Whole-Buildings Life Cycle Assessment Sensitivity to Scenario Choices

G D Guimarães, L Zucarato, M Saade, M Silva and V G Silva
224 Saturnino de Brito Street – Campinas, Brazil / University of Campinas

g192227@dac.unicamp.br; vangomes@unicamp.br

Abstract. Life cycle assessment (LCA) is an important technique to measure environmental impacts of products and processes and its application to diagnose and optimize whole-buildings’ environmental performance has increased in the past years. However, LCA results carry uncertainties which may limit their utility as environmental decision-making support. Since normative choices are unavoidable within whole-building LCA (wbLCA) modelling, it becomes important to analyze their inherent uncertainty. Recent literature indicates that different material wastage values, lifetime choices and end of life scenarios are the main uncertainties drivers on wbLCA. To understand how these choices influence wbLCA results, we conducted a scenario analysis to estimate the effects that parameters and input choices produce on final results by describing possible future situations. Cumulative Energy Demand (CED) and CML 2001 v.2.05 methods were selected for calculating embodied energy and global warming potential in SimaPro 7.3. Our results indicate that wbLCA outcomes vary greatly with different alternatives for normative choices, and a scenario uncertainty analysis is necessary to understand all implications of its results.

1. Introduction
Life Cycle Assessment (LCA) offers a holistic approach to environmental analysis. However, the number of input parameters required, lack of adequate database, varied methodological approaches, use of simplistic models and the unavoidable assumptions regarding normative choices weaken the assessment’s quality. In addition, deterministic outcomes fail to capture the inherent variability and uncertainty, giving a false sense of certainty to the assessment [1], whilst LCA results can be highly doubtful [2].

Assessments at whole-building level (wbLCA) add in considerable complexity, due to the high number of materials and processes considered, each with its own inherent uncertainties which are propagated and summed to those resulting from normative choices and assumptions made along the life cycle stages (Figure 1) and to describe future situations [3] during and after a building’s long lifespan. A building may change in form and function, and such change can be as environmentally significant as the original product delivery [4]. Its environmental performance is also susceptible to occupant behaviour, construction technology, regulatory policies, future trends, among other aspects. Although recommended for all types of life cycle assessments, these unique characteristics increase and emphasise the need for uncertainty analysis in wbLCA.
Figure 1. Building life cycle information[5]

Some uncertainty drivers are connected to poor data quality (parameter uncertainty) and imprecise reality depiction (model uncertainty). Other refer to the intrinsic normative choices which must be made by the analyst at certain moments of the assessment [6] to represent plausible situations potentially experienced over the lifecycle stages. These choices eventually lead to varied modelling paths and results [7] and introduce the so-called ‘scenario uncertainty’, which will be focused on this paper.

Our systematic literature review revealed the most frequent studied wbLCA choices. Together with an expert analysis of the ones critical to the reality considered, the studied points are:

- Inclusion of accurate lifetime information supports improved assessment outcomes [8]; [9]. wbLCA studies frequently use typical and definite values to represent temporal horizon, however, this tactic does not realistically evaluate the environmental impacts. Several building materials are replaced or undergo maintenance during a building’s life cycle, at a frequency that affect the total amount of material extraction and waste generation over the reference study period [10]. When LCA results are annualized, long-lasting materials will appear worse on shorter periods than on longer ones;
- Waste disposal flows for each material cannot be generically evaluated, since there is more than one route for handling construction and demolition waste (CDW)[11];
- Excessive (wastage) material use per built area unit is recurrent in the Brazilian context and wastage percentages are different for each material [12].

Authors [13] and [14] recommend sensitivity analysis to propagate scenario uncertainty on LCA, and some wbLCA publications have already used this method ([15], [16], [9], [17]). Still, most LCA articles on the building sector do not tackle uncertainties [2], not even by applying simplified approaches like sensitivity analysis [18]. To address this gap, we assessed sensitivity of wbLCA results to different lifespan choices, material wastage scenarios and waste disposal alternatives, illustrated by two life-cycle indicators – embodied energy and GHG emissions – calculated for a case study.

2. Method
This research was developed in three steps: (i) scenario planning and detailed description of a case study’s materiality; (ii) calculation of life-cycle embodied energy and GHG emissions; and (iii) sensitivity analysis.

Our case study is the ‘minimum lifecycle embodied energy and emissions’ (minLCee) building designed for the University of Campinas, Brazil (Figure 2). Developed as a demonstration of sustainable construction, valid for a high level-certifiable by LEED 2009 (BD + C) and Brazilian
PROCEL rating system, it has a steel frame, integrated design process, optimization of low-energy resources use, stormwater management, low-energy space conditioning installations, green roof, PV array, online resource use and internal monitoring, among other recommended practices.

![Figure 2. minLCee Living Lab’s BIM model [19]](image)

The LCA was developed in accordance with ISO 14040 [20] and the European Standard BS EN 15978:2011 [5]. Table 1 summarizes the methodological choices made throughout the evaluation.

Even though using a single database is theoretically recommended for consistency sake, it results unfeasible in practice, and some parameters were taken from literature.

Table 1. LCA information summary.

| Objective                        | wbLCA Sensitivity to normative choice |
|----------------------------------|--------------------------------------|
| Scope                            | Cradle-to-Grave ‘with options’ (A1-A3, A4-A5, B1-B6, C1-C2) |
| Functional unit                  | Whole-building                        |
| Inventory data                   | Ecoinvent v3.2 (preferred data source) |
| Impact assessment methods        | CML 2001 and CED                      |
| Impact categories                | EE and GWP                            |
| Material wastage scenarios       | 50, 75 and 100 years                  |
| Reference service life (RSL) scenarios | Zero waste, TCPO and Agopyan et al (2003) |
| End of life (EoL) scenarios      | Pessimistic, average and optimistic    |

To understand how wbLCA results are influenced by different material wastage values, lifetime choices and end of life alternatives the authors chose to use ‘scenario analysis’, a type of sensitivity analysis whose procedure includes estimation of the effects that parameters and input choices produce on final results by describing possible future situations [14]. For each normative choice, three realistic alternatives were formulated, aligned with the ideal design suggested by [21], composed of a base scenario plus two alternatives focusing on critical uncertainty sources. A total of 27 scenarios were analysed (Figure 3), each of them representing a possible future value in terms of total impacts.

Material wastage is related to the construction (and maintenance) activities of a wbLCA, and can derive from inadequate transport, handling, storage, service quality, rework needs and excessive material loss or incorporation. Since wbLCA are typically carried out before actual construction takes place, wastage is estimated and the choice for wastage input source may influence the overall environmental performance. Here, the studied scenarios were: zero waste on site; wastage prescribed by
the Brazilian Table of Price Composition (TCPO) [22], typically used in construction cost estimates nationwide; and values extracted from Agopyan et al (2003) [12], which reflects measured waste in different regions of the country. For both sources, different probabilities are recommended for each material and, in case of data unavailability, a default value was applied (average of existing rates).

![Figure 3. wbLCA scenarios considered](image)

The chosen lifespan scenarios (50, 75 and 100 years of RSL) were respectively inspired by the minimum and superior compliance levels for design service life, as prescribed by the Brazilian performance standard [23]; and by the international trend of producing buildings with elongated service life, which could also dilute environmental impacts and delay new raw material extraction cycle. Though the latter hypothesis was verified in highly industrialized and standardized construction contexts, less controlled contexts, characterized by waste- and maintenance-intensive technologies like in Brazil, might not follow the same trend.

To reach the lifespans considered, the steel frame requires appropriate protection against corrosion. An evaluation of the surrounding ‘micro-climate’ is necessary to classify the environment and its corresponding corrosion rates. The case study’s location has a C3 corrosivity category (average) according to BS EN ISO 12944-2:2017 [24], thus the chosen protection system was an 200mm-thick alkyd resin surface coating, with 15 years or durability, which creates a barrier between the metal surface and the exposure environment.

Regarding end of life management, different scenarios were developed to represent realistic alternatives for post-use waste disposal (Table 2).

Table 2. Assumed end of life management scenarios.

| Waste Disposal | Materials                  | Scenarios |
|----------------|----------------------------|-----------|
|                |                            | Pessimistic| Average | Optimistic |
| Reuse          | Steel frame                | 0%        | 0%      | 0%         |
| Recycle        | Concrete, Steel, Aluminium | 0%        | 25%     | 70%        |
| Incineration   | Wood                       | 0%        | 25%     | 70%        |
| Landfill       | Others                     | 100%      | 100%    | 100%       |
The pessimistic scenario outlines an extreme – though plausible – inadequate waste disposition, with no reuse nor recycling. The average scenario acknowledges the Brazilian construction reality, by proposing a 21% total recycling rate [25]. Of these, the recovered concrete will be recycled as an aggregate and metals as scraps, and wood incineration will not recover energy. The remaining materials would be landfilled. Finally, the optimistic scenario reflects the EU waste management policy, which targets 70% of construction waste recycling by 2020 [26].

3. Results
The results for all scenarios analysed are displayed in Table 3, for both EE NREN and GWP. For a given scenario, e.g. 50 years of RSL, material wastage can add up to, respectively, 11.23% and 10.7% to life cycle EE NREN and GWP values. However, the lifespan is clearly the most influential variable, particularly as assumed wastage decreases: doubling RSL from 50 to 100 years increases EE NREN by 94% (Agopyan et al 2003) to 105% (Zero waste) and GWP by 85% (Agopyan et al 2013) to 94% (Zero waste), and such increase can indeed be beneficial under specific circumstances.

| Scenario | Lifespan (years) | Material wastage approach | End of life approach | EE NREN (MJ) | GWP (tCO₂eq) |
|----------|------------------|---------------------------|---------------------|--------------|--------------|
| 1        |                  | Zero                      | Pessimistic         | 29368,92     | 3.699,41     |
| 2        |                  |                           | Average             | 29492,82     | 3.700,43     |
| 3        |                  |                           | Optimistic          | 29616,20     | 3.701,41     |
| 4        | 50               | TCPO                      | Pessimistic         | 30755,15     | 3.859,37     |
| 5        |                  |                           | Average             | 30879,05     | 3.860,39     |
| 6        |                  |                           | Optimistic          | 31002,43     | 3.861,38     |
| 7        |                 | Agopyan et al (2003)     | Pessimistic         | 32695,14     | 4.093,81     |
| 8        |                  |                           | Average             | 32819,04     | 4.094,83     |
| 9        |                  |                           | Optimistic          | 32942,42     | 4.095,81     |
| 10       |                  | Zero                      | Pessimistic         | 44778,66     | 5.429,72     |
| 11       |                  |                           | Average             | 44902,56     | 5.430,74     |
| 12       |                  |                           | Optimistic          | 45025,94     | 5.431,72     |
| 13       | 75               | TCPO                      | Pessimistic         | 46164,90     | 5.589,68     |
| 14       |                  |                           | Average             | 46288,79     | 5.590,70     |
| 15       |                  |                           | Optimistic          | 46412,17     | 5.591,69     |
| 16       |                 | Agopyan et al (2003)     | Pessimistic         | 48104,88     | 5.824,12     |
| 17       |                  |                           | Average             | 48228,78     | 5.825,14     |
| 18       |                  |                           | Optimistic          | 48352,16     | 5.826,12     |
| 19       |                  | Zero                      | Pessimistic         | 60188,40     | 7.160,03     |
| 20       |                  |                           | Average             | 60312,30     | 7.161,05     |
| 21       |                  |                           | Optimistic          | 60435,68     | 7.162,03     |
| 22       | 100              | TCPO                      | Pessimistic         | 61574,64     | 7.319,99     |
| 23       |                  |                           | Average             | 61698,53     | 7.321,01     |
| 24       |                  |                           | Optimistic          | 61821,91     | 7.322,00     |
| 25       |                 | Agopyan et al (2003)     | Pessimistic         | 63514,62     | 7.554,43     |
| 26       |                  |                           | Average             | 63638,52     | 7.555,45     |
| 27       |                  |                           | Optimistic          | 63761,89     | 7.556,43     |
The current lack of adequate information regarding end of life treatments in the available databases influences two findings from the sensitivity analyses (Figure 4 and Figure 5). EOL waste management alternatives had negligible effect (under 1%) on the wbLCA outcome. That said, the pessimistic EOL scenario generates the lowest impact in all situations, since it basically comprises less detailed demolition and transportation to a single location, whilst computing specific recycling actions for different materials would factor in additional impacts.

![Figure 4](image1.png)

**Figure 4.** Annualized lifecycle non-renewable energy embodied impacts, for the scenarios considered.

![Figure 5](image2.png)

**Figure 5.** Annualized lifecycle global warming potential impacts, for the scenarios considered.

The zero waste scenario evidently showed the lowest values for both environmental indicators, but represents underestimated impacts, given the current Brazilian reality. On its turn, TCPO describes national average values from the database most frequently adopted in national bidding processes and cost estimates. Finally, values from Agopyan et al (2003) would be more representative in the regions with the highest deviation from national average.

Annualized GWP always decreased with longer lifespan (Figure 5). Contrastingly, annualized EE NREN would be reduced only in scenarios of high material wastage: for zero waste practice, increasing lifespan would increase EE NREN (Figure 4) – even though not proportionally, while average waste practice (TCPO) is not sensible to either EOL or lifespan.

### 4. Conclusions

This study assesses the sensitivity of whole-building LCAs results to the lifespan, material wastage and end of life scenarios considered. The adopted reference service life fundamentally influences LCA results, as it affects material quantities, maintenance programs, and corresponding emissions and waste
through a building’s life cycle. Understanding the proper impact of longer lifespans in a specific reality demands comparative analysis of scenarios outcomes.

On the other hand, material wastage and waste disposal alternatives do not impact significantly a wbLCA outcome. Even though recycling and reuse are important aspects of a buildings sustainability, End of Life as a phase does not contribute highly to the overall LCA, hence modifications in its calculation won’t result into robust changes. Nevertheless, due to a study limitation, we did not account for Model D in this wbLCA, that is, the avoided impacts concerning end of life were not calculated. In addition, CO₂ biogenic carbon were not modelled due to a discussion regarding the necessity and proper methodology required, and incineration with heat recovery was not analyzed as it is usual seldom used. Although these limitations could improve wbLCA results, it does not compromise the study in view of this article objective. Regarding material wastage, its importance is only valid when considering one lifespan.

Our results confirmed that increased lifespans can be attractive – as the impact per additional year of service life is considerably reduced over time – even though the selected option for maintenance programs implies in added material and corresponding impacts. But it is a choice dependable on other alternatives throughout the wbLCA, since some scenarios do not confirm this result.

Lastly, we highlight two fronts to be further investigated. In this paper, we analysed scenario uncertainty using sensitivity analysis. Despite being a valid method for visualizing different outcomes and alternatives for the same wbLCA, there are some recommendations in the literature that suggest the use of statistical methodology to provide more information for the assessment result. In addition, our calculations were illustrated for greenhouse gas emissions and embodied energy only. It is known that other impact categories, such as acidification and eutrophication potential, may be also relevant for specific building materials or in specific contexts. All these aspects are targeted in ongoing investigations.

References

[1] Lloyd S M and Ries R 2007 Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches J. Ind. Ecol. 11 161–81

[2] Pomponi F, D’Amico B and Moncaster A M 2017 A method to facilitate uncertainty analysis in lcas of buildings Energies 10 2–15

[3] Pomponi F, De Wolf C and Moncaster A 2018 Embodied Carbon in Buildings: Measurement, Management, and Mitigation (Switzerland: Springer)

[4] Khasreen M M, Banfill P F and Menzies G F 2009 Life-Cycle Assessment and the Environmental Impact of Buildings: A Review Sustain. 1 674–701

[5] CEN 2011 BS EN 15978: Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method p 64

[6] Huijbregts M A J, Gilijamse W, Ragas A M J and Reijnders L 2003 Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling Environ. Sci. Technol. 37 2600–8

[7] Cherubini E, Franco D, Zanghelini G M and Soares S R 2018 Uncertainty in LCA case study due to allocation approaches and life cycle impact assessment methods Int. J. Life Cycle Assess. 17 1432-6

[8] Aktas C B and Bilec M M 2012 Impact of lifetime on US residential building LCA results Int. J. Life Cycle Assess. 17 337–49

[9] Sandin G, Peters G M and Svanström M 2014 Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling Int. J. Life Cycle Assess. 19 723–31

[10] Haefliger I-F, John V, Passer A, Lasvaux S, Hoxha E, Mendes Saade M R and Habert G 2017 Buildings environmental impacts’ sensitivity related to LCA modelling choices of construction materials J. Clean. Prod. 156 805–16
[11] Martínez E, Nuñez Y and Sobaberas E 2013 End of life of buildings: Three alternatives, two scenarios. A case study *Int. J. Life Cycle Assess.* **18** 1082–8

[12] Agopyan V, Souza U E L, Paliari J C and Andrade A C 2003 Alternativas para redução do desperdício de materiais nos canteiros de obra *Coletânea Habitare – Vol. 2 – Inovação, Gestão da Qualidade e Produtividade e Disseminação do Conhecimento na Construção Habitacional* pp 224–49 (Porto Alegre: Carlos Torres Formoso and Akemi Ino)

[13] Huijbregts M A J 1998 Application of Uncertainty and Variability in LCA Part I: A General Framework for the Analysis of Uncertainty and Variability in Life Cycle Assessment *Int. J. Life Cycle Assess.* **3** 273–80

[14] Bjorklund A E 2002 Survey of Approaches to Improve Reliability in LCA *Int. j. Life Cycle Assess.* **7** 64–72

[15] Cellura M, Longo S and Mistretta M 2011 Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: The case study of an Italian tile *Renew. Sustain. Energy Rev.* **15** 4697–705

[16] He X, Liu Y, Li T and Chen J 2013 Does the rapid development of china’s urban residential buildings matter for the environment? *Build. Environ.* **64** 130–7

[17] Fouquet M, Levasseur A, Margni M, Lebert A, Lasvaux S, Souyri B, Buhé C and Woloszyn M 2015 Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment *Build. Environ.* **90** 51–9

[18] Guimarães G D, Baiocchi A G and Silva V G 2018 Uncertainty types, sources and drivers in whole-building LCAs *VI Congresso Brasileiro sobre Gestão do Ciclo de Vida* pp 756–62

[19] Gomes V, Saade M, Lima B and Silva M 2018 Exploring lifecycle energy and greenhouse gas emissions of a case study with ambitious energy compensation goals in a cooling-dominated climate *Energy Build.* **173** 302–14

[20] International Organization for Standardization 2006 ISO 14040:2006, Environmental management – Life cycle assessment – Principles and framework. ICS 13.020.60-10 vol 2006 (Switzerland)

[21] Wack P 1985 Scenarios: Uncharted Waters Ahead *Harv. Bus. Rev.* **63** 139-50

[22] Pini 2013 Tabela de Composições de Preços para Orçamentos TCPO (São Paulo)

[23] Associação Brasileira de Normas Técnicas ABNT 2013 NBR 15575-1 Edificações Habitacionais – Desempenho. Parte 1: Requisitos gerais

[24] International Organization for Standardization 2017 Paints and varnishes-Corrosion protection of steel structures by protective paint systems-Part 2: Classification of environments (Switzerland)

[25] Miranda L F R, Torres L, Vogt V, Brocardo F L M and Bartoli H 2016 Panorama Atual do Setor de Reciclagem De Resíduos de Construção E Demolição no Brasil *Xvi Encontro Nacional De Tecnologia Do Ambiente Construído* (São Paulo) pp 4247–67

[26] European Union 2010 Being wise with waste: the EU’s approach to waste management (Luxembourg: European Comission)