as a decomposition of building in  $c$  materials/elements

$$217 \quad I_f = \sum_{i=1}^c I_{f,i} \quad (12)$$

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

$$219 \quad I_{f,i} = m_i \times k_{f,i} \times n_i \quad (13)$$

220 Where

221  $m_i$  is the mass of material  $i$  used for the construction of the building

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

224  $n_i$  is the number of time the material  $i$  has to be replaced during the service life of the  
 225 building;

$$226 \quad n_i \text{ is calculated as: } n_i = \frac{LB}{LM_i} \quad \forall n_i \in \mathbf{R}, \quad (14)$$

227 where:

228  $LB$  is the service life of the building;

229  $LM_i$  is the service life of the material  $i$ ;

230 The contribution analysis of buildings has therefore to be done at two different scales: the  
 231 material scale and the building scale because equations which are defining the associated  
 232 impacts are different at the two scales.

233

## 234 2.2.1. Contribution analysis method for life cycle assessment of buildings

235 The contribution analysis has to be applied at two different scales.

236 At the material scale, the variability of the results for the environmental performance of the  
237 materials (13), can be expressed as:

238 
$$\Delta I_{f,i} = \sigma_{k_{f,i}} \left| \left( \frac{\partial I_{f,i}}{\partial k_{f,i}} \right)_{X^0} \right| + \sigma_{m_i} \left| \left( \frac{\partial I_{f,i}}{\partial m_i} \right)_{X^0} \right| + \sigma_{n_i} \left| \left( \frac{\partial I_{f,i}}{\partial n_i} \right)_{X^0} \right| \quad (15)$$

239 With:  $X^0 = (k_f^0, n^0, m^0)$ , that are the mean value.

240 The relative contributions from the different input parameters to the output result are:

241 
$$RC_{M2}(k) = \frac{\Delta I_k}{\Delta I_{f,i}} \times 100 ; RC_{M2}(m) = \frac{\Delta I_m}{\Delta I_{f,i}} \times 100 ; RC_{M2}(n) = \frac{\Delta I_n}{\Delta I_{f,i}} \times 100 \quad (16)$$

242 with:  $\Delta I_k = \sigma_{k_{f,i}} \left| \left( \frac{\partial I_{f,i}}{\partial k_{f,i}} \right)_{X^0} \right| ; \Delta I_m = \sigma_{m_i} \left| \left( \frac{\partial I_{f,i}}{\partial m_i} \right)_{X^0} \right| ; \Delta I_n = \sigma_{n_i} \left| \left( \frac{\partial I_{f,i}}{\partial n_i} \right)_{X^0} \right|$

243 At the building scale, the environmental impact of one building can be presented by equation  
244 (12). However, as the partial derivative of the different building material is equal to 1:

245 
$$\frac{\partial I_f}{\partial I_{f,i}} = 1 \quad \forall i \in [1; c]. \quad (17)$$

246 The contribution of inputs variables is then simplified and reduced to the sum of uncertainties  
247 of each material.

248 
$$\Delta I_f = \sum_{i=1}^n \sigma_{I_{f,i}} \quad (18)$$

249 The relative contributions from the different inputs variables to output variable are then only:

250 
$$RC_{M2}(I_{f,i}) = \frac{\sigma_{I_{f,i}}}{\Delta I_f} \times 100 \quad (19)$$

251 with:  $\Delta I_{f,i} = \sigma_{I_{f,i}}$

252

253 2.3. *Uncertainty analysis*

254 2.3.1. *Central limit theorem*

255 The second fundamental theorem of probability is the Central Limit Theorem. This theorem  
 256 proposes that if  $\mathbf{z} = f(x_1, x_2, \dots, x_i, \dots, x_n)$  is the sum of  $n$  mutually independent random  
 257 variables, then the distribution function of  $\mathbf{z}$  is well-approximated by a certain type of  
 258 continuous function known as a normal density function, which is given by the formula:

$$259 \quad f(x, x_{\text{mean}}, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-x_{\text{mean}})^2}{2\sigma^2}\right) \quad \text{for } -\infty \leq x \leq +\infty \quad (20)$$

260 where:  $x_{\text{mean}}$  is the mean (location parameter) and  $\sigma$  is the standard deviation (scale

261 parameter).

262

263 2.3.2. *Calculation of uncertainty propagation*

264 Different methods have been proposed to calculate and propagate uncertainties, such as  
 265 analytical uncertainty propagation methods, calculation with intervals and fuzzy logic and  
 266 stochastic modelling etc., (SETAC, 2001). In this research we focused on uncertainty  
 267 propagation using Taylor series expansion. Using equation (5) for evaluation of uncertainties  
 268 in impact environmental of materials we will obtain:

$$269 \quad \text{var}(I_{fi}) \approx \text{var}(k_{fi}) \left(\frac{\partial I_{fi}}{\partial k_{fi}}\right)_{x^0}^2 + \text{var}(m_i) \left(\frac{\partial I_{fi}}{\partial m_i}\right)_{x^0}^2 + \text{var}(n_i) \left(\frac{\partial I_{fi}}{\partial n_i}\right)_{x^0}^2 \quad (21)$$

$$270 \quad \sigma_{I_{fi}} = \sqrt{\text{var}(I_{fi})} \quad (22)$$

271 And the variances of environmental performance of building are calculated by equation:

$$272 \quad \text{var}(I_f) \approx \sum_{i=1}^c \text{var}(I_{fi}) \quad (23)$$

$$273 \quad \sigma_{I_f} = \sqrt{\text{var}(I_f)} \quad (24)$$

274 The uncertainties in environmental performance of building can be calculated by its standard  
275 deviation.

276

### 277 **3. Application: Case study on two projects**

278

#### 279 *3.1. Presentation of the two studied projects*

280 In this case study we have applied the methodology presented above in order to compare two  
281 different projects of single-family detached house. The studied houses are not real case study  
282 but have been designed as reference house by the Centre Scientifique et Technique du  
283 Bâtiment (CSTB), France. The surface area of houses is equal to 100 m<sup>2</sup> and the service life is  
284 considered to be equal to 50 years. One of the projects is a house with a reinforced concrete  
285 structure and the second one is made with a wood structure. Figure 1 presents the plan and a  
286 3D model of the reference houses. The detailed quantities of materials taken into account in  
287 each project are presented in the table 1.

288

#### 289 *3.2. Sources of uncertainties at material scale*

290 The uncertainties come from combined factors at the material scale. As shown in equation  
291 (15), uncertainties are considered to come from the mass, the service life and the elementary  
292 environmental impact of each material.

293

##### 294 *3.2.1. Mass*

295 To evaluate the uncertainties associated with mass variation of materials, we used data  
296 coming from value of waste generated on construction site (ADEME, 2001). We also used  
297 data from discussion with experts to evaluate differences which can exist between provisional  
298 maps and the reality. As a consequence, we have considered in this study, variations from -

299 5% to +10% of materials quantity for all building materials. The mean is considered to be  
300 equal to the quantity of material defined in the project, and the standard deviation is  
301 calculated by supposing a triangular distribution for the uncertainties considered (Heijungs  
302 and Frischknecht, 2005).

303

### 304 3.2.2. *Service life of building materials*

305 Service life of materials has been calculated through the use of different references in order to  
306 define a mean value and a standard deviation for each material. In the table 2 we have  
307 presented the minimum and maximum values found in references and mean and standard  
308 deviation calculated for each non-structural materials and elements. It has to be noted that  
309 uncertainties are not issued from durability studies, nor from detailed sociological studies on  
310 user behaviour but from a survey we did on scientific literature that define a service life of  
311 building materials to perform LCA studies. Therefore the mean and standard deviation values  
312 on table 2 shows the variability, which currently exists between studies. We can also suppose  
313 that these studies have chosen valid service life values and that the variability we identify is  
314 then linked with an effective variability in the use of building materials. For the structural  
315 materials, we considered that their service life was similar to the one of the house.

316

### 317 3.2.3. *Elementary environmental impact of each building material*

318 The environmental impact of each building material is based on values from the French  
319 environmental products declaration (EPD) available in INIES database (INIES, 2009). These  
320 data are company specific or collective data and are calculated with French NF P 01-010  
321 standard (AFNOR, 2004) on construction products EPD. As it is EPD data, they follow the  
322 same general principles as EPDs assessed through the European standard EN 15804. It means  
323 that the environmental impact value covers all the life cycle of a product (production,



324 transport, use, demolition and end of life). The impact categories are the one from the NF P  
325 01-010 standards (AFNOR, 2004). These standards are close to CML methods (Guinée et al.,  
326 2002). It has to be noted that it is only because we used this EPD data format, that we could  
327 simplify the LCA of building materials involved in the life cycle of a building as a  
328 multiplication of elementary impact of the building material (through all the life cycle), the  
329 mass used for the construction of the building and the number of time we have to replace it.

330 When the EPD doesn't exist, environmental impacts have been calculated from Ecoinvent  
331 database (Kellenberger et al., 2007). However, as Ecoinvent is a calculation from cradle to  
332 gate (production at plant), results need to be adapted to be compared to INIES database  
333 (cradle to grave). In this case, the environmental impacts of material's production (cradle-to-  
334 gate) have been calculated using Simapro v2.2 software (Goedkoop and Oele, 2004) and  
335 Ecoinvent database. Then then other phases such as transport, use and end of life have been  
336 added by taking a given ratio from the production phase. Actually, previous works have  
337 shown that it was possible, without deteriorating too much the results, to consider the other  
338 phases of the life cycle as a given percentage of the production phase (Lasvaux, 2010). The  
339 details of these percentages are presented in table 3c.

340 Concerning the standard deviation used for the elementary impact  $k$  of building materials,  
341 three cases have been considered:

342 **Case 1:** There are several EPDs for the same material or element. In this case the mean and  
343 standard deviation was calculated using these EPDs. A list of materials for which the  
344 elementary environmental impact uncertainties have been calculated with this method is  
345 presented in table 3a.

346 **Case 2:** There is only one EPD linked to the material or element considered. In this case, the  
347 standard deviation coming from the pedigree matrix of the process associated with the  
348 production of the material in the Ecoinvent database has been used; and the EPD value has

349 been considered as the mean value. A list of materials for which the elementary  
350 environmental impact uncertainties have been calculated with this method is presented in  
351 table 3b.

352 **Case 3:** There is no EPD in the INIES database. In this case, mean value is calculated from  
353 EcoInvent once adapted to cradle-to-grave and the standard deviation is coming from the  
354 pedigree matrix of the process associated with the production of the material in the Ecoinvent  
355 database. In the only case of reinforced concrete elements, a further uncertainty concerning  
356 the amount of steel has been added (table 3c).

357

### 358 3.3. *Uncertainty calculation*

359 Once all the uncertainties are defined, we used the equation (22) for evaluation of  
360 uncertainties in environmental performance of material and then equation (24) for evaluation  
361 of uncertainties in environmental performance of building. From the central limit theorem, the  
362 uncertainties in environmental performances of building are presented two standards  
363 deviation  $2\sigma$  away from the mean.

364

365

## 366 4. Results

367

### 368 4.1. *Environmental assessment of the two projects*

369 Figure 2 shows eight indicators of environmental impact for the two projects.

370 The variability of the results takes into account the uncertainties from building materials. Two  
371 types of results can be seen depending on the impact category. For the impact category related  
372 to global warming (GWP) the results show that the project with reinforced concrete structure  
373 with a variation between 469.7 and 674.5 kg eq CO<sub>2</sub>/m<sup>2</sup> has a significant greater

374 environmental impact than the wood structure where values vary from 232.6 kg  
375 eq CO<sub>2</sub>/m<sup>2</sup>. However, for all the other impact categories uncertainties induce variations so that  
376 the two projects do not have significant differences (Figure 2).

377 In order to reduce the uncertainties and choose the best project, we propose to identify the  
378 contribution of the different material to the global results in order to evaluate where are the  
379 easiest and most efficient improvements which can be done to reduce this variation and have  
380 finally a significant difference between the two projects.

381

#### 382 4.2. Contribution analysis

383 To do so, it is necessary to perform a contribution analysis which is done by the simplified  
384 method at the material level (equation (16)) and at the building level (equation (19)). Results  
385 are shown in Figure 3.

386 The contribution analysis at the material scale allows distinguishing which one of the 3  
387 parameters (service life, mass and elementary impact) has the greatest contribution to  
388 variability. It seems clear that uncertainties on the exact mass of material used do not  
389 influence the variability. Furthermore, except for structural materials which have, by  
390 hypothesis, a service life equal to the house's service life, the variability for the other  
391 materials seems to be essentially controlled by the service life uncertainties. A few exceptions  
392 such as plaster, non-structural wood and zinc have a contribution of service life and  
393 elementary impact on uncertainties which are comparable.

394 At the building scale, figure 3 shows clearly that thermal insulation (rock wool), PVC and  
395 bitumen (waterproofing) are sharing most of the variability of the houses. It is also interesting  
396 to note that even if the mean contribution of reinforced concrete is important (mass x  
397 elementary environmental impact), its uncertainty is so low that the variability at the building  
398 scale is still quite low. On the contrary, there are materials such as bitumen or plaster which

399 have not a great contribution to the mean environmental impact of the projects, but that due to  
400 uncertainties on service life (and partly on elementary environmental impact), could  
401 contribute in some circumstances (shortest service life with an inefficient production  
402 process) to a much larger part of the global building's environmental impact.

403

## 404 **5. Discussion**

405

### 406 *5.1. Sensitivity of results to hypothesis on uncertainties*

407 The result that we have obtained in terms of relative contribution of the different materials to the  
408 variability of building's environmental impact are, of course, dependent on the uncertainties  
409 on the 3 parameters ( $m$ ,  $k$ ,  $n$ ) of each material. Therefore, it seems important to evaluate the  
410 accuracy of these uncertainties. What can be observed from figure 3 is that the  
411 contribution of one material is never controlled by mass uncertainties for atmospheric  
412 acidification indicator. However, it is the parameter that has been calculated with the lowest  
413 accuracy (only expert advice) and for which we have then taken the largest possible variations  
414 (15%). Therefore, it is reasonable to assume that even, if the accuracy of mass uncertainties is  
415 not perfect, the fact that we had a very low contribution of mass, shows that this parameter is  
416 not important for uncertainty calculation.

417 Concerning assumption on service life, the uncertainties on service life of building materials  
418 are based on an extensive review and even if they could be improved, this study presents for  
419 the first time, as far as we know, a methodology for the comparison of two different projects  
420 considering the uncertainties and variability in service life on different building materials  
421 associated with uncertainties on their individual environmental impact. The only strong  
422 hypothesis we made is to consider that structural material lasts as long as the house. This

423 assumption where concrete, bricks or wood last as long as the house, could be discussed and  
424 probably improved. We think that the appropriate way of assessing this uncertainty would be  
425 to have uncertainty on the service life of the house rather than on the structural materials.  
426 Actually, it can be explained as the fact that if concrete is deteriorated through corrosion or  
427 that if bricks wall is fractured, it might reduce the service life of the entire house, rather than  
428 just inducing the replacement of structural materials. It can be easily demonstrated that the  
429 contribution of the service life, impact coefficient and quantity taken off in material and  
430 element level doesn't depend in the service life of building. But the contribution of material at  
431 building scale can be controlled by the service life of the building. This aspect should  
432 however be assessed in more details in further works. Thus, it is worthwhile to note that the  
433 methodology would be the same.

434 Finally, uncertainties on individual environmental impact of materials have been taken as  
435 much as possible form variability between EPDs. From that point of view, these variations are  
436 more related to difference in process efficiency between companies as EPDs are industry  
437 based data and can be specific to one industry company and therefore to the efficiency of their  
438 production process. It is different from variability values coming from EcoInvent where the  
439 standard deviation comes from the PEDIGREE matrix which characterize the quality of the  
440 data. Typically how many surveys have been done, are data measured or coming from  
441 experts, etc... It is not related with a "physical" variability between industrial sites but rather  
442 a variability related to assumption on the quality of data.

#### 443 5.2. *Towards a decision tool ?*

444 In that situation, the developed method provides a first step towards a tool, which will give  
445 the relative contribution of each material to the variability of the building. In this particular  
446 case, we identified bitumen, PVC and rock wool (in the reinforced concrete house) as major  
447 contributors, due to uncertainties on their service life. It could then be possible to try to

448 improve the service life of the specific products to reduce the uncertainty. For instance, a  
449 control on site work could be done, just after that the rock wool has been fixed in order to  
450 certify that it has been done correctly (vapour barriers, humidity control, etc.). Similar work  
451 could be done for bitumen where it could for instance be mandatory to avoid an exposition to  
452 UV or high temperature in order to reduce bitumen potential deterioration and assure a given  
453 service life. Finally, PVC tubes which represent a total length of 83 meter in this project,  
454 could be installed in a way that they can easily be checked and only partially removed so that  
455 the majority of PVC tubes can also have given service life expectation. But the identification  
456 of specific materials is also due to internal bias of our method. Firstly it can be due to the  
457 house we studied and the quality of the data collected. Is 83 m of PVC tube in a single house  
458 of 100 m<sup>2</sup> reasonable or very particular? Further case study should then be assessed with the  
459 method developed in this study to strengthen the study. It can also be due to the fact that the  
460 EPD we used for one building material is specific to one very specific product which is not  
461 exactly the same as the one used in the house. For instance, for PVC tube, the only data  
462 provided in the INIES database is for tubes with a diameter of 12.5 cm. It is probably not the  
463 only size of PVC tube used in the house and the contribution of PVC might then be  
464 overestimated.

465 The methodology proposed here is then a potential tool for stakeholders to quickly evaluate in  
466 a project which aspects will induce a large variability on the expected environmental  
467 performance related to building materials. However, before that, more case studies should be  
468 done and the database on building materials expanded as for the moment, all building  
469 materials do not have EPDs.

470

## 471 **6. Conclusion**

472 This paper focused on the uncertainties associated with building materials when assessing  
473 environmental impact of building. To do so, our methodology was based on the statistical  
474 method of contribution analysis which is used to identify parameters having the greatest  
475 contribution to the uncertainty of final results.

476 Previous studies have been working with Monte Carlo analysis which is time consuming  
477 when addressing uncertainties of each material. In this study, we developed and tested a  
478 simplified method based on Taylor series expansion. This allows very quickly knowing, at the  
479 building scale, which material has the greatest contribution to the environmental impact  
480 variability when we only focus on the impact of building materials used during the life cycle  
481 of a building and do not consider energy and water used during the operation phase and the  
482 possible relationship between operation energy and grey energy. This fast identification could  
483 then be one of the tools stakeholders can use to constrain constructors or design offices to  
484 provide controls or design modification on specific aspect of the building, in order to better  
485 constrain service life of some building materials.. These first results presented here are  
486 encouraging as it has been shown that it is possible to choose which materials' parameters has  
487 to be constrained in order to significantly reduce the uncertainty on the results. However  
488 further work is needed, in particular to improve the database on uncertainties at the material  
489 scale and the number of materials covered in the EPD database.

490

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495

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688

689 **Figure caption**

690 Figure 1. Floor plan for the reference house.

691 Figure 2. Comparison between two projects of single houses for different environmental  
692 impact categories. Uncertainties at the material scale are calculated and propagated  
693 using the methodology developed in this study. Error bars represent standard deviation  
694 ( $\pm 2\sigma$ )

695 Figure 3. Relative contribution of the different parameters at the two scales studied for the  
696 two house projects. At the building scale, the contribution of the different materials with  
697 their uncertainties is shown and compared between the two projects. At the material  
698 scale, the contribution of the mass, the elementary impact and the lifetime expectancy  
699 are shown. Error bars represent standard deviation ( $\pm\sigma$ ).

700

701 **Table caption**

702 Table.1. List of materials used for the construction of the two studied houses.

703 Table 2 Expected lifetime of materials. Mean value and standard deviation are calculated  
704 from a number of reference values for each material. Minimum and maximum values  
705 are also shown. References for these variations are: [1] Pi BAT, 1995; [2] Frenandez,  
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713 Table.3.a. List of materials for which variation in the elementary environmental impact  
714 (Mean, SD) has been calculated directly from the EPD values.

715 Table.3.b. List of materials for which the EPD value is used as a mean value and standard  
716 deviation is calculated with Pedigree matrix from ecoinvent.

717 Table.3.c. List of materials for which no EPD exist. The environmental impact is calculated  
718 from Ecoinvent production process data on which a percentage of the impact of the  
719 material production is added to the result to build an equivalent of the EPD.

720

721 **Highlights:**

722 We perform a life cycle assessment of two different projects on the same single house

723 We propagate the uncertainties and variability on inputs data at building scale

724 A method is proposed to analyse the relative contributions of input variables

725 This method is used to strengthen comparison between projects

Building materials or elements	details	Reinforced concrete house	Wooden house	Unit
		Qty	Qty	
Non-structural clay materials	Tiles	130	Idem	m <sup>2</sup>
Structural clay materials	Wall	25727	-	kg
	Mortar	1530	-	kg
Non-structural concrete	Sill	347	-	kg
	Blinding concrete	1.44	Idem	m <sup>3</sup>
	Concrete layer/grout	4.94	Idem	m <sup>3</sup>
	Beam	3.216	-	m <sup>3</sup>
	Column	0,9821	-	m <sup>3</sup>
Reinforced concrete	Foundations	11.31	Idem	m <sup>3</sup>
	Stairs	0,4935	-	m <sup>3</sup>
	Floor	8,276	-	m <sup>3</sup>
	Slab	15	Idem	m <sup>3</sup>
	Garage door	4.8	Idem	m <sup>2</sup>
Non-structural steel	Uprights and rails	54.5	Idem	kg
	Valves	27.5	Idem	kg
	Ext. & int. doors	13.45	Idem	m <sup>2</sup>
Non-structural wood	Cabinet for sink	0.065	Idem	m <sup>3</sup>
	Shutter	-	15.63	m <sup>2</sup>
	Paneling	-	54.54	m <sup>2</sup>
	Truss construction	3.82	Idem	m <sup>3</sup>
	Beam	-	1.13	m <sup>3</sup>
Structural wood	Column	-	0.32	m <sup>3</sup>
	Stairs	-	0.2657	m <sup>3</sup>
	Deck	-	6	m <sup>3</sup>
	Wall	-	6.8015	m <sup>3</sup>
Thermal insulation	Glass wool	-	809	kg
	Rock wool	1211	-	kg
	Shutter	15.63	-	m <sup>2</sup>
PVC	Pipelines	519.5	-	kg
	Paneling	54.54	-	m <sup>2</sup>
Bitumen	Waterproofing	159.25	Idem	m <sup>2</sup>
Plaster	Products for false ceilings/suspended ceilings/Wall coverings	4643	Idem	kg
Acoustic insulation	Polyurethane	243.5	Idem	kg
Solar hot water panels	Water heater	4	Idem	m <sup>2</sup>
Window	PVC	15.61	-	m <sup>2</sup>
	Bois	-	15.61	m <sup>2</sup>
Paint	Paint	166.6		kg
	Varnish		115.2	kg
Electrical installation	Outlets/light-switch/ mini- breakers/ lamps/etc.	1	Idem	u
	Porcelain WC	2	Idem	u
	Porcelain Sink	2	Idem	u
	Acrylic Bathtub	1	Idem	u
Sanitary installation	Enameled sandstone Kitchen sink	1	Idem	u
	Enameled sandstone shower plate	1	Idem	u
	Porcelain paving	72.13	24	m <sup>2</sup>
Zinc	Gutter system	10.6	Idem	m <sup>2</sup>

Building materials or elements	details	Lifetime				Number of data	References
		Min	Mean	Max	SD		
Non-structural clay materials	Tiles	15	49.44	100	19.09 N=18	[36,49,50,52,56,57,59,60,63,64]	
Non-structural concrete	Mortar	15	36.52	100	15.75 N=36	[36,44,52,56,58]	
	Sill					Same as windows	
Non-structural steel	Garage door	10	18.57	35	7.48 N=19	[44,47,51,56]	
	Uprights and rails					Same as plaster	
	Valves	10	16.25	25	4.41 N=12	[44]	
Non-structural wood	Ext. & int. doors	10	37.15	80	16.67 N=58	[36,44,45,47,49,50,52,54,57,58,59,62,63]	
	Cabinet for sink					Same as porcelain sink	
	Shutter	10	28.75	60	10.97 N=36	[44,49,51,53,55,58,59,62]	
	Paneling	10	3.26	100	16.54 N=46	[44,45,48,50,51,55,58,59,62,63]	
Thermal insulation	Glass wool	20	38	60	15.49 N=10	[36,49,52,58,62]	
	Rock wool	20	37.5	60	15.85 N=10	[36,49,58,62]	
PVC	Shutter	15	25.05	40	9.33 N=18	[36,49,55,58,59,62]	
	Pipelines	15	25.64	60	9.34 N=22	[36,44,47,49,50,57,58,59,62]	
	Paneling	15	27.14	50	12.19 N=7	[36,49,50,55,58,59]	
Bitumen	Waterproofing	5	27.78	60	16.9 N=50	[36,44,45,47,48,49,50,52,58,59,62]	
Plaster	Products for false ceilings/suspended ceilings/Wall coverings	15	33.14	70	13.17 N=68	[36,45,47,49,52,57,58,59,62,63]	
Acoustic insulation	Polyurethane	20	37.14	60	16.03 N=7	[36,49,52,55,58,62]	
Solar hot water panels	Water heater	10	23.21	60	13.53 N=14	[36,44,49,50,52,59,60,61]	
Window	PVC	20	33.06	50	10 N=18	[44,49,50,51,52,59,62]	
	Wood	15	37.76	60	12.92 N=29	[36,44,45,49,50,51,52,58,59,62]	
Paint	Paint	5	15.64	50	8.92 N=83	[36,44,45,46,48,49,51,55,57,58,62,63]	
	Varnish					Same as paint	
Electrical installation	Outlets/light-switch/ mini- breakers/ lamps/etc.	5	19.31	60	9.4 N=204	[36,44,47,51]	
Sanitary installation	Porcelain WC	15	27.92	50	10.54 N=12	[36,44]	
	Porcelain Sink	15	26.43	40	8.99 N=7	[36,44]	
	Acrylic Bathtub	10	27	50	11.12 N=13	[36,44,48]	
	Enameled sandstone Kitchen sink					Same as porcelain sink	
	Enameled sandstone shower plate					Same as bathtub	
	Porcelain paving	10	47.3	100	23.37 N=26	[36,44,46,48]	
Zinc	Gutter system	10	18	30	5.87 N=10	[49,53,57,59,59,62]	

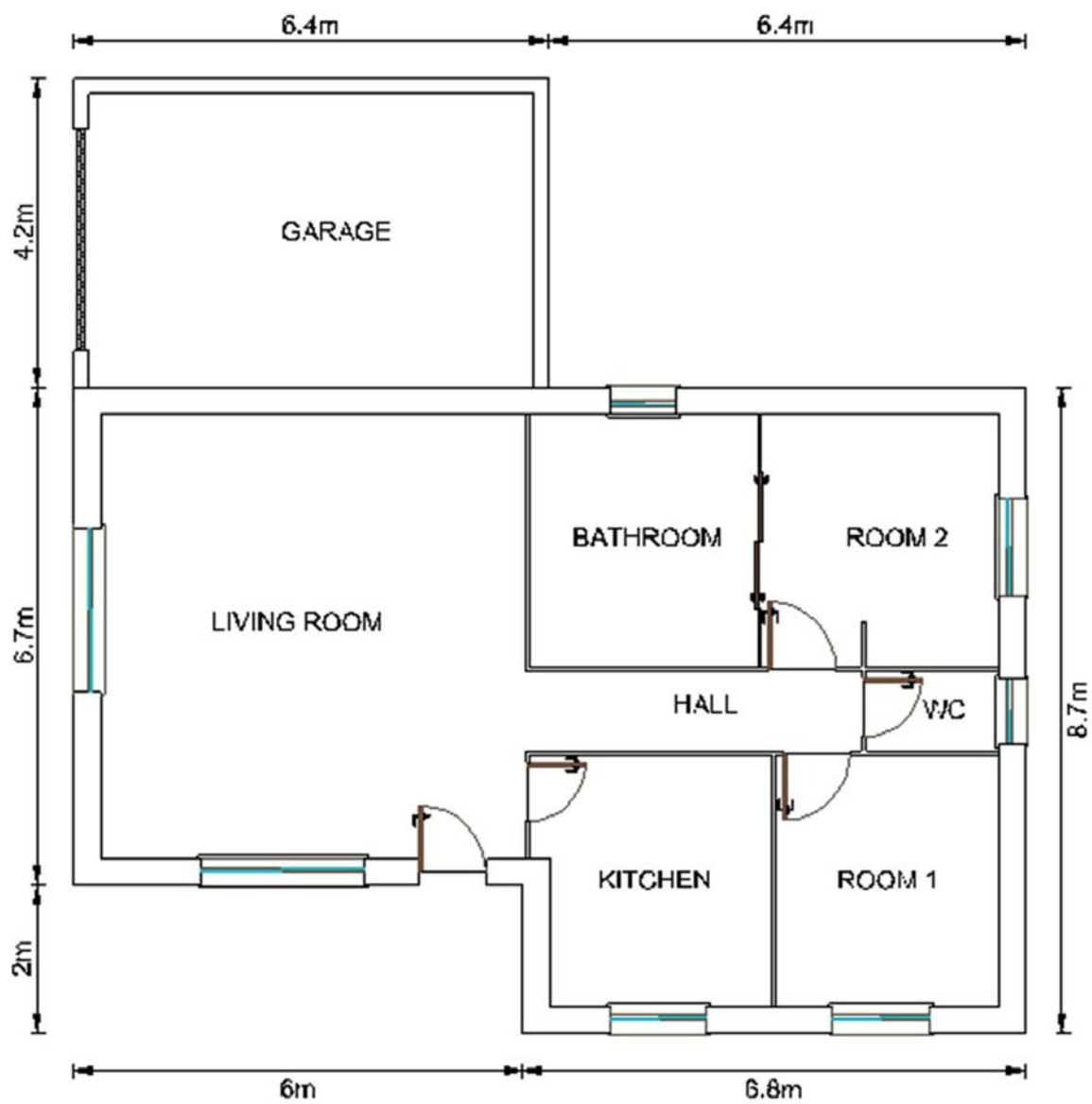
<b>Materials</b>	<b>Elements</b>
Non-structural clay	Tiles
Structural clay	Wall
Non-structural concrete	Mortar Sill
Non-structural steel	Garage door Uprights and rails Valves
Structural wood	Truss construction Stairs Deck
Thermal insulation	Glass wool Rockwool
PVC	Paneling
Bitumen	Waterproofing
Plaster	Ceilings / walls
Acoustical insulation	Polyurethane
Paint	Paint Varnish
Sanitary installation	Porcelain paving

<b>Materials</b>	<b>Elements</b>
Non-structural concrete	Blinding concrete Concrete layer/grout
Structural wood	Beam Column
PVC	Pipelines
Bitumen	Waterproofing
Window	Wood
Electrical installation	Outlets/light-switch/ mini-breakers/ lamps/etc.
Sanitary installation	Porcelain WC Porcelain Sink Acrylic Bathtub Enameled sandstone Kitchen sink Enameled sandstone shower plate

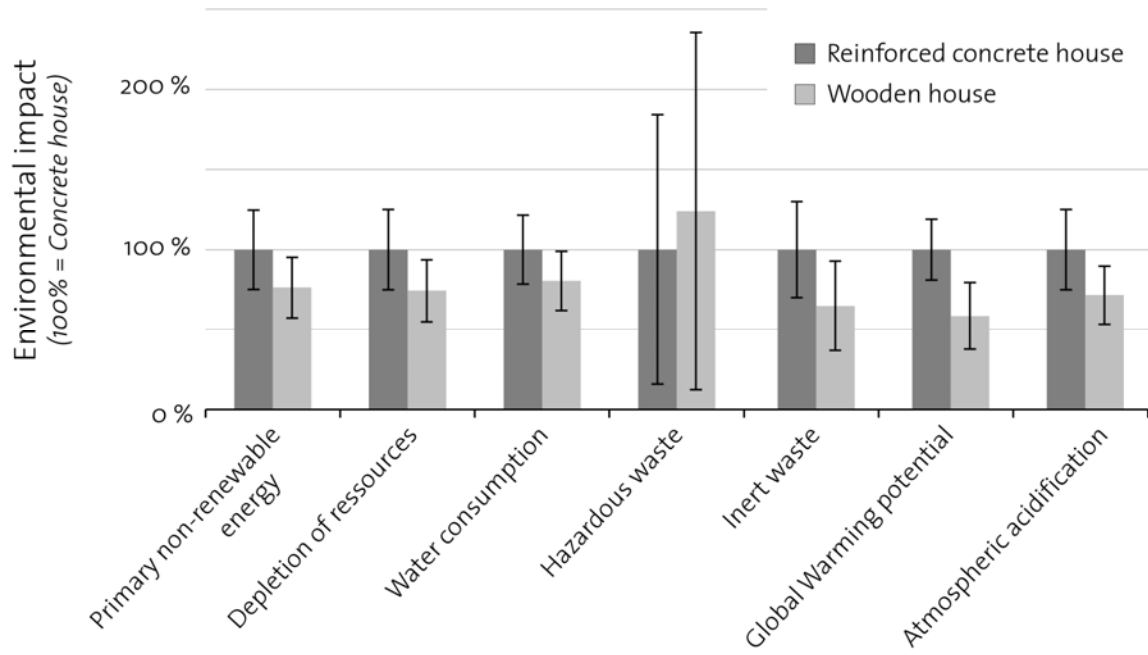
Materials	Elements	Contribution of the other life cycle phase (%) *	Variability in steel quantity (kg) (min-mean-max)
Reinforced concrete	Beam	Concrete: r(3),u(20),w(2) Steel: u(20),w(5)	80-130-180
	Column	Idem	50-80-150
	Foundations	Idem	20-40-80
	Stairs	Idem	5-40-100
	Floor	Idem	5-40-100
	Slab	Idem	5-40-60
Non-structural steel	Garage door	r(10),u(20),w(3)	
	Uprights and rails	u(20),w(5)	
	Valves	u(20),w(5)	
Non-structural wood	Cabinet for sink	r(10),u(20),w(2)	
	Shutter	r(10),u(20),w(9)	
	Paneling	r(10),u(20),w(9)	
Structural wood	Wall	u(20),w(2)	
PVC	Shutter	r(10),u(20),w(1)	
Solar hot water panels	Water heater	u(20),w(5)	
Window	PVC	u(20),w(15)	
Zinc	Gutter system	r(4),u(20),w(1)	

\* life cycle phase not integrated in Ecolnvent cradle to gate data are:

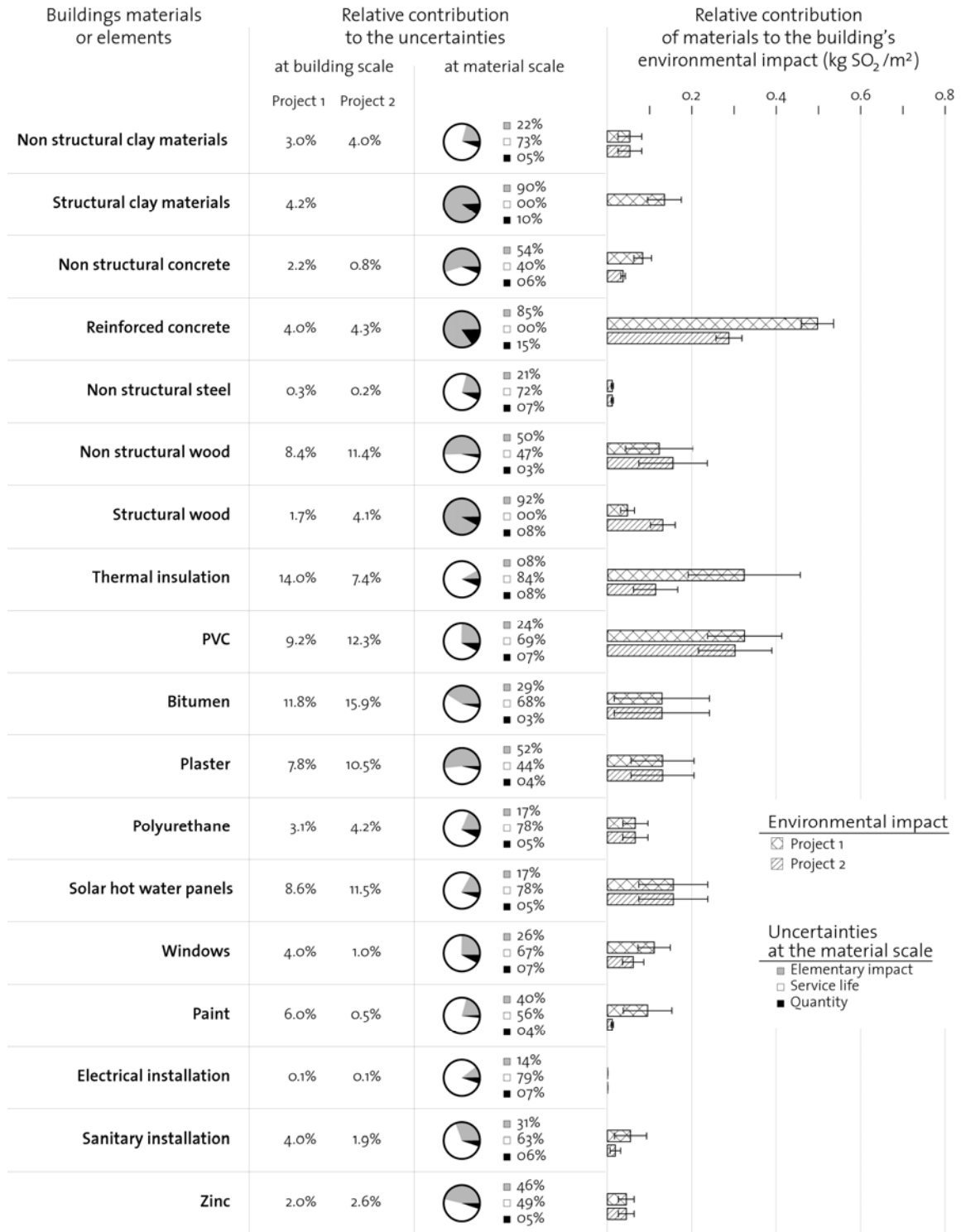
r: Raw materials; u: transport and end of life; w: waste on construction site







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We perform a life cycle assessment of two different projects on the same single house

We propagate the uncertainties and variability on inputs data at building scale

A method is proposed to analyse the relative contributions of input variables

This method is used to strengthen comparison between projects

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