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Scenario uncertainties assessment within whole building LCA

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Abstract. Uncertainties evaluation is increasingly gaining traction within life cycle assessment (LCA), due to its key role as environmental decision support tool. When applied at whole-building scale, the large variety of materials, subjective choices and long lifespans introduce parameter, scenario and model uncertainties throughout the life cycle. Since normative choices are unavoidable within whole-building LCA (wbLCA), in this article we carried out a so-called 'scenario' uncertainty assessment for one illustrative case study. First, three uncertainty sources were selected, to include the two drivers most frequently cited in literature (reference service life and end of life management alternatives) and material wastage, a relevant issue to factor in variable construction optimization levels in contexts like Brazil. Cumulative energy demand (CED) and CML 2001 v.2.05 methods were used for calculating deterministic values of non-renewable embodied energy and global warming potential in SimaPro 7.3 The uncertainty assessment combined scenario analysis, stochastic modelling (Monte Carlo simulation of triangular probability distributions for the uncertainty drivers investigated) and global sensitivity analysis (GSA). The GSA confirmed the dominant contribution of the operational phase - strongly influenced by components replacement rate - to of life cycle non-renewable embodied energy and global warming potential result variance, whilst construction and end of life stages showed no correlation with life cycle results. Findings from this research also highlight the strategic importance of gathering service life information adherent to the assessed context. Building components replacement rates induced by the Brazilian standard are overestimated relatively to international figures used in LCAs worldwide.

1. Introduction

The environmental assessment of whole-buildings inevitably includes uncertainties, since they are complex assemblies with a high number of materials, unpredictable lifespans, and hard to predict future uses [1]. Scenario uncertainties can be defined as those resulting from normative choices made throughout the building's life cycle, which create multiple possibilities of conducting the assessment and therefore a range of values for its results [2].

Although the need to assess the influence on normative choices in wbLCA is acknowledged, no consensus was reached on the most appropriate methodology to do it [3]. Scenario analysis practice is recurrent to aggregate uncertainty information to LCA results [3–6]. Despite strategically highlighting materials and life cycle stages that most influence results, it assumes linearity and ignores correlations between parameters [3,7]. A higher number of choices and materials, for example, impose challenges to accurate evaluation through deterministic values, which means that its interpretation is limited.

On their turn, statistical evaluations aims at adding information to how assertive the result value is [8]. Selecting representative distributions is essential to uncertainty analysis, especially when it comes to high influence inputs. Each scenario developed has particular chances of occurring. Uniform distributions can be used when little more is known beyond its minimum and maximum values. Indeed, the scarce studies using MC in the wbLCA literature normally assume uniform probability distributions, which assigns equal probabilities of occurrence to all possible alternatives (scenarios) [2,9]. Though the use of uniform distribution is a step forward relatively to simply performing scenario analysis, it is unlikely to properly describe real life events. Triangular distributions are still imperfect and based on very limited information but can be useful for deriving approximate probability distributions through estimation of three points (minimum, maximum, most frequent) pertaining to that distribution, thus improving assignment of different probabilities to all alternatives considered.

Given the lack of a consensus procedure for assessing how 'scenario uncertainties' affect wbLCA results, in this paper we tested three alternative techniques for a selected case study, to identify the most promising approach(es).

2. Method

The LCA was developed in accordance with ISO 14040 [10] and the European Standard BS EN 15978:2011 [11]. The functional unit was the whole-building, and the scope of the study was Cradle-to-grave with options, restricted to modules A1-A3, A4-A5, B1-B6, C1-C2. Using a single inventory database is recommended for consistency sake but was unfeasible at the time of study. We used primary data on cement, mineral admixtures and concrete products. Most secondary data were collected from the Ecoinvent database v3.2, with some inputs from literature. Non-renewable Embodied Energy (EE NREN) and Global Warming Potential (GWP) were selected to illustrate our study, through the use of CML 2001 and Cumulative Energy Demand (CED) impact assessment methods.

The selected case study was a steel frame building designed as a "minimum lifecycle embodied energy and emissions' (minLCee) Living lab [12], as shown in Figure 1. Its integrated design process optimized resource use, and included storm water management, low-energy space conditioning installations, green roof and wall, PV array, online resource use and internal monitoring, among other recommended practices.

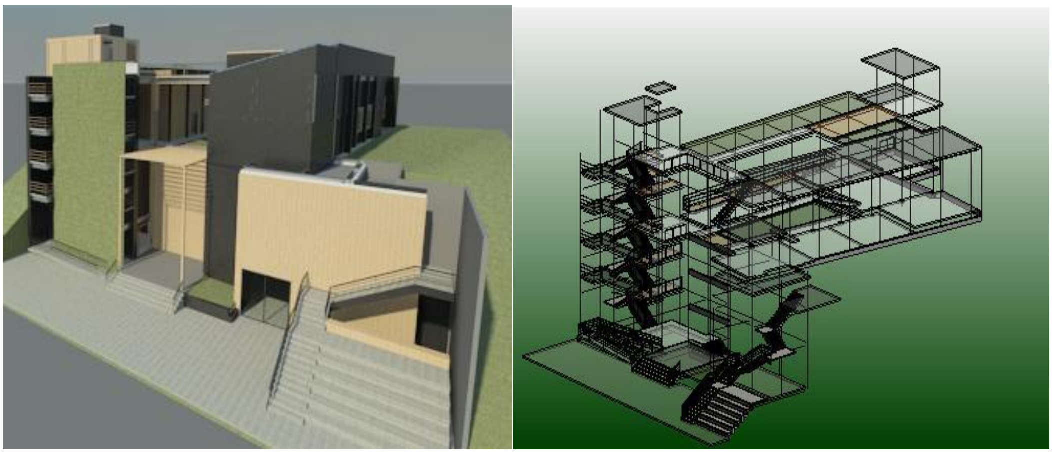

Figure 1 - Renderings from the minLCee living lab's building information model

Insights provided by three different approaches for scenario uncertainty assessment were analysed: multi-scenario analysis, stochastic modelling with uniform distribution, and stochastic modelling with triangular distribution.

2.1. Multi-scenario analysis

We began the uncertainty assessment by using multi-scenario analysis to run the LCAs and consider variations induced by each choice investigated. Scenario analysis is a type of sensitivity analysis frequently applied to evaluate LCA results, which consists of estimating and comparing effects that normative choices introduce in the results, by formulating different corresponding scenarios. Three alternatives plausible in the present or short-term Brazilian context were suggested for each uncertainty source studied [13], and an overall analysis considered the range of possible outcomes. A total of 27 scenarios was developed (Figure 2).

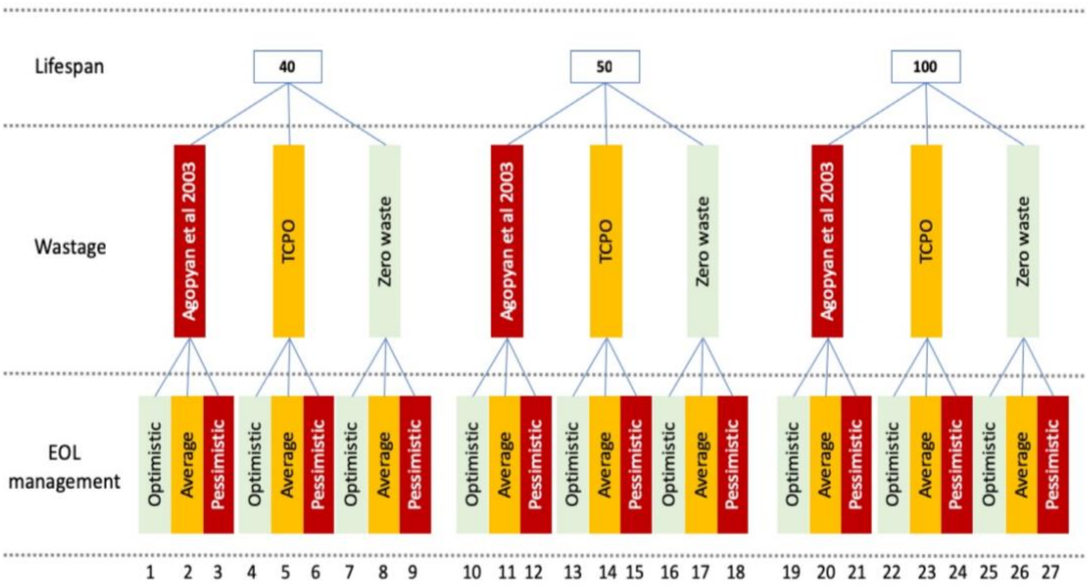

Figure 2 - Range of scenarios analyzed

Our systematic literature review indicated that the most frequently studied wbLCA choices are the building's reference service life information and waste disposal flows. The chosen lifespan scenarios were based on the Brazilian performance standard [14] minimum compliance level (50 years), and inspired by the lowest (40 years) and highest (100 years) values found in the literature review, to respectively take into account the international trend of producing buildings with elongated service life to make better environmental use of resources, as well as developing countries reality characterized by waste and maintenance intensive technologies [15].

To meet the stipulated reference service lives scenarios, the steel frame was protected against corrosion. Since the case study is situated in a C3 corrosivity category environment [16], the protection system was a 200mm-thick alkyd resin surface coating that creates a barrier between the environment and the structure, with a durability of 15 years.

Regarding waste disposal flows, different scenarios were developed to represent realistic alternatives for demolition/deconstruction and material transport to suitable management sites. Scenario A outlines an extremely inadequate disposal, in which 100% of the produced CDW is sent to the city landfill. Scenario B acknowledges the Brazilian construction reality, in which a 21% of CDW is recycled [17]. Finally, scenario C follows the European waste policy new directive for 2020, in which waste is seen as a valuable resource and 70% of CDW is recycled [18].

Finally, a third uncertainty source was included to consider material wastage during construction and maintenance activities. Since wbLCA are typically carried out before actual construction takes place, wastage is estimated and the choice for value source might influence the overall environmental performance. Although wastage is not explicitly addressed in the wbLCA literature reviewed, and the latter scenario seems to be assumed as default, such procedure would significantly underestimate impacts in the Brazilian reality. For this article, we considered a zero waste scenario and two additional variants, using the wastage values extracted from the Brazilian Table of Price Composition (TCPO) [19] and from Agopyan et al [20], whose collection of bottom-up representative field data from all over the country exposed the significant deviations that some construction services and activities could show relatively to the national average, although data were representative for construction practiced 15 years ago and such deviations can be outdated. TCPO presents typical average values and is an information source largely used by the national construction community and offers an updated - though less inclusive - outlook to ground contextualized assessments.

2.2. Stochastic modelling and global sensitivity analysis

Stochastic modelling was performed by running Monte Carlo sampling simulations (MC) with the @ Risk Excel add-in to quantitatively estimate the uncertainties arising from modeling choices made over the wbLCA. The analysis used 10,000 iterations for each impact category, as recommended in the literature.

Production stage modules A1-A3 and construction module A4 (transport) were calculated as deterministic points since they are not influenced by the normative choices considered (material wastage, service life, EOL management strategy). The output computed in the MC simulations were the sum of values in each life cycle stage.

The input data for MC depends on the probabilistic distribution chosen to best represent the model. Triangular probabilistic distributions assumed for each of the uncertainty sources analyzed in the construction, use and end of life stages. Three point's estimates were derived from occurrence frequency of each normative choice extracted from the reviewed literature for each scenario.

From the MC-simulated results, we ran global sensitivity analysis to identify the most influential inputs in the output's uncertainty measurement (contribution to variance) and in obtaining additional parameters iteration information [7].

3. Results and Discussion

3.1. Multi scenario analysis

Figure 3 and Figure 4 show life cycle results for the multiple scenarios developed. For both impact categories selected (non-renewable embodied energy and global warming potential), the influence of reference service life on wbLCA results is very clear: the columns are basically proportional to the reference service life, with slight contributions from the other (construction wastage and EOL) aspects factored in.

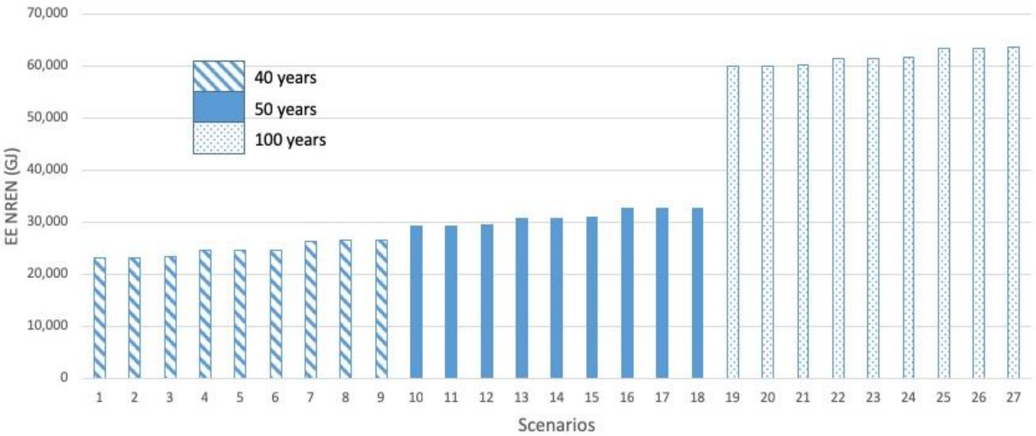

Figure 3 - Multi-scenario results for embodied energy, non-renewable

The variation resulting from waste disposal alternatives after the building's service life was negligible, and alterations between scenarios do not exceed 2%. As to material wastage during construction activities, discrepancies between wastage values extracted from [19] and [20] were not expressive, but figures in both sources are considerably higher than zero waste assumption.

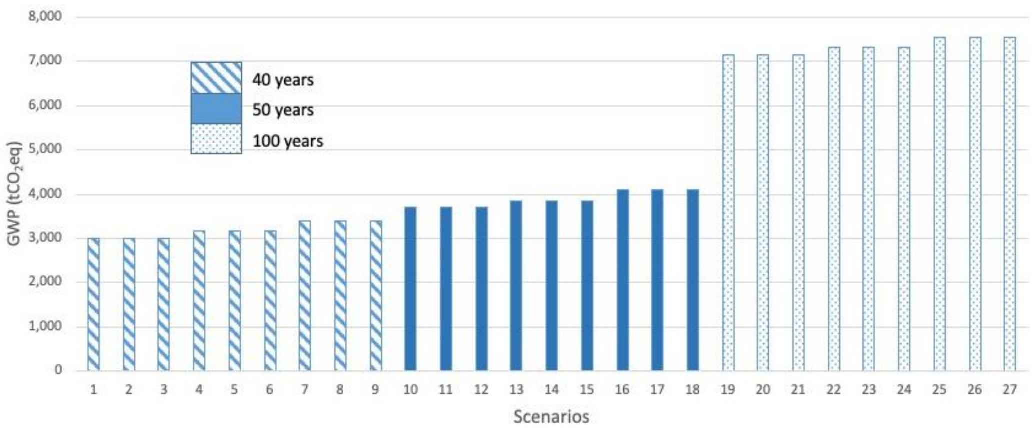

Figure 4 - Multi-scenario results for embodied GWP

3.2. Stochastic modelling

Table 1 details the inputs used in the uncertainty analysis. Even though the calculation model is simplistic in terms of its inputs and chosen distribution, it represents current whole-building LCA practice, in which accurate probability distributions are typically unknown and input parameters to generate even simple distributions unavailable.

In order to show how triangular distributions improve a given input's description relatively to less-informed uniform distributions, Figure 5 superposes uncertainty histograms displaying the range of possible final results for non-renewable embodied energy and respective occurrence probability . The uniform distribution flattens the curve and dislocate the (lower value, most probable) upper portion mostly towards higher (but least probable) values instead.

Table 1 - Input parameters for the Monte Carlo simulation

Input parameter detailing					
Variable	**wbLCA stage**	**Impact category**	**Values**		
			Min	**Average**	**Max**
Wastage	Construction (A5)	EE NREN (GJ)	382	1,768	3,708
Lifespan	Use (B1-B5)		8,902	15,066	45,886
EOL management	End-of-life (C1-C2)		164	225	349
Wastage	Construction (A5)	GWP (tCO_{2eq})	537	697	931
Lifespan	Use (B1-B5)		878	1,570	5,031
EOL management	End-of-life (C1-C2)		7	7	8

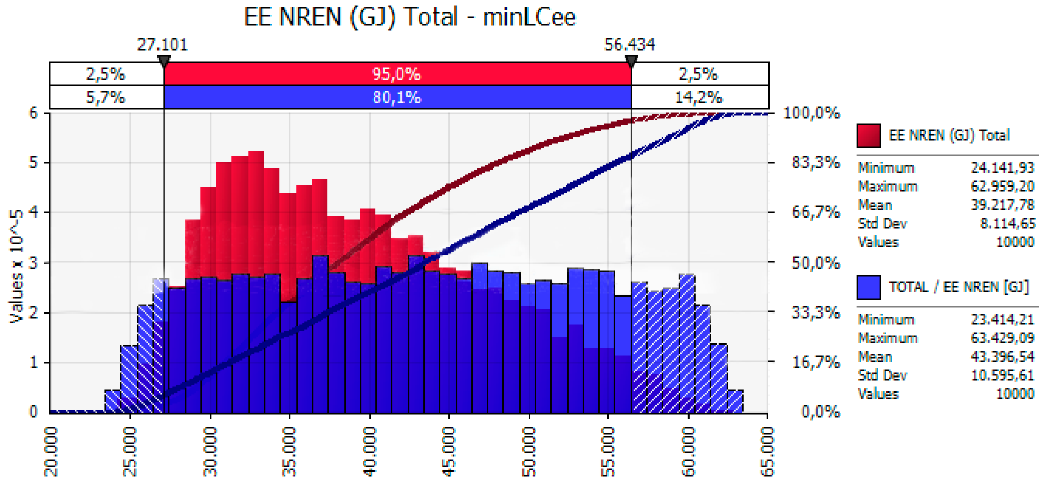

Figure 5 - Uncertainty statistical evaluation histograms, with the range of probable occurrence frequencies (axis Y) for the possible case study results for non-renewable embodied energy when uniform (blue) and triangular (red) probability distributions are assumed

Figure 6 features scatter plots showing the lack of correlation (homogeneous clouds, with Pearson coefficients near zero) between values of non-renewable embodied energy at construction (red dots) and end of life (green dots) stages and the life cycle total.

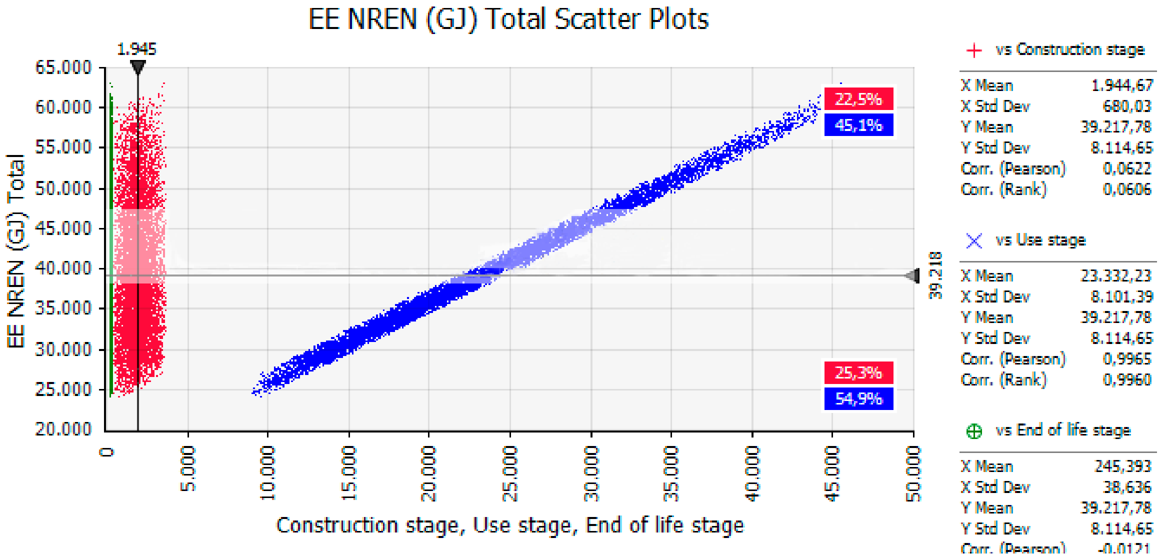

Figure 6 - Scatter plots for embodied energy non-renewable at construction, use and end of life stages

The data points resulting from the operational stage iterations (blue dots), which is strongly influenced by components replacement rates to achieve the established service life, assume a linear layout that indicates a solid correlation with the wbLCA results (Pearson coefficient near 1). Global warming potential results follow exactly the same pattern.

The global sensitivity analysis also confirmed the dominance (99,2%) of the operational phase's contribution to final wbLCA result variance. The uncertainty modelled in the construction stage contributed with the remaining 0,79%, whilst EOL effect was negligible, as shown in the radar graph (Figure 7). Such analysis is particularly useful in LCAs with a high number of choices to consider, for enabling evaluation of each input contribution separately.

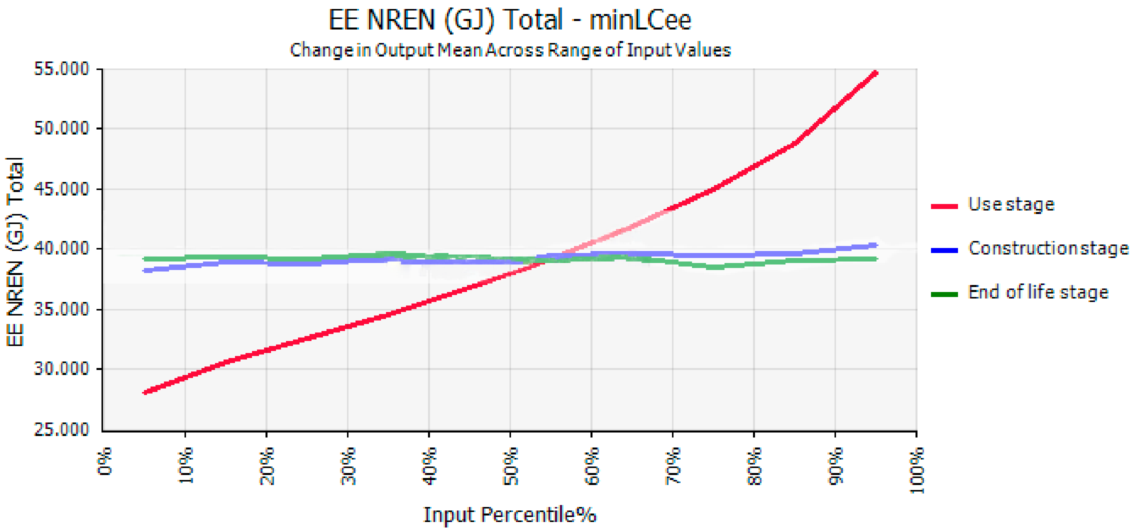

Figure 7 - Radar graph for EE NREN showing how the average output (life cycle EE NREN) changed through every input (values for use, construction and EOL stages) value interval. The sharper the slope of the line, the greater the influence.

4. Conclusions

To assess how scenario uncertainties affects wbLCA results, and to identify proper approaches to carry out such assessment, we performed uncertainty analysis through different, but incremental techniques: scenario analysis followed by stochastic modelling with probability distribution.

The sensitivity analysis presented a range of possible outcomes, with the use of deterministic values. It is a simplistic way of finding outcome variations attached to a diverse set of alternatives, and usually takes an expert eye to extract detailed and relevant insights. Nevertheless, it is important to point out macro trends and hotspots, like the use phase, in the case study analyzed.

After that, stochastic analyses were conducted to provide refined descriptions by adding occurrence probability in distribution curves. It became clear that uniform distributions typically represent the ignorance or data limitation regarding the input to be modelled rather than provide a good description of real-life phenomena. In this sense, triangular distributions offer a better approach to refine data entry and support further propagation of uncertainties regarding the realistic preferences of analysts in relation to the normative choices involved. Ideally, more accurate probability distributions should be pursued to describe the normative decisions involved in LCAs, but this seems still distant from quotidian decision-making processes in the construction sector. Also, this is a simple calculation model with few (only three) input parameters, devised for preliminarily testing a potentially improved methodological procedure. As such, the influence of triangular distributions and rectangular distributions on the result are still very clear. Increasing the number of iterations to 100,000 does not change the histograms shape. However, if several calculation steps are performed with multiple inputs, the results would possibly have to take a different form due to the central limit theorem. This should be further investigated.

Regardless of the classification, scenario analysis does not detract from the use of uncertainty assessment methods, since they have different purposes. At the current status of wbLCA inventory in countries like Brazil, despite failing to account for realistic variability, uniform distributions might be still useful to support MC simulations in cases of extreme lack of information.

The global sensitivity analysis showed the contribution of variation for each input data to the total uncertainty, and the correlation between the simulated data points for the inputs relatively to both impact categories outputs considered. For this study, the use stage contribution to the result variance was roughly 100%. Such findings highlight the strategic importance of gathering service life information adherent to the assessed context. Our model used building components replacement rates induced by the Brazilian standard, which are clearly overestimated relatively to international figures used in LCAs worldwide. It does not mean that international figures are better grounded, since recommended figures for carrying out LCA in some countries were basically transferred from elsewhere and some tools and e.g. certification approaches admit usage of the same values worldwide.

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