Environmental Sensitivity Analysis of the Life-cycle of an Office Building

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Summary

This study performs a sensitivity analysis of the materials manufacturing, construction, use, maintenance, renovation/retrofit, and end-of-life phases of an office building in Finland, and concentrates on eighteen different model, input, and obsolescence scenarios. The results show that the building LCAs are expected to be sensitive to some model and outside conditions, such as energy mix and obsolescence, and thus these should be clearly stated when presenting the results of an LCA study.

1. Introduction

In life-cycle analysis, the service life chosen for buildings is often 50 years. In cost analysis, the end part of the life-cycle has typically only a minor significance due to discounting. However, in environmental life-cycle assessments (LCA), the future is typically valued the same as the present, and as a result the end part of the life-cycle can have a significant influence on the overall result. Thus the long life span of the buildings may cause additional uncertainty to the result of the building LCAs.

One way of assessing the impact of uncertainty is through sensitivity analysis [1]. Technically, sensitivity is the influence of one parameter (the independent variable) on the value of another (the dependent variable) [2]. The independent variable in LCAs can be either continuous or discrete. The system inputs are typically continuous parameters and the system boundaries, allocation, model choices and process choices are discrete parameters. Sensitivity analyses should focus on the most significant issues to determine the influence on variation in assumptions, methods, and data. Sensitivity analysis can use arbitrarily selected ranges of variation, or known ranges of uncertainty.

One type of sensitivity analysis that is often used in LCAs is scenario analysis. The scenario refers to the different choices of the used model, input parameters and outside conditions of the studied system [3], [4]. Pesonen et al. [3] separate two kinds of scenario development for LCA purposes, *What if* and *Cornerstone* scenarios. The *What if* scenarios are used to compare quantitatively different alternatives in the system or to test some specific changes within the system. The *Cornerstone* scenarios are more fundamental and comparable to scenarios in future studies. An additional separating feature is that only a relatively small number of scenarios should be included in *Cornerstone* studies, whereas the *What if* approach can include a large number of scenarios. In both cases, an important part of using scenarios is to provide a valid reasoning for selection of certain parameters.

Although sensitivity analysis is a recommended part of an LCA study, it is still not a standard practice [5]. However, it has been performed in some building LCA studies. For example, Adalberth et al. [6] have assessed the effects of three alternative scenarios for a multi-family building in

Sweden. They found that the used energy mix had a considerable influence on the result, and that the material data and the amount of operational energy only a minor influence. In another study, Peuportier [7] has performed a sensitivity analysis for a single-family house in France. He has tested four alternative scenarios and found that the type of heating energy used has a major influence and the alternative building materials used a minor, but still a considerable influence.

Two Finnish studies have estimated the effects of numerous alternative scenarios on the result of building LCA. Junnila [8] has assessed the influence of 23 alternative scenarios of a multi-family building and found that the result is most sensitive to the assumptions made about the life span of the building and the energy mix used. Vaahterus & Saari [9] have tested the sensitivity of an ice-skating facility LCA with fifteen different scenarios. They reported that the result is most sensitive to the operating hours, the indoor temperature, and the possible installation of heat recovery equipment.

Obsolescence is a special feature of a building life-cycle that has not yet been included in most sensitivity analyses in building LCAs. Typically the technical life span of the building is very long and it can even be extended with proper maintenance. In LCAs a life span typically used for buildings is 40 to 60 years, which in technical terms is quite a feasible or even a cautious estimate. However, the situation may change dramatically if obsolescence is included in the model. Lemer [10] argues quite strongly that the impact of obsolescence has been largely neglected. In his opinion the design service lives are set typically with very limited rationale, and the assumptions of service life should in many cases be shorter than is currently common practice. Another study has noticed that buildings undergo significantly more renovations to all systems (structure, enclosure, services, interior finishes) than is commonly assumed [11].

The articles discussing obsolescence have indeed presented considerably shorter building life spans than are typically used in LCAs. For example, Barras & Clark [12] in their extensive study of obsolescence of office buildings in Central London have found that over 12 years the net acquisition of newer properties at the expense of older has rejuvenated the post-war portfolio to the extent that its average age has remained fairly constant at around 15 years. In addition, they estimate that obsolescence will accelerate over the next 10-15 years. Also, other studies have presented that a realistic service life of a building is around 15-30 years [13], [14], [15].

This study continues the tradition of assessing the sensitivity of an LCA by using alternative scenarios. The paper performs a sensitivity analysis of the material manufacturing, construction, use, maintenance, renovation/retrofit, and end-of-life phases of an office building in Finland. The paper puts in perspective the alternative scenarios with the base case scenario and calculates the relative significance of the alternative scenarios. The sensitivity analysis concentrates on significant issues of the building’s life-cycle and uses eighteen different model, input, and obsolescence scenarios to test sensitivity.

2. Method

The LCA framework was selected to analyze the environmental aspects of a new high-end office building in Southern Finland. Fifty years of use was assumed to be the basic life-cycle. The study can be called a screening product LCA because it utilizes mostly existing LCA data [16].

The LCA had three main phases: inventory analysis for quantifying emissions and wastes, impact assessment for evaluating the potential environmental impacts of the inventory of emissions and wastes, and interpretation for assessing the sensitivity of the results. The inventory included all the major life-cycle phases of an office building: building materials manufacturing, construction processes, use of the building (electrical, heating and other services), maintenance, and demolition.

The emission inventory data were mainly collected from the actual producers in Finland. The age of the emission data was typically less than 5 years, and it had been verified by an independent third party organization. The quality of the data used was evaluated using a six-dimensional estimation framework recommended by the Nordic Guidelines on Life Cycle Assessment and was set at the second highest level (two of five) in the framework [17].

In the impact assessment the following impacts were studied: climate change, acidification, eutrophication, and dispersion of harmful substances, which included summer smog and heavy metals. The impact categories were chosen according to those designated by the Finnish

Environmental Institute [18], and they were calculated using the KCL-Eco software [19].

Finally, sensitivity analysis was performed for the most significant issues identified in the contribution analysis [20]. The ranges of variation of identified assumptions and inputs were determined based on empirical data. The reasoning for the selection of studied alternatives and the used ranges are presented in the following section.

3. Presenting the base case and scenarios

The case used in the study is a new high-end office building [21]. The users of the building are medium-sized high-tech organizations. The building has 15,600 m^2 of gross floor area, and a volume of 61,700 m^3. The building consists of three 5-story office towers. The structural frame is made of cast-in-place concrete. The most common exterior wall structure is a masonry wall made of clay bricks having a steel-profile support and mineral wool insulation. The building has two major partition wall types, one made of calcium-silicate bricks, and the other of particleboard with glue-laminated studs and mineral wool sound board. More than 120 different building elements consisting of over fifty different building materials were identified in the inventory.

The alternative scenarios used in the sensitivity analysis are presented in Table 1. The alternative scenarios for the **electricity mix** are based on data from the actual energy companies providing electricity in Finland. The emissions from electricity generation were taken from the environmental reports of the selected companies. In the case of combined heat and power production (CHP), the emissions were allocated to the products in proportion to the fuel consumption of the alternative non-CHP production plants [22].

Sensitivity to the **heating energy mix** was tested with two district heating energy profiles available in Finland. The emissions of heat production were based on environmental reports of the selected companies. In the case of CHP, the emissions were allocated to the products in proportion of the fuel consumption of the alternative non-CHP production plants [22].

The scenario for **wastewater treatment** was tested with one theoretical and one actual treatment plant. Instead of the current plant a theoretical that fulfils the requirements of the new urban wastewater treatment directive [23] was used (mostly the current plant performs already better than the new requirements, in which case the current performance has been maintained). The pessimistic scenario was based on a low-performance, but still operating treatment plant [24].

In the case of **manufacturing of building materials,** the pessimistic scenario was based on older production data (10-15 years old) within a wider geographical area (US, OECD) resulting in an average 31% increase in emissions [25]. The optimistic scenario was based on a purely theoretical value of 30% improvement.

In the base case scenario no allocation of emissions was assumed to the future products due to the **recycling of building materials**. The first alternative scenario assumed a 90% recycling ratio and endless recycling for the metals used in the building equaling a 50-90% allocation to the future [26]. The second scenario assumed the same for metals, but in addition, a 90% recycling ratio with one time

Table 1. The scenarios used in the sensitivity analysis.

Model assumptions	**Optimistic**	**Expected**	**Pessimistic**
Electricity mix		CHP	CHP
- hydro	42 %	-	-
- gas	-	50 %	-
- coal	-	17 %	95 %
- nuclear	58 %	11 %	-
- other	-	21 %	5 %
Heating energy mix	CHP	CHP	CHP
- bio (wood, peat)	71 %	-	-
- recycled paper	19 %	-	-
- natural gas	-	63 %	-
- coal	-	35 %	95 %
- others	10 %	7 %	5 %
Water treatment			
- P, w	90 %	90 %	74 %
- N, w	80 %	60 %	15 %
Materials manuf.	-30 %	Finland	30 %
Recycling metals	50-90%	no allocat.	no allocat.
Recycling all	40-90%	no allocat.	no allocat.
Inputs	**Optimistic**	**Expected**	**Pessimistic**
Oper. electricity	-50 %	25 kWh/m^3	50 %
Oper. heat	-35 %	18 kWh/m^3	35 %
Maintenance cycles			
Steel profile			
-external envelope	-15 %	40 yrs	15 %
-roof	-20 %	30 yrs	20 %
-ventilation plant	-10 %	25 yrs	10 %
Paints			
-external surfaces	-15 %	15 yrs	15 %
-internal surfaces	-60 %	10 yrs	60 %
Obsolescence	**Optimistic**	**Expected**	**Pessimistic**
Rebuilding	>50 yrs	>50 yrs	30 yrs
Refurbishment	>50 yrs	>50 yrs	15 yrs

recycling for all other building materials equaling a theoretical 40% allocation to the future products.

The scenarios for the **operational electricity** consumption were created based on statistical data of energy-audited private sector offices in Finland [27]. The operational energy of the office was assumed to vary by the amount of the standard deviation of the metered offices (±50%). The scenarios for the **operational heat** consumption were created based on the same data source having a range of ±35% for heating.

The **building material maintenance** scenario was based on a maintenance guideline [28]. The variations for building material/element maintenance cycles were typically 10-20% of the reported maintenance cycle, with the exception of painted surfaces where a variation of 50-60% was reported.

The effects of obsolescence were tested with two scenarios. The first scenario assumed a total **rebuilding** of the office once during the life-cycle. The second scenario assumed a major **refurbishment** of the building every 15 years [12]. The major refurbishment included the renewal of the following building elements: internal complementaries, building services, and all the internal surfaces.

4. Results

4.1 The base case

The results of the base scenario LCA are presented in Table 2. Most of the building's life-cycle phases have significant impacts in some category. However, two life-cycle phases, electrical services and building material manufacturing seem to be significant in all studied categories, with heating services closely behind. In each impact category the three life-cycle phases with the highest scores account for at least 80% of the impact, with the exception of summer smog and eutrophication where the sum of the four highest scores exceeds 80%.

Table 2. Environmental impacts of an office building with 50 years of service life. The figures in bold indicate the issues that account for 80% or more of impact in each category [29].

Office building LCA results	Climate change [ton CO_2 equiv.]	Acidification [kg SO_2 equiv.]	Summer smog [kg H_2C_4 equiv.]	Eutrophication [kg PO_4 equiv.]	Heavy metals [kg Pb equiv.]
Building materials	**4,800**	**19,000**	**7,600**	**1,900**	**7.4**
Construction	820	5,800	530	960	0.3
Electrical service	**25,000**	**59,000**	**4,900**	**5,500**	**3.8**
Heating service	**11,000**	**25,000**	2,400	**2,300**	1.2
Other services	3,900	11,000	**2,600**	**4,000**	0
Maintenance	1,600	8,400	**5,700**	850	**2.1**
Demolition	440	4,400	680	720	0.3
Total	*48,000*	*130,000*	*24,000*	*16,000*	*15*

4.2 Sensitivity analysis

As Table 3 shows, the alternative scenarios can have a significant influence on the results of the study. The scenarios with the highest influence were related to model assumptions; the electricity mix (pessimistic and optimistic), rebuilding (pessimistic), heating energy mix (pessimistic), and refurbishment (pessimistic) all caused a variation of 50% or more in at least one impact category (electricity mix – pessimistic in three). The input scenarios that affected the most, over 25%, were operational electricity (pessimistic, optimistic) and recycling (all materials). Water treatment and maintenance scenarios seem to have the least significant influence on the results.

Table 3. Results of sensitivity analysis of an office building life-cycle assessment.

Sensitivity Analysis Scenarios	Climate change [CO_2 equiv.]	Acidification [SO_2 equiv.]	Summer smog [H_2C_4 equiv.]	Eutrophication [PO_4 equiv.]	Heavy metals [Pb equiv.]
Base Case	48,000 ton	130,000 kg	24,000 kg	16,000 kg	15 kg
Electricity mix, optimistic	**-52 %**	**-43 %**	-17 %	**-31 %**	**-27 %**
Electricity mix, pessimistic	**60 %**	**119 %**	-6 %	**58 %**	2 %
Heating energy mix, optimistic	-19 %	18 %	-3 %	1 %	-3 %
Heating energy mix, pessimistic	21 %	**42 %**	-3 %	21 %	**52 %**
Water treatment, optimistic	0 %	0 %	0 %	-6 %	0 %
Water treatment, pessimistic	0 %	0 %	0 %	19 %	0 %
Materials manufact., optimistic	-4 %	-8 %	-17 %	-6 %	-20 %
Materials manufact., pessimistic	4 %	8 %	21 %	6 %	20 %
Recycling, metals	-3 %	2 %	-21 %	2 %	3 %
Recycling, all	-8 %	-8 %	**-38 %**	-6 %	-20 %
Operational electricity, optimistic	**-27 %**	-23 %	-8 %	-13 %	-13 %
Operational electricity, pessimistic	**27 %**	23 %	13 %	19 %	13 %
Operational heat, optimistic	-8 %	-8 %	0 %	-6 %	0 %
Operational heat, pessimistic	8 %	8 %	4 %	6 %	7 %
Maintenance, optimistic	0 %	0 %	-8 %	0 %	0 %
Maintenance, pessimistic	0 %	0 %	13 %	0 %	7 %
Rebuilding, pessimistic	13 %	23 %	**38 %**	**25 %**	**53 %**
Refurbishment, pessimistic	6 %	15 %	**33 %**	13 %	**60 %**

5. Discussion

The purpose of the study was to analyze the sensitivity of an office building LCA to the possible changes in the used model, input parameters, and outside conditions of the studied system. The results proved to be the most sensitive (over 50% effect on the results) to the changes in the electricity mix, rebuilding, heating energy mix, and refurbishment scenarios.

The results of the study are to an extent comparable to other studies that have tested the sensitivity of a building LCA. Several studies have reported the energy mix having a significant influence on the results [6], [7], [8]. However, the effects of obsolescence have not yet been flagged as a significant cause of sensitivity in building LCAs. In this study, both obsolescence scenarios, rebuilding and refurbishment were found to be among the most significant ones to cause sensitivity. One reason may be that most of the other studies have estimated the sensitivity of multi-family buildings or homes where obsolescence is perhaps not as relevant as it is in the case of office buildings, like in this study.

The present study investigated only some of the possible scenarios and focused on the environmental aspects with high contribution in the base case scenario. This approach may leave some aspects with low contribution but high uncertainty undetected, which could have an influence on the overall sensitivity [30]. Also, the selection of ranges of uncertainty used in the scenarios were chosen based on empirical evidence, but not on statistical uncertainty. Finally, the approach uses a static model for evaluating sensitivity and does not assess simultaneous effects of uncertainty as, for example, Monte Carlo simulation would.

It is expected that building LCAs would be sensitive to some model and outside conditions, such as energy mix and obsolescence, and thus these should be clearly stated when presenting the results of an LCA study. But by the same token affecting these conditions is a way of influencing the environmental impacts of office buildings. Effective ways to reduce the environmental impacts of an office building would be to use an environmentally preferable electricity mix and to pay special attention to the rate of obsolescence of buildings.

6. References

[1] ISO 14040, *Environmental Management, Life Cycle Assessment, Principles and Framework*, SFS-EN ISO 14040, Finnish Standards Association SFS, Finland, 1997.

[2] Björklund, A. E. “Survey of Approaches to Improve Reliability in LCA”, *Int. J. of Life Cycle Assessment,* Vol. 7, No. 2, 2002, pp. 64-72.

[3] Pesonen, H.-L., Ekvall, T., Fleischer, G., Huppes, G., Jahn, C., Klos, Z., Rebitzer, G., Sonnemann, G., Tintinelli, A., Weidema, B. P. and Wenzel, H., “Framework for Scenario Development in LCA”, *Int. J. of Life Cycle Assessment*, Vol. 5, No. 1, 2000, pp. 21-30.

[4] Lindfors, L.-G, “Assessment of Data Uncertainties of the Study”, *Nordic Guidelines on Life Cycle Assessment*, Nord 1995:20, Nordic Council of Ministers, Copenhagen, Denmark, pp. 69-70.

[5] Ross, S., Evans, D. and Webber, M., “How LCA Studies Deal with Uncertainty”, *Int. J. of Life Cycle Assessment*, Vol. 7, No. 1, 2002, pp. 47-52.

[6] Adalberth, K., Almgren, A. and Petersen E. H., “Life Cycle Assessment of Four Multi-Family buildings”, *Int. J. of Low Energy and Sustainable Buildings*, Vol. 2, 2001.

[7] Peuportier, B. L. P, “Life Cycle Assessment Applied to the Comparative Evaluation of Single Family Houses in the French Context”, *Energy and Buildings*, Vol. 33, No. 5, May 2001, pp. 443-450.

[8] Junnila, S., *Quantitative Estimation of Environmental Burdens of a Finnish Apartments Building*, Licentiate Theses, Helsinki University of Technology, Faculty of Civil and Environmental Engineering, Construction Economics and Management, 1998.

[9] Vaahterus, T. and Saari, A., *Environmental Loads of a Finnish Indoor Training Ice-Skating Rink*, Helsinki University of Technology, Construction Economics and Management, Publications 194, Espoo 2001.

[10] Lemer, A. C., “Infrastructure Obsolescence & Design Service Life”, *J. of Infrastructure Systems*, Vol. 2, No. 4, 1996, pp. 153-156.

[11] Slaughter, E. S., “Design Strategies to Increase Building Flexibility”, *Building Research & Information*, Vol. 29, No. 3, 2001, pp. 208-213.

[12] Barras, R. and Clark, P., “Obsolescence and Performance in the Central London Office Market”, *J. of Property Valuation and Investment*, Vol. 14 No. 4, 1996, pp. 63-78.

[13] Seo, S. and Hwang, Y. ”Estimation of CO_2 Emissions in Life Cycle of Residential Buildings.” *J. of Construction Engineering and Management*, Vol. 127, No. 5, September/October 2001, pp. 414-418.

[14] Iselin D. G. Lemer A. C. *Fourth Dimension in Building: Strategies for Avoiding Obsolescence*, National Academy Press, Washington, 1993, pp. 11-25.

[15] Wong, K.C., “Valuing the Refurbishment Cycle“, *Property Management*, Vol. 18, No. 1, 2000, pp. 16-24.

[16] Wenzel, H. “Application Dependency of LCA Methodology: Key Variables and Their Mode of Influencing the Method”, *Int. J. of Life Cycle Assessment*, Vol. 3, No. 5, 1998, pp. 281-288.

[17] Neuvonen, P. (2000). "The Environmental Declarations of Building Products in Finland." *Proceedings of the CIB/GBC/Novem 2nd International Conference on Sustainable Building 2000*. October 22-24, 2000, Maastricht.

[18] Rosenström, U. & Palosaari, M. *Indicators for Sustainable Development in Finland*. Finnish Environment 404. The Finnish Environment Institute, 2000.

[19] KCL-ECO 3.0, LCA software, *Finnish Pulp and Paper Research Institute*, 1999, Espoo, Finland.

[20] Heijungs, R. and Kleijn, R., “Numerical Approaches toward Life Cycle Interpretation”, *Int. J. of Life Cycle Assessment*, Vol. 6, No. 3, 2000, pp. 141-148.

[21] Junnila, S. and Rintala, T., “Comprehensive LCA Reveals New Critical Aspects in Offices”, *CIB/ iiSBE International Conference on Sustainable Building*, Sept. 23-25, 2002, Oslo, Norway.

[22] Liikanen, J., *Allocation of Emissions in Combined Heat and Power Production*, Ministry of Trade and Industry, Report 19/1999. Finland.

[23] *Council Directive 91/271/EEC of 21 May 1991* Concerning Urban Wastewater Treatment. http://europa.eu.int/smartapi/cgi/, acessed April 29, 2003.

[24] Finnish Environment Institute, *Water Treatment Plants in Finland*, [24][1] http://www.vyh.fi/palvelut/julkaisu/elektro/sy542/sy542.htm, accessed May 7, 2003.

[25] Boustead I, *The Boustead Model 3 for Life Cycle Inventory Calculations*, Boustead Consulting Ltd, UK, 1997.

[26] Building Information, *Environmental Declaration*, Building Information Ltd. http://www.rts.fi/ymparistoselosteet/nro34.htm, accessed May 7, 2003.

[27] Suomi, U., *Energy Auditing in Buildings*, Motiva Publication 1/2001, Information Centre for Energy Efficiency and Renewable Energy Sources. Interviewed April 23, 2003.

[28] Building Information, *KH 90-00159 Maintenance File*, Building Information Ltd, 1998, Finland.

[29] Junnila, S. and Horvath, A., “Life-cycle Environmental Effects of an Office Building.” In print, *J. of Infrastructure Systems*, ASCE, 2003.

[30] Heijungs, R., “Identification of Key Issues for Further Investigation in Improving the Reliability of Life-cycle Assessments”, *J. of Cleaner Production*, Vol. 4, No. 3-4, 1996, pp. 159-166.