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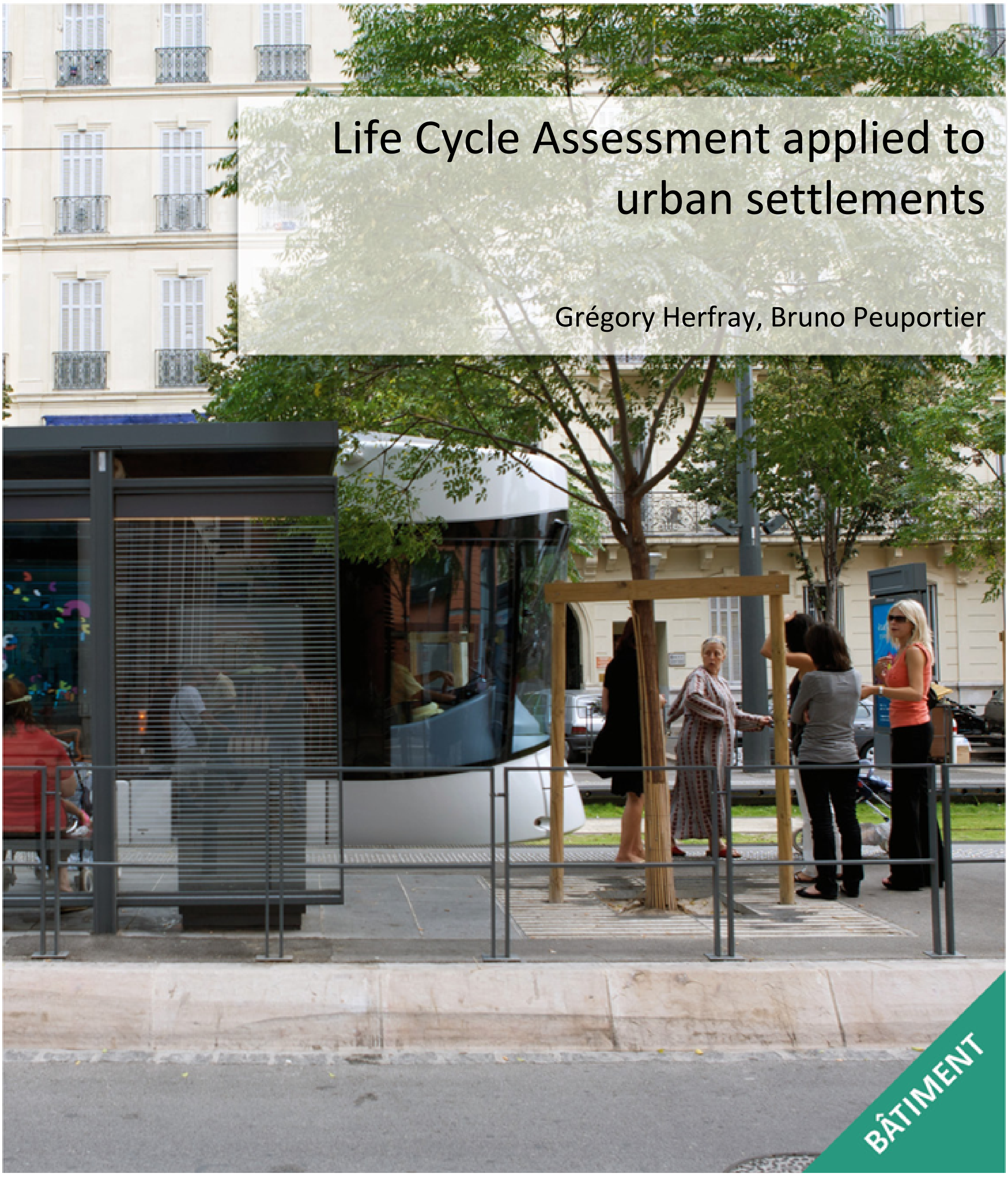
Life Cycle Assessment applied to urban settlements

Grégory Herfray, Bruno Peuportier



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Life Cycle Assessment applied to urban settlements

HERFRAY Gregory
CEP, MINES ParisTech
gregory.herfray@mines-paristech.fr
PEUPORTIER Bruno
CEP, MINES ParisTech
bruno.peuportier@mines-paristech.fr

INTRODUCTION

Life cycle assessment has been applied to buildings in order to evaluate and reduce environmental impacts in this sector, and many tools have been developed in order to provide assistance in the design process. But the application of this method on a larger system like an urban islet allows more aspects to be studied like global planning, mutual shading and shared equipment (e.g. district heating, compost system…). The work presented here focuses on the scale of an urban settlement, and aims to better understand the links between decisions and impacts. The objective is the development of a tool providing help in the design process of a settlement, by evaluating the impacts of the project. This will permit a comparison between design alternatives, and the study of some new concepts integrated in the settlement, like plus energy buildings.

METHODOLOGY

Existing tools for environmental assessment

There are nowadays different methods to determine the environmental impacts of any human-linked system, particularly:

- "Impact studies", focused on the local implications of a project
- The Mass Flow Accounting method, or the calculation of energy needs, that give some intermediate results
- The External Costs method, or the Ecological Footprint method, giving more synthetic results, but including more subjective aspects
- Life Cycle Assessment, more exhaustive but non-localized

We consider here that in the case of a settlement, most impacts are related to the production of energy, water, materials etc, which occurs out of the settlement. For this reason LCA has been used rather than impact evaluation. Impacts can occur on a global scale, like in the case of climate change, or the depletion of the ozone layer, at a regional scale, with the acidification or eutrophication problems, or at a local scale, as with smog or waste production. We choose here to use the LCA methodology, in order to get the most exhaustive information about the consequences of settlement on the environment. Using LCA, we can obtain results on the most relevant aspects for this specific sector, by calculating chosen indicators in our studies. This methodology also permits the calculation of more sophisticated indicators, damage-oriented, regarding the human health, the biodiversity or resource depletion.

LCA: methodology

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Life Cycle Assessment is a standardized methodology for the evaluation of environmental impacts of a system, from its production to its end of life. LCA is composed of 4 main steps, summarized in the next figure:

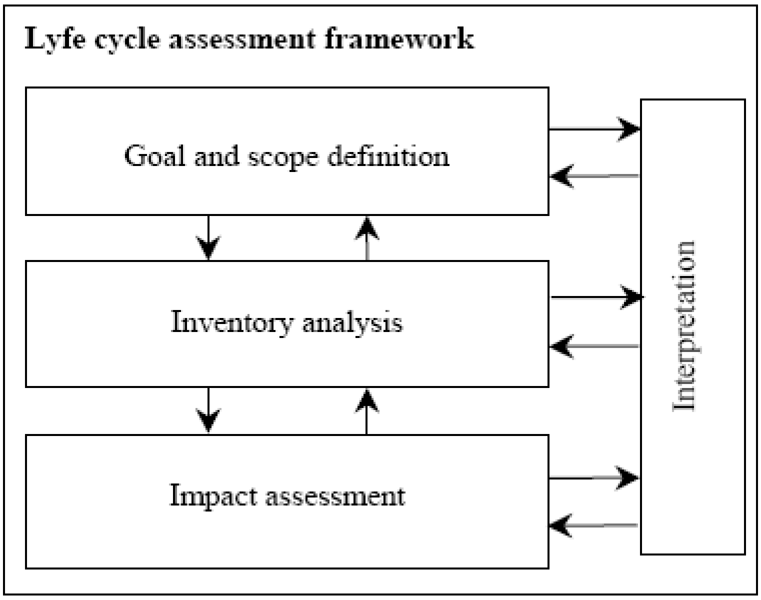

Figure 1: LCA steps, ISO 14040, 1997 (1)

After the definition of the goal and the scope of the study, the system is clearly defined (principally its functional unit and boundaries) and the hypothesis of the study specified, then the inventory analysis will be performed. This inventory is an account of all substances taken and emitted in the environment, during the whole life cycle of the system. From this account, indicators corresponding to impacts are calculated. All those steps are directly linked with an interpretation phase, which may imply a new definition of the system or the goal and scope of the study (for example if a lack of data appears during the inventory phase).

LCA OF AN URBAN SETTLEMENT

Definition of the system: functional unit

The goal of our work is here to develop a tool adapted to the design phase of a settlement, allowing comparison between different alternatives from an environmental point of view. As a consequence, it won't be interesting to strictly define what the functional unit of our system is. This will depend on the goal of the study performed with the tool: for example the functional will be different if the goal is to compare different possible sites for a new settlement, or if the goal is to study the architectural design for a given location. But some common aspects have to be included in the functional unit in order to compare alternatives:

- Some quantities: dwelling area, offices, shops, public spaces, or number of users (inhabitants, workers…)
- Functions: residential, works, leisure…
- Quality of the function: comfort (thermal, visual, acoustic…), quality of life…
- duration: for example 1 year

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Then the boundaries of the system have to be defined. In the case of a settlement, two types of boundaries are defined, as shown in the next figure:

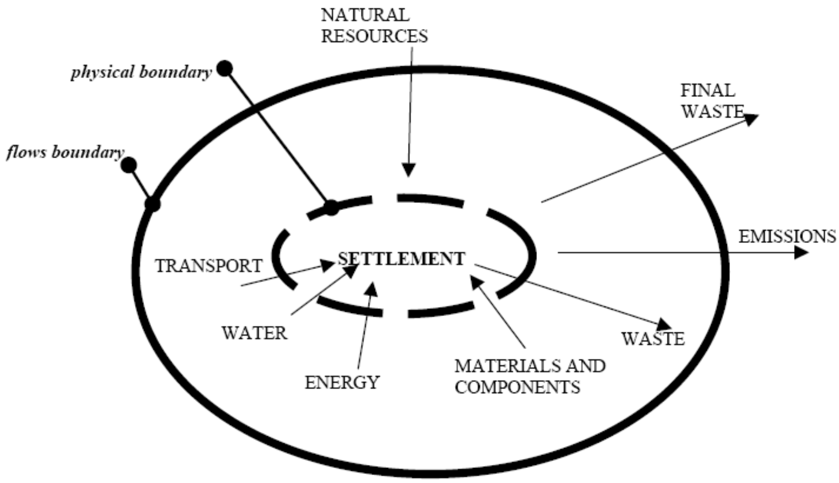

Figure 2: Boundaries of the system, (2)

We can see here that the calculation of the inventory will be based on two different aspects: first on the production, the renovation and the elimination of what is included in the physical boundary, then on the assessment of all that is included in the flows boundary.

The inventory analysis: specificities of the settlement

A settlement is a complex system, composed of many elements, of different types, each linked and interacting with others. To study and calculate the impacts of the operation phase, it is important to account for aspects like the occupants' behavior, the climate, etc.

The LCA of a settlement is partly based on the LCA of the included buildings. For a building, boundaries are defined similarly as for the urban settlement, with a distinction between physical and flows boundaries. Four steps for the life cycle of a building are considered, as shown in the next figure:

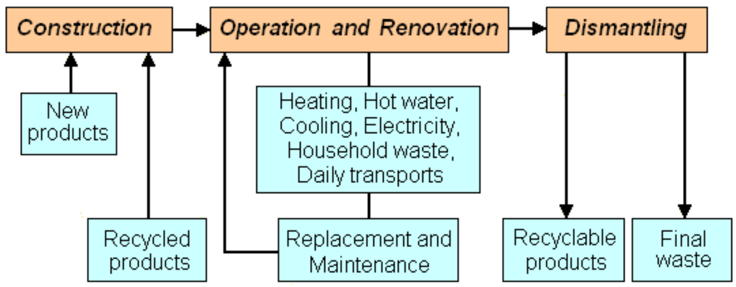

Figure 3: Description of the building's life cycle, adapted from (3)

During the operation phase, energy related impacts constitute a large part of the global balance. A dynamic multi-zonal simulation of the building is performed using a tool named COMFIE, in order to determine the heating and cooling loads, according to the comfort level defined in the previous step of LCA.

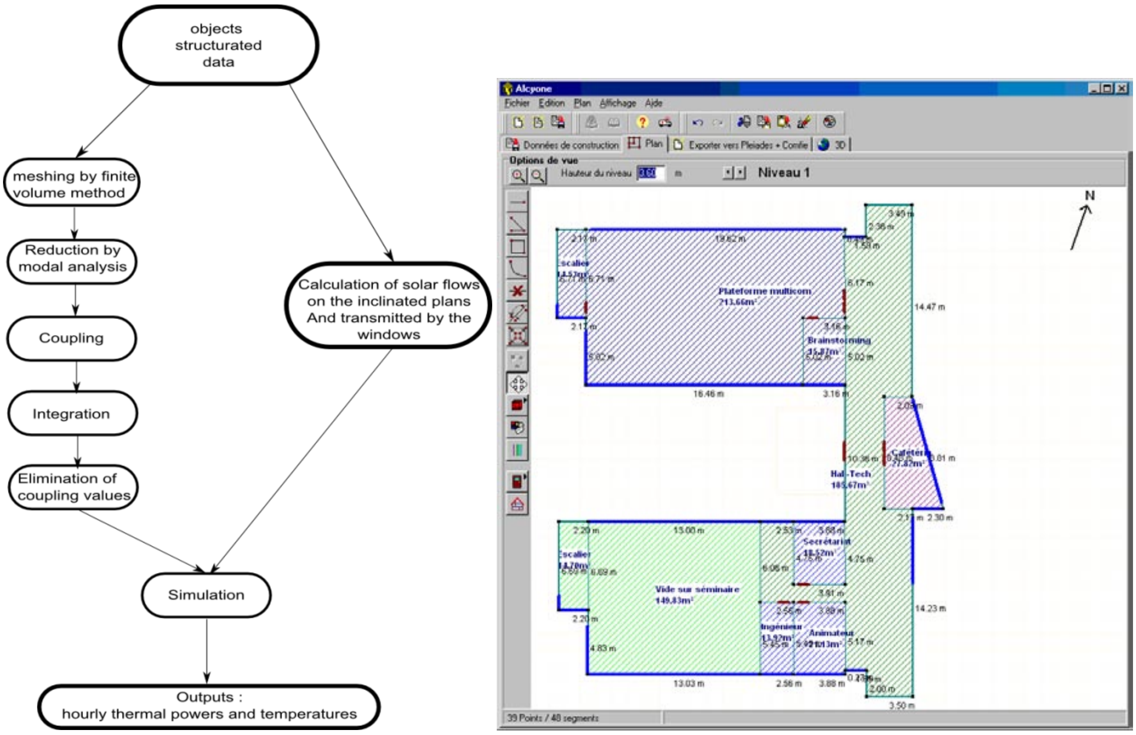

Figure 4: Thermal simulation algorithm and multi-zonal geometry input

The shading effects between all buildings compounding the settlement are here taken into account, as shown in the next figure:

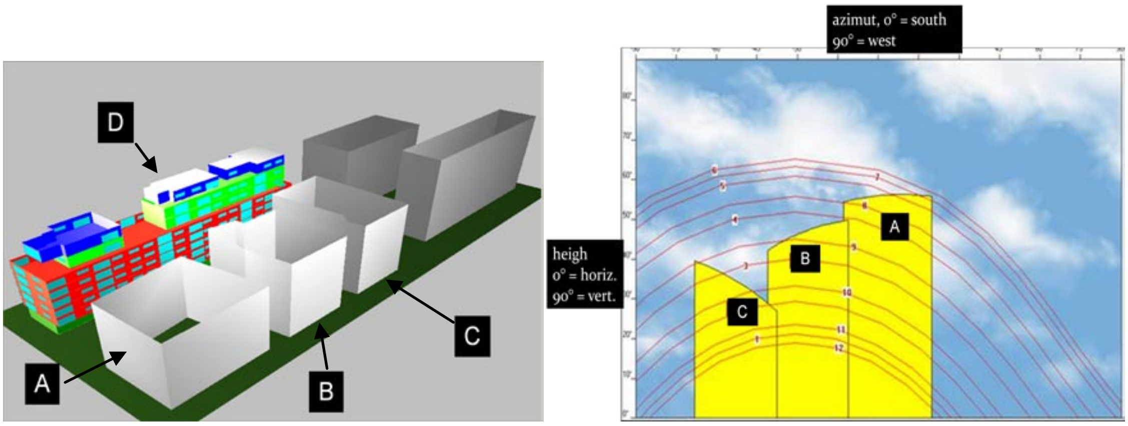

Figure 5: shading effects examples, in Lyon Confluence settlement. Shadings on the building D, generated by A, B and C buildings (right), as considered in COMFIE

All those data are then used to solve the thermal equations of the building for each thermal zone defined:

$$C\frac{dT}{dt} = A * T + E * U \tag{1}$$

$$Y = J * T + G * U \tag{2}$$

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Where C is the matrix of thermal capacities, T is the discretized temperature field, U is the solicitations vector (external temperature, solar flows,…), Y is the outputs vector (zone temperatures), A is the matrix including exchange terms between mesh, E is the matrix with exchange terms between mesh and solicitations, J linking outputs and mesh temperatures, G linking outputs and solicitations. From those equations are determined the temperature and the heating and cooling loads for each thermal zone, according to the temperature set point (chosen level of comfort).

The results of the thermal simulation are then used as an input data for the LCA of each building in the settlement, performed using a tool called EQUER. The LCA results obtained for each building are then used as an input data for ARIADNE, modeling the whole settlement, which may also include open spaces like streets, green spaces, power generators, networks… as shown in the next figure.

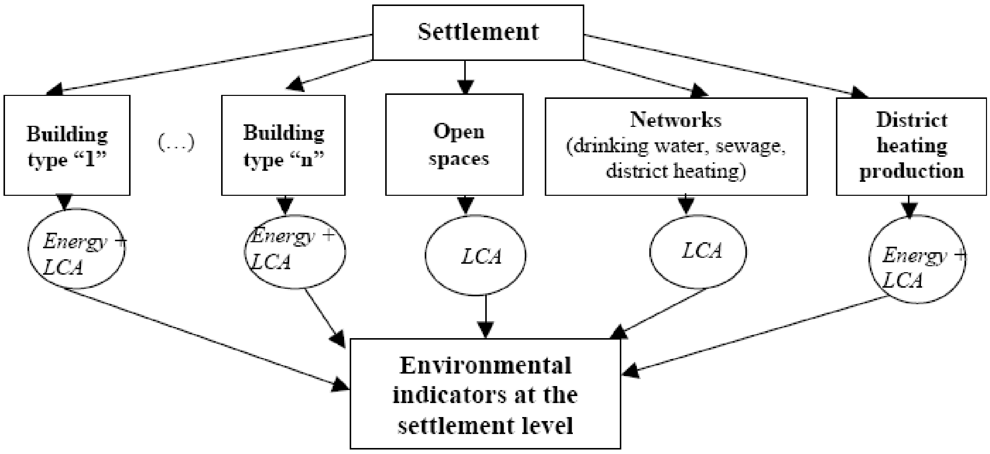

Figure 6: Principles of the settlement's structure and LCA

Impact assessment: indicators

Based on the inventory, some relevant indicators are then calculated. Different models have been developed, concerning various important environmental aspects. The indicators chosen here, linked with the particular environmental aspects of a settlement, and principally taken from the CML (4) and the Eco-Indicator 99 (5) methods, are listed in the table below. These indicators are implemented in the Ecoinvent database, currently used to perform LCA.

Environmental indicator	Approach	Type	Unit
Cumulative Energy Demand (CED)	Problem	Quantitative*	GJ equiv.
Water consumption	Problem	Quantitative	m^3
Abiotic Depletion Potential (ADP)	Problem	Potential	kg Antimony equiv.
Waste creation	Problem	Quantitative	t eq.
Radioactive waste creation	Problem	Quantitative	dm^3
Naturalness Degradation Potential [NDP]	Problem	Potential	m^2*years
Naturalness degradation due to land transformation	Problem	Potential	m^2*years
Built area/Total area	Problem	Quantitative	dimensionless
Average imperviousness of the settlement surface	Problem	Quantitative	dimensionless
Global Warming Potential (GWP)	Problem	Potential	t CO_2 equiv.
Acidification Potential (AP)	Problem	Potential	kg SO_2 equiv.
Photochemical Oxidant Formation Potential (POCP)	Problem	Potential	kg C_2H_4 equiv.
Eutrophication Potential (EP)	Problem	Potential	kg PO_4^{3-} equiv.
Damage cause by the ecotoxic emission to ecosystems	Damage	Potential	PDF*m^2*year
Damage to human health	Damage	Potential	DALY
Odour Threshold Value (OTV)	Problem	Potential	m^3contaminated air

Table 1: Indicators used for the settlement's LCA, (2)

One of the main difficulties of the settlement's life cycle assessment is the complexity of the model, inducing a huge amount of data to consider and assess. It is therefore important to study model reduction techniques.

REDUCTION OF THE SETTLEMENT'S MODEL

The reduction of the model can be performed in two main different ways:

- The reduction of the buildings and settlements' description, by neglecting some elements, materials…
- The reduction of the inventory. Nowadays different databases exist, with different detail levels. This level of detail can have some important effects on the calculation of indicators, particularly in the case of elaborated indicators involving a lot of substances.

Inventories reduction: principles

One of the possible ways to reduce the inventories is to aggregate substances in some relevant generic categories. In the indicators calculation, a unique characterization factor will then be considered for all the categories defined, instead of defining one for each substance.

Detailed model		Simplified model	
Substance flow	Characterization factor	Flow for a substance category	Characterization factor for the categories
S_1	F_1		
S_2	F_2	G_1	$\tilde{F}_1$
S_3	F_3	.	.
.	.	.	.
.	.	.	.
.	.	G_p	$\tilde{F}_p$
S_n	F_n		

Figure 7: Principle of inventory reduction

This methodology is used in the French national database for construction materials, INIES (6). It is useful to study the possible consequences of this reduction on the impact assessment.

Study of the reduction methodology

In order to evaluate the influence of simplifying the inventories, we have compared the values obtained for two different indicators (the DALY indicator, implemented in Ecoinvent, based on the Ecoindicator 99 methodology (5), and the INIES specific indicator for air polluting, expressed in m3 of polluted air, based on the critical volumes methodology (6)), using :

- Detailed Ecoinvent data
- Ecoinvent data reduced applying the INIES inventory methodology

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- Ecoinvent data reduced using the INIES inventory methodology, considering separately the dioxins

The purpose of the study is to determine recommendations aiming at reducing the error on the indicator value. This requirement can be expressed as:

$$\sum_{\substack{i=1 \\ s_i \in G_j}}^{m} s_i * F_i - G_j * \widetilde{F_j} < \varepsilon$$

(3)

According to the definition of flows (s_i andG_j) and factors (F_i and $\widetilde{F_j}$) introduced in the previous board, ε being the error limit considered acceptable.

A simple calculation, knowing that we have $G_j = \sum_{\substack{i=1 \\ s_i \in G_j}}^{m} s_i$(4) leads to:

$$\sum_{\substack{i=1 \\ s_i \in G_j}}^{m} \frac{s_i}{\sum_{\substack{i=1 \\ s_i \in G_j}}^{m} s_i} * F_i - \widetilde{F_j} < \tilde{\varepsilon}$$

(5)

From this expression, we can identify two important aspects to be evaluated when studying the possibility to combine different substances in a single category:

- The value used for the characterization factor of each category
- The relative importance of each substance in the category

Results

Calculation has been performed here in the case of two different flooring materials, one made of PVC, the other one of wood, considering the production and the end of life (incineration and landfill). We show here the results obtained for the INIES indicator value (m3 of polluted air), in the two cases introduced before where the inventory has been reduced.

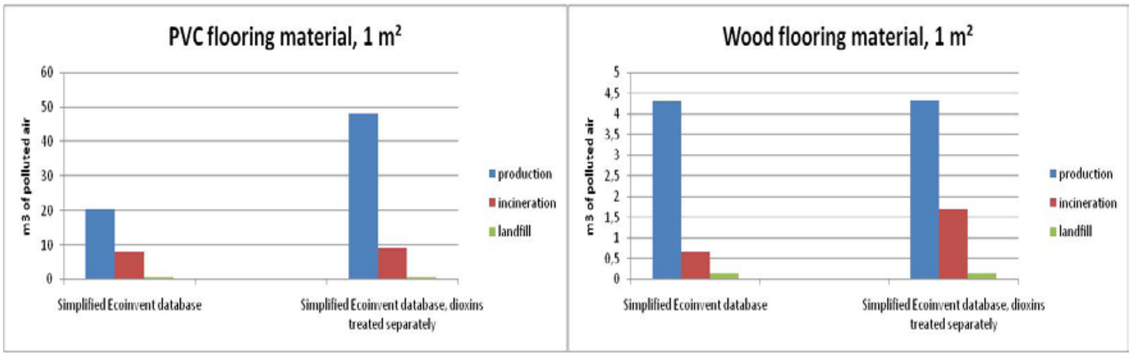

Figure 8: m3 of polluted air for the two floor covering materials after inventory reduction, compared with the INIES data

Comparing the values obtained by the calculation performed here with the values given in the INIES database and also with the results using Ecoinvent data and methodology, we can see that the simplification doesn't change the tendencies of the comparative results given by the LCA: the impacts related to wood flooring are much lower than in the case of PVC. But some important quantitative difference appears. We assume that the methodology used to build the categories could be improved. Substances are gathered regarding their general chemical family (e.g. volatile organic compounds). But some toxicological specificity, particularly here in the case of dioxins, may not be properly accounted for. The categories definition could therefore be modified, e.g. considering separately some particular substances, to improve the precision of impact assessment. An example of the results obtained is shown in the next figure:

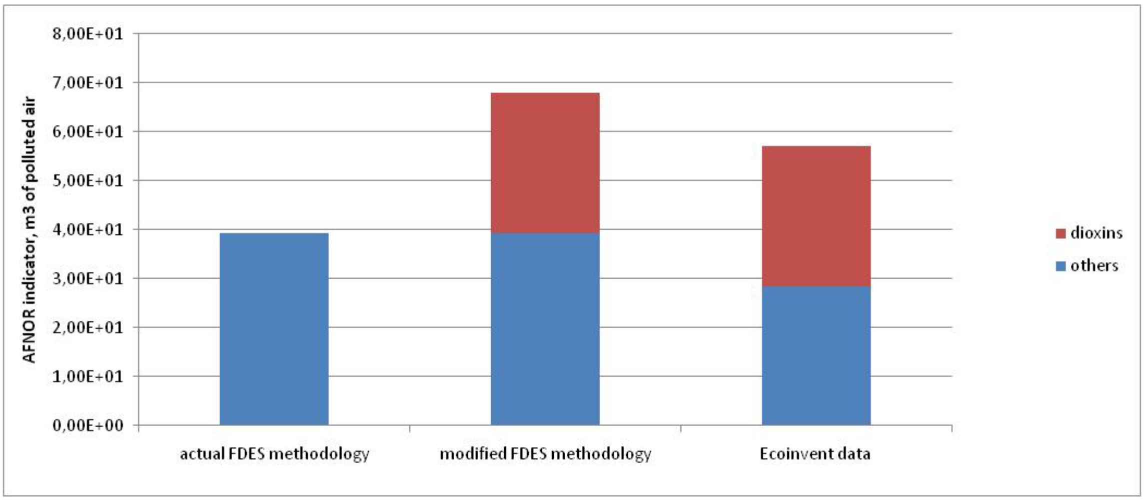

Figure 9: calculation of the INIES indicator for the production and the incineration of 1 m² PVC flooring

The inventory reduction may have important effects in the case of the calculation of elaborated indicators. We have here performed a calculation in the case of the DALY indicator, which implies a lot of substances emitted. When reducing the inventory, the characterization factor used for each category is the average value of each substance's factor included in a category. The results are shown below:

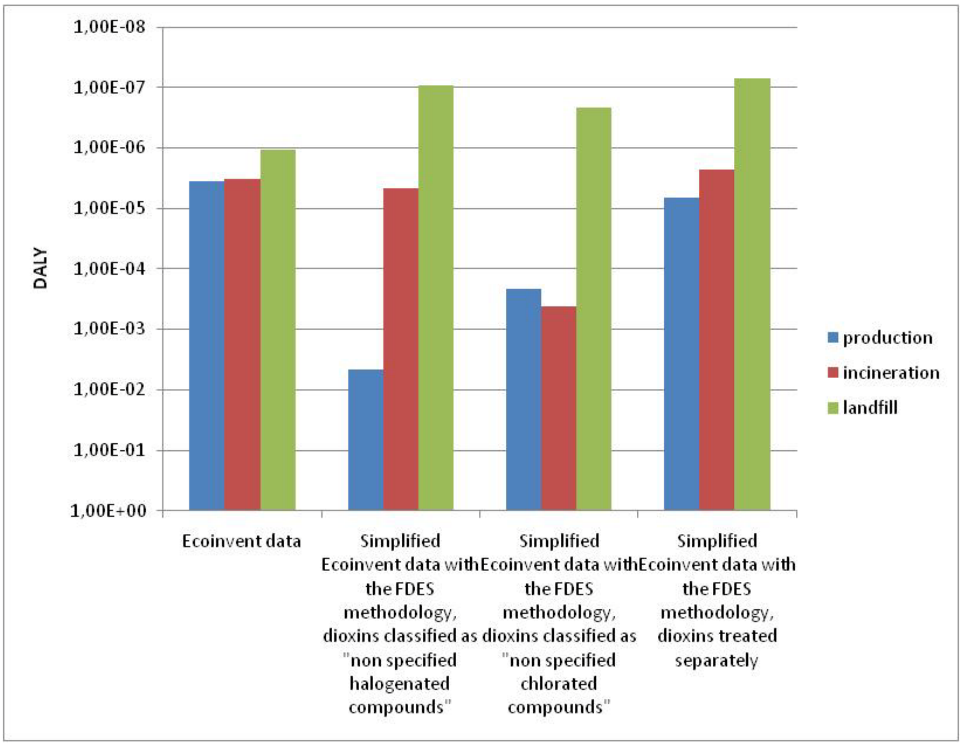

Figure 10: DALY values obtained after reduction of the inventory, in logarithm scale

We can see here that the inventory reduction and the method used to calculate the characterization factor for each category leads to an over-evaluation of the DALY. This is due to the high value of the dioxins factor which leads to a higher average value for the category where those substances are integrated, and over evaluation of the toxicity of the others substances in the category. This is illustrated in the case of a specific accounting method for dioxins. This shows the importance of the factor's value chosen, but also the importance of how the categories are built: the relevance of these categories depends on their consistency with the indicators calculation models, and the different possible uses of the inventory according to the objectives of the LCA study.

Conclusion

The simulation tool presented in this paper aims at studying a complex system like a settlement, including many interacting elements. Work is performed to simplify and reduce the settlements' model. As shown here, the inventory reduction is a key aspect to facilitate LCA. But this reduction has to be consistent with all environmental issues of concern, and permit a relevant evaluation of each potential impact.

In order to improve the physical model on which impact assessment is based, it is planned to develop a dynamic LCA. A specific study on the electricity production mix will permit to determine what are the specific impacts of each use of electricity, depending on time, temperature… The evolution of the characteristics of the different components of a settlement (energy supply infrastructures, thermal comportment of buildings, boilers efficiency) during its life span will also be assessed.

Acknowledgment

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