Zurich, June 15-17 2016
Sustainable Built Environment (SBE) Regional Conference

Expanding Boundaries:
Systems Thinking for the Built Environment

TOWARDS A RELIABLE COMPARISON BETWEEN ENVIRONMENTAL AND ECONOMIC COST OF SWISS DWELLINGS: A MODEL WITH BUILDING MATERIALS' SERVICE LIFE UNCERTAINTY

I.-F. Haefliger[1], V. John[1]*, S. Lasvaux[2], E. Hoxha[2], A. Passer[3], G. Habert[1]

[1] ETH Zurich, Chair of Sustainable Construction, Zurich, Switzerland
[2] Université Paris Est, CSTB, Grenoble, France
[3] TU Graz, Institute of Technology and Testing of Building Materials, Graz, Austria
*Corresponding author; e-mail: viola.john@ibi.baug.ethz.ch

Abstract

Purpose: In this study, the authors develop a method for the estimation of uncertainties arising from the building material service-life in the context of building LCA and LCC. Method: Life Cycle Assessment and Life Cycle Costing analysis were conducted on four newly built Swiss dwellings. The related uncertainties arising for the variability of the building material service lives was evaluated with a Monte Carlo simulation. Findings: The outcome of the study shows that the greenhouse gas emissions or the cost uncertainties of the replacements represent between 6 and 16% of the total result of the buildings' LCA or LCC. Furthermore, the uncertainties' estimation of the replacements allows to compare more accurately the buildings' environmental or economic performances.
Conclusion: The study highlights the interest of taking into account uncertainty estimation for the replacement phase, especially in the context of more energy efficient buildings.

Keywords:
LCA; LCC; uncertainty; building material service life; Monte Carlo simulation

1 INTRODUCTION

Buildings are the largest emitters of greenhouse gases, both in the developed and developing countries. In continental Europe, the energy used in buildings is responsible for up to one third of all greenhouse gas emissions [1]. Urgent changes are therefore required to lower those emissions through for instance energy savings, use of renewable resources, or the reuse and recycling of building materials. However, in order to be able to focus on the pertinent and most sensitive aspects of the building sector, it is fundamental to accurately identify which stages of the building life cycle and which construction materials are the main contributors to the buildings' greenhouse gas emissions.

Concerning buildings, the reliability and robustness of Life Cycle Assessment (LCA) results is even more complex than for the other industrial sectors due to their very long service life. Furthermore, some building materials have to be replaced during a building's life cycle in order to maintain its usability and comfort. In building LCA, the frequency of replacements of those materials is calculated based on a service life (SL) of building material with regard to a building reference study period (RSP) [2]. The SL of building materials can be influenced by many factors which are not only the physical properties of the materials but also socio-economic aspects, such as a change in the consumer needs or a change of the building's user [2]. All these factors will strongly affect the SL of building materials and consequently, the amount of needed construction materials throughout the building's service life and the related greenhouse gas emissions.

The estimation of the uncertainties that are induced by the SLs strengthens the results of LCA and allows for a robust and reliable comparison between building outcomes. Ciroth et al. proposes an overview of different approaches

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_78, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

for the estimations of uncertainties in LCA [3]. They are divided into two types: Monte Carlo simulations or approximation methods. One can find an example in a study undertaken by Hoxha et al. [4], the study estimates the uncertainties in building LCA, originated by the SL with an approximation method.

Since in this study the evaluation of the greenhouse gas emissions of buildings is linked to their economic performance, the uncertainty estimation method developed by Hoxha et al. [4] could not by applied. This is due to the discontinuity of the cost evaluation functions. In this study, the evaluation of the economic performance of the buildings is made through a Life Cycle Costing (LCC) analysis. Arja et al. [5] analyses that most of the studies and researches about uncertainties in LCC for buildings focus mainly on the business or the institution risks, whereas the physical uncertainties such as the one induced by the building materials SL are very little investigated. Therefore, this study tries to develop an uncertainty estimation method regarding the SL applicable for both LCA and LCC, and to evaluate the influence of the SL on LCA and LCC results.

2 DATA AND METHODS

For the uncertainty estimation induced by the SL, a Monte Carlo simulation based on 30’000 iterations is conducted for both LCA and LCC. The input distribution for the Monte Carlo simulation is the building material SL, and the output is the number of replacements (Nr) probability distribution for this material. The distributed SL are based on a database provided by the CSTB, which gives the SL mean and standard deviation value for different building materials. Based on those values, normally distributed SL for a specific building material are constructed and used as input distribution for the simulation.

The simulation is implemented in a way that randomly distributes the replacements over the reference study period of the building (Figure1 (a)) and not linearly over time (Figure 1 (b)). Furthermore, the distribution function of the Nr for the LCC is weighted with a related discounting factor. This means, that the discounting factor is associated with the Nr and not with the cost of a replacement.

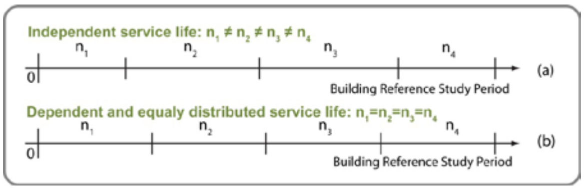


Fig. 1: Distribution of the replacement over the reference study period.

This was possible because all replacement costs were identical with real values over time. The fact that the discounting factor was associated with the Nr made it possible to integrate it into the Monte Carlo simulation, which simplified the uncertainty estimation. This approach made it possible to evaluate the uncertainties for LCA and LCC with the same methodology.

The simulation output for a specific material gave either the probability distribution of the Nr for the greenhouse gas emissions or the Nr for the costs. The probability distribution is fitted with a lognormal distribution.

The simulation was run at the material scale, e.g. a simulation for every building material was conducted. For every material and its related SL, distributed Nr were calculated and for each building material, a minimum and maximum Nr for both LCA or LCC were assessed. This was based on the approach of Slob [6]: the minimum and maximum values were calculated with the geometric mean and standard deviation. A confidence interval of 68% was considered. The minimum and the maximum Nr were calculated by (1).

$$probability\left\{\frac{\mu_g}{\sqrt{Cf}} < X < \sqrt{Cf}\cdot\mu_g\right\} = 0.68 \quad (1)$$

Where μ_g is the geometric mean of the sample and Cf is the confidence factor and equals: $Cf = e^{2\sigma^*}$ with σ^* as the scale parameter of the lognormal distribution. The mean value for the Nr is evaluated by the mean of the lognormal distribution μ.

Based on the minimum and the Maximum Nr, it is possible to evaluate the environmental impacts or the cost with (2), (3) and (4).

$$Mean_i\, impact/cost\, material\, i = \mu_i * Q_i * Eval_i \qquad (2)$$

$$Min_i\, impact/cost\, material\, i = \frac{\mu_{g_i}}{\sqrt{Cf_i}} * Q_i * Eval_i \qquad (3)$$

$$Max_i\, impact/cost\, material\, i = \mu_{g_i}\cdot\sqrt{Cf_i} * Q_i * Eval_i \qquad (4)$$

Where the index *i* represents a material, Q_i the quantities in kg of material *i*, and $Eval_i$ the evaluation function for the costs or the environmental impacts expressed respectively in [kg CO_2eq/kg] or [CHF/kg].

In order to estimate the uncertainty at the building scale, it is assumed with the central limit theorem that the uncertainties are normally distributed:

$$\sigma_{building} \approx \sqrt{\sum_{i=1}^{k}\left(\frac{max_i - min_i}{2}\right)^2} \qquad (5)$$

Where max_i and min_i are the minimum and maximum replacement cost or environmental impact for a given material at the material scale and k represents the different materials. The mean value of the replacements at the building scale $\mu_{building}$ is the sum of the various means at the element scale (6).

$$\mu_{building} \approx \sum_{i=1}^{k} \mu_i * Q_i * Eval_i \qquad (6)$$

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_78, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

General Information	B1	B2	B3	B4
Construction type	Massive	Medium weight	Light weight	Massive
AE energy area [m2]	12'430	350	374	622
Floor area[m2]	16'746	886	517	868
Energy standard	Minergie	Minergie-ECO	Minergie-P	SIA 380/1
Accomodation units [-]	111	2	3	4
Basement [Yes/No]	Yes	Yes	No	Yes
Number of floors [-]	5	3	3	2
Heating & ventilation systems				
Heating device	Heat pump	District heating	Heat pump	Heat Pump
Energy source	Electricity	Wood chips	Electricity	Electricity
Solar panels	No	No	Yes	Yes
Annual heat demand [MJ/m²]	130	106	70	169
Annual hot water demand [Mj/m²]	73	75	21	121
Annual ventilation demand [MJ/m²]	14	24	3	-

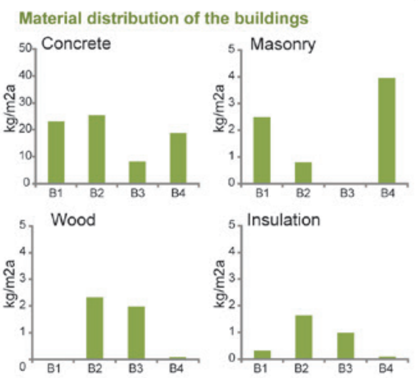


Fig. 2: Main construction materials for the buildings.

2.1 Case Study

For this study, four Swiss buildings were selected (B1, B2, B3 and B4). The four buildings show various characteristics: they differ in size, construction type, construction materials, and their energy performances. Thus, they represent a large variety of newly built Swiss dwellings. Figure 2 summarises the building characteristics and their composition in terms of their main building materials. The buildings were selected from the doctoral thesis of V. John [7], where also further detailed building information on the sample is available (buildings: mfh01, mfh02, mfh03 and mfh04).

The four buildings are assessed for their greenhouse gas emissions with the LCA method, and for their costs with the LCC approach. The uncertainty estimation method presented previously is applied to the building sample. The system boundary of the LCA is defined to be a

Cradle-to-Grave analysis, focusing on the structural components (Structural components include: walls, ceilings, roof, foundations, windows, external doors.) as well as on the energy consumption during the use phase. Heating and ventilation devices are also taken into account, while transportation and the contributions of craftsmanship are neglected. The greenhouse gas emissions are evaluated with the Swiss Bauteilkatalog BTK [8] and with the indicator Global Warming Potential (GWP) 100a. The tool BTK is based on data from the Swiss ecoinvent database (v.2) (www.ecoinvent.org/). The LCA results for annual energy demand for heating and ventilation energy demands are taken from the doctoral thesis of V. John [7]. The functional unit is chosen as one square metre of energy reference area per one year of building study period. Figure 3 presents the LCA parameters used in this study.

The system boundary for the LCC is selected in accordance with that of the LCA analysis. The structural element costs are evaluated in Swiss francs (CHF) using the Swiss Bauteilkatalog [8] with its reference prices for construction materials. The costing is evaluated following the dynamic approach given by the Swiss Research Centre for Rationalisation in Building and Civil Engineering CRB [9], implemented with the reference energy costs proposed by the Canton of Zurich [10]. The costs for the heating and ventilation devices are evaluated based on data from the Swiss Department for Statistics [11]. Those costs account for 12% of the structural construction costs. The results of the LCC are also expressed with the functional unit previously defined. Figure 3 presents the LCC parameters applied in this study.

General parameters	Parameters
System boundaries	Cradle-to-Grave
Building RSP	60 years
Material service life	Normal distributed variable
LCA parameters	
Software and database	Bauteilkatalog (KBOB), ecoinvent v2.0 database
Indicator	Global Warming Potential (GWP) 100a
LCC parameters	
Discount rate	3%
Electricity costs	0.234 [CHF/kWh]
Electricity price evolution	1.4% (linear increase per year)
Wood pellet costs	0.074 [CHF/kWh]
Wood pellet price evolution	1.6% (linear increase per year)
Heat pump COP	3.5
Software and database	Bauteilkatalog (KBOB), guidline prices 2010

Fig. 3: LCA and LCC system parameters ADD GWP 100a.

3 RESULTS

The next paragraphs will present the LCA and LCC results and the related uncertainties for the

replacements. Figure 4 shows the results for the LCA and LCC results of the four buildings and the related uncertainties. First, the relation of uncertainties and energy performance of the buildings will be highlighted. Secondly, the influence of the uncertainties on the building results for LCA and LCC will be assessed.

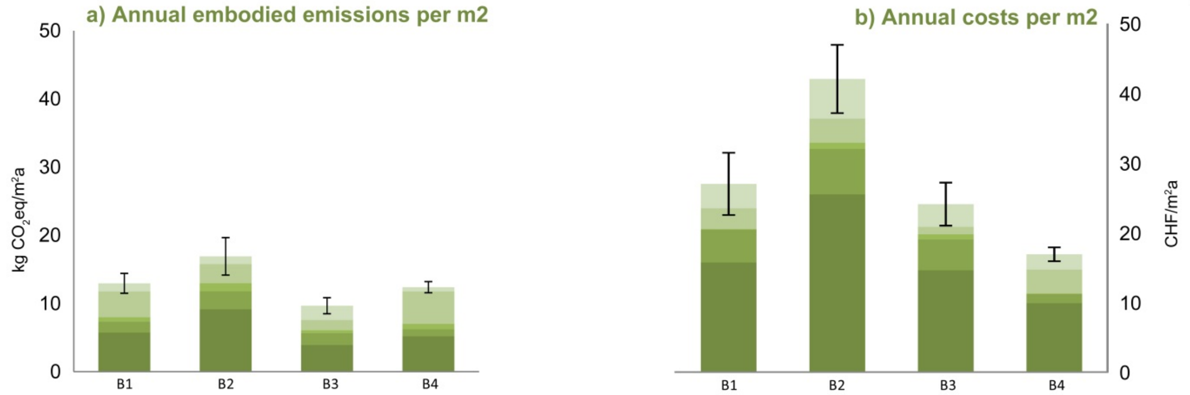
The uncertainties related to the replacements represent on average ± 6 to 16% of the total LCA

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_78, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

or LCC results (Figure 4 (a), (b)). The building (B4) presenting the lowest uncertainties (6.7% for emissions, and 5.9% for the costs), is also the building with the highest energy needs for the utilization phase. Building B2 bears high uncertainties for cost as well as greenhouse gas emissions; it is also one of the most energy efficient buildings. This trend underlines the causality between energy efficient building and uncertainties of the replacement phase. More construction materials, especially insulation materials, are required for high energy-efficient buildings. Therefore, the embodied greenhouse gases and the costs for the construction as well as for the replacement phase are more consistent. In opposition to the energy, greenhouse gas emissions and costs are decreasing with better insulated buildings.

This leads to a shift in the life cycle results; the replacement phase is gaining in importance. Thus, with the development of new energy efficient buildings, the necessity to introduce uncertainty estimation for the replacement of building materials is becoming more significant for both LCA and LCC.

Furthermore, the integration of uncertainties into LCA or LCC results allows for a stronger comparison of buildings' outcomes. In this case study, the uncertainty estimations enable better ranking of the buildings in terms of greenhouse gases, as well as in term of costs. Indeed, when considering the results of the buildings Figure 4 (c) without uncertainties, B3 is the most environmentally friendly building and B1 the cheapest one. Concerning uncertainty, one can define that the difference in terms of greenhouse gases between those two buildings (B1 and B3) is not significant, whereas in terms of Swiss francs, it is. **Uncertainties allow to compare more accurately the performance of buildings**. In our case, we could tell that B3 is significantly different from B4, regarding life cycle costs.



	B1	B2	B3	B4		B1	B2	B3	B4
	11%	16%	12%	7%	Uncertainites	16%	12%	13%	6%
	9%	7%	22%	5%	Heating devices	13%	14%	14%	13%
	29%	17%	15%	38%	Energy	11%	8%	4%	20%
	5%	6%	5%	7%	Disposal	0%	2%	3%	1%
	13%	16%	18%	8%	Replacement	19%	17%	19%	8%
	44%	54%	40%	42%	Construction	57%	60%	60%	58%

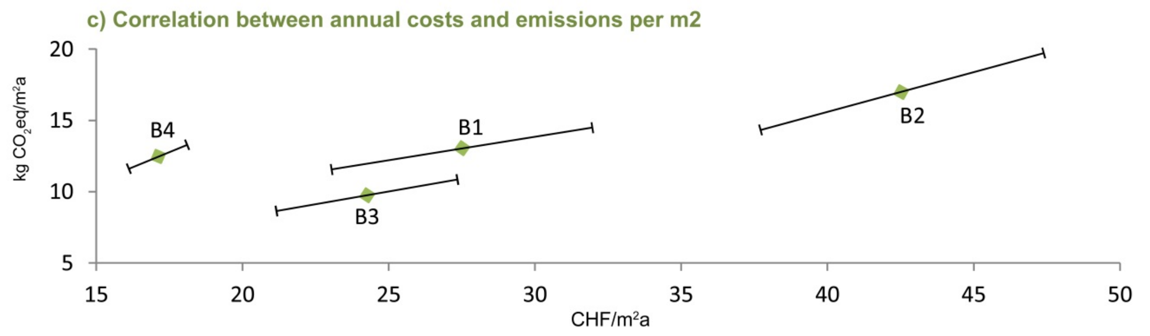


Fig. 4: LCA and LCC for the four buildings with uncertainty. Error bars represent standard deviation ($\pm 2\sigma$).

G. Habert, A. Schlueter (eds.): Expanding Boundaries © 2016 vdf Hochschulverlag AG an der ETH Zürich
DOI 10.3218/3774-6_78, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

4 DISCUSSION

This study underlines the importance of the replacement uncertainties arising from SL in the context of increasing energy efficiency of buildings. However, to strengthen those results, the analysis should be carried out more deeply in details at the material scale, as well as by increasing the number of evaluated buildings. Also, one should be careful about the strong variation of the buildings' characteristics and the scattering of the LCA or LCC results.

Finally, there seems to be a correlation between economic and environmental cost; the most environmental friendly building of the sample is also one of the most economical buildings, while being of similar comfort and service. This study may open the discussion on future perspectives in the construction industry by raising the question, if the track we are following at the moment really is the most effective one for new sustainable buildings.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the CSTB for the provided database concerning the material service lives uncertainties.

6 REFERENCES

1. UNEP, U.N. (2009). Buildings and Climate Changes: Summary for Decision-Makers. Paris. Nations Environment Programme.

2. EN 15978 (2010). Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method. Brussels. European Committee For Standardization.

3. Ciroth A., Fleischer G. and Steinbach J. (2004). Uncertainty Calculation in Life Cycle Assessments – A Combined Model of Simulation and Approximations. *International Journal of LCA*, 9(4): 216 – 226, doi: 10.1065/lca2004.05.158.

4. Hoxha E., Habert G., Chevalier J., Bazzana M. and Le Roy R. (2014). Method to analyse the contribution of material's sensitivity in buildings' environmental impacts. *Journal of Cleaner Production,* 66: 54-64, doi: 10.1016/j.jclepro.2013.10.056.

5. Arja M., Sauce G. and Souyri B. (2009). External uncertainty factors and LCC : a case study. *Building research & Information*, 37(3): 325-334, doi:10.1080/09613210902863609.

6. Slob W. (1994). Uncertainty Analysis in Multiplicative Models. *Risk Analysis*, 14(4): 571 – 576, doi:10.1111/j.1539-6924.1994.tb00271.x.

7. John V. (2012). Derivation of reliable simplification strategies for the comparative LCA of individual and "typical" newly built Swiss apartment buildings. *ETH Zurich*, doi:10.3929/ethz-a-007607252.

8. Koordinationskonferenz der Bau- und Liegenschaftsorgane der Öffentlichen Bauherren KBOB (2012). *Ökobilanzdaten im Baubereich 2009/1.* Bern. KBOB.

9. Schweizerische Zentralstelle für Baurationalisierung CRB (2012) *LCC Leitfaden – Planung der Lebenszykluskosten*. Zurich. CRB.

10. Koordinationskonferenz der Bau- und Liegenschaftsorgane der Öffentlichen Bauherren KBOB (2012). *Wirtschaftlichkeitsrechnung im Hochbau – Draft version 2014.* Bern. KBOB.

11. Office Fédéral de la Statistique OFS (2012). *La statistique suisse des prix de la construction octobre 2010.* Neuchâtel. OFS.