LCA APPLICATION IN URBAN DESIGN

Bruno Peuportier (1), Eric Vorger (1) and Grégory Herfray (1)

(1) Center for Energy and Processes, MINES ParisTech, France

Abstract

A life cycle simulation tool has been developed to model urban settlements including various buildings, streets, green and other public spaces, and networks (drinking water, waste water, district heating...). This tool, developed in an object oriented approach, associates dynamic thermal simulation and building LCA, complemented with modules for open spaces and networks. A set of environmental indicators is evaluated, e.g. resource depletion, energy and water consumption, global warming, waste generation, toxicity. Several alternatives can be compared using graphs, constituting an urban design aid.

This communication presents a case study in order to illustrate a possible application of this tool. Several urban morphologies are compared: apartment buildings, single family houses, and Plus energy houses similar to the “solar city” in Freiburg. Each alternative is defined according to the same functional unit: providing dwelling for one inhabitant during 80 years, in the Greater Paris Area context and climatic conditions. The results are presented and perspectives are proposed to refine the model and complement it.

1. INTRODUCTION

Applying models and particularly simulation in urban design is not common, essentially due to the complexity of the studied system. Detailed energy simulation has been complemented with energy and mass flow analysis, e.g. [1]. Coupling simplified building simulation and multi-agent transport simulation is also studied [2]. The present contribution aims at evaluating environmental impacts and not only energy and mass flows. Due to the complexity of the model, requiring both energy and life cycle simulation, the neighbourhood scale is addressed.

Numerous models have been developed since the 80’s to evaluate environmental impacts of buildings using life cycle assessment, e.g. [3], [4], [5]. Eight tools have eventually been compared in the frame of the European thematic network PRESCO [6]. In parallel to scientific work, standardization committees have elaborated standards but due to the need of reaching a consensus, important issues like human toxicity and biodiversity haven’t been integrated e.g. in the set of indicators included in the European standard regarding the assessment of environmental performance of buildings.

Building LCA tools allow various alternative designs to be compared, regarding architectural and technical choices. But important decisions are also taken at a more global scale, e.g. the street planning, organisation of buildings in an urban block, large scale equipment like district heating, centralized parking, public transport etc. Developing a model at this scale is therefore useful. Many municipalities create new urban districts targeting sustainability objectives, but subjective approaches are still used. The importance, geographic scale, duration and irreversibility of impacts suggest that decisions should be made on a more precise basis. LCA could contribute in such a process by providing a quantified assessment.

2. OBJECT ORIENTED MODELLING OF URBAN SETTLEMENTS

An urban area may include: different building types (dwellings, shops, offices, schools etc.), public spaces (streets, parking places, green spaces etc.) and also utilities infrastructure (water distribution system, sewage system, waste management, district heating, etc.). Besides the elements listed above, a life cycle assessment at the settlement level should also take into account aspects related to the residents behaviour (water and energy consumption, domestic waste treatment, recycling percentage etc.) and site characteristics (climate, public transport, electricity production mix, district heating production mix, etc.).

The settlement model presented here has been developed in an object-oriented approach. Such a structure makes the comparison of alternatives easier, e.g. replacing a material with another, adding an equipment etc. All objects defined by the same characteristics are grouped in classes: for instance the open space class gathers all streets, roads (asphalt space subclass) gardens, and parks (green space subclass). Figure 1 hereunder shows the object classes and the graphical description of the logical relations between them.

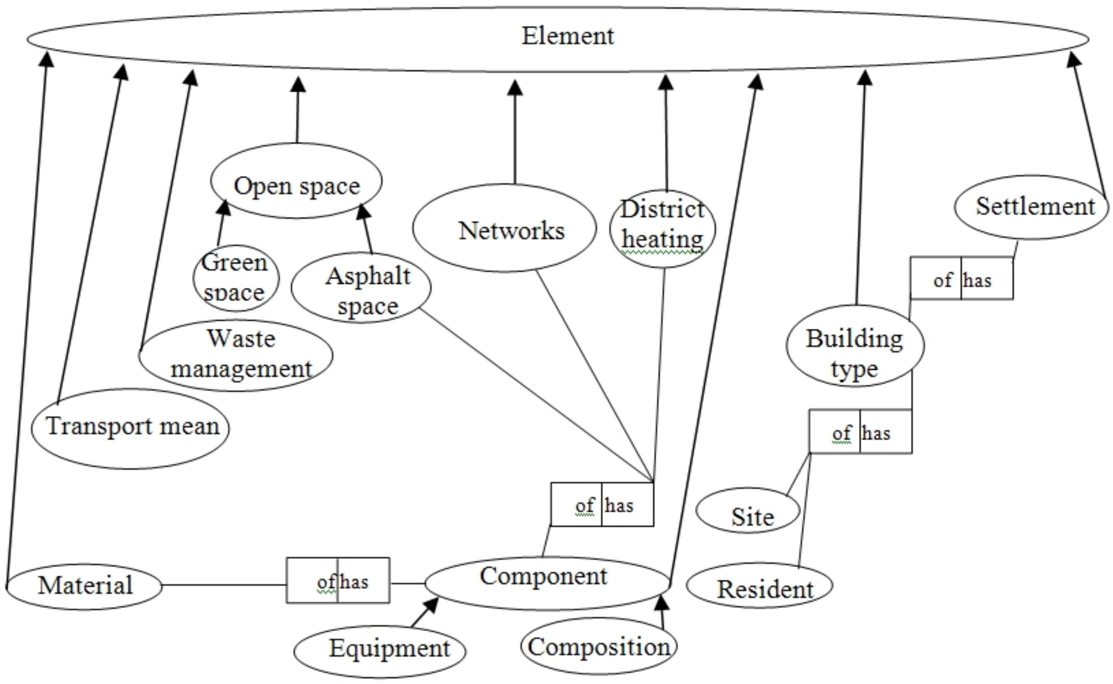

Figure 1: Settlement object oriented model

The very general class “Element” is defined as “mother” class. All other classes that are linked by arrows to it, called the “daughter” classes, inherit the characteristics of the “Element” class. The creation of a daughter class is justified by the presence of at least one characteristic that differences it from its mother class. For instance the mother class “Open space” has two daughter classes: “Green Space” and “Asphalt Space”. For an asphalt space, the life span of its components (e.g. asphalt, bitumen, concrete layer or edges) is important for renovation time calculation, on the other hand this parameter has no sense for a green space.

The “open space” class includes the following data: Previous land use (type of land according to [7]), Area, Imperviousness (%), Drinking water quantity used for cleaning/watering per year (l/m²/year), Quantity of waste generated per year (kg/m²/year), Lighting level of the open space (bright, standard, shade, no lighting), Pointer to Equipment (lighting system).

The Green Space class is a subclass of Open Space, therefore including the same data, plus the following: Organic waste quantity generated per year, Number of grass cutting/cleaning work per year, Pointer to Waste management (e.g. composting, landfill...).

The Asphalt Space class is another subclass of Open Space defined by other complementary data: Life span, Surplus of materials used in construction process (e.g. asphalt or concrete surplus on the building site, which is considered as waste), Pointer to Waste management, Number of ice removing/snow cleaning work per year, Pointer to Composition.

The Composition class includes a list of materials and thicknesses, the duration between two renovation works and the thickness of the added layer.

Another type of relation between classes is “of/has”. For instance, if an urban area includes 30 houses and 3 office buildings, we define an object named “House” and one named “Office” both of the class “Building type”. The object of the class “Neighbourhood” will be defined by the number of houses, the number of offices, and by pointers to the two building type objects. A user friendly interface allows data input for the different objects, see Figure 2 hereunder.

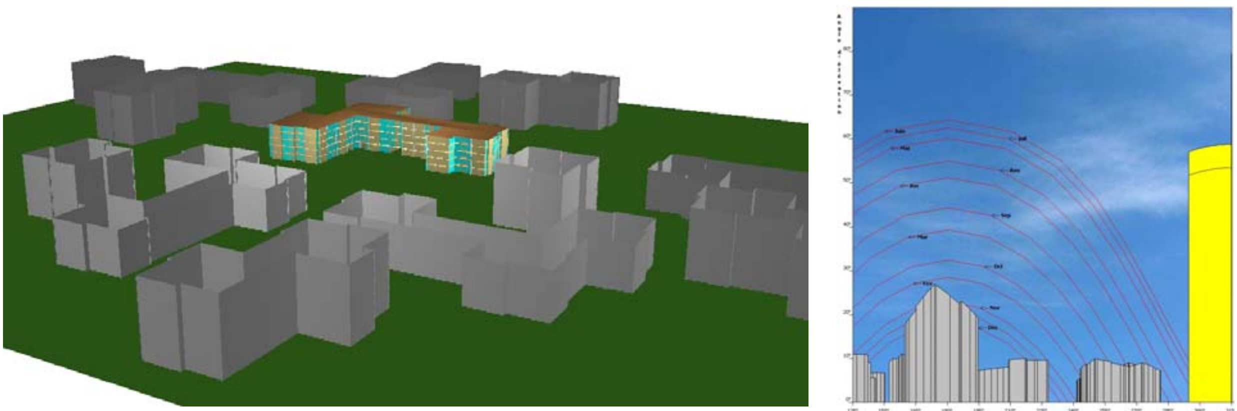

Figure 2: Graphical modeller (left) and shading visualization (right)

This object oriented model provides data to the life cycle simulation module: calculation methods are attached to the different objects.

3. LIFE CYCLE SIMULATION

Most LCA tools multiply life cycle inventories by the quantities related to functional units (e.g. kg of each material, number of units for equipment, etc.), then add the contributions of all components to evaluate the impacts of the studied system. The model presented here uses numerical simulation instead, with a yearly time step. Each object has a time counter. When this counter reaches the life span of the object, the impacts corresponding to the end of life and new fabrication of the object are accounted. The objective is to allow a dynamic simulation process to be implemented.

Objects include data as seen in the previous paragraph, but also calculation methods. For instance a composition includes the calculation of Life cycle inventories (LCI) for the fabrication, assembly, dismantling and end of life of the constituents, as well as a method to detect years when the component has to be replaced. It is assumed that no element is replaced after 90% of the building life span.

Environmental impacts of whole buildings are evaluated using the EQUER life cycle simulation tool. Data bases including LCI data are used: the INIES data base [8] concerns French building product manufacturers, and the Ecoinvent data base [9] generally provides European average values, including also processes.

Most products influence the energy consumption of buildings: windows provide solar gains, that can be stored in masonry if the building finish does not block them (e.g. the high thermal resistance of a carpet reduces the amount of solar energy stored in a floor slab). Due to the long life span of buildings, the operation phase and particularly the energy consumption has a large influence on the overall environmental balance. EQUER has therefore been linked to a dynamic simulation tool, COMFIE [10], allowing also thermal comfort to be evaluated. It is indeed useful to check if the compared alternatives correspond to the defined functional unit. Because it may be necessary to evaluate many buildings when studying an urban project, model reduction techniques are used to reduce the computation time.

The life cycle simulation procedure is described in the following graph, showing the different life cycle stages.

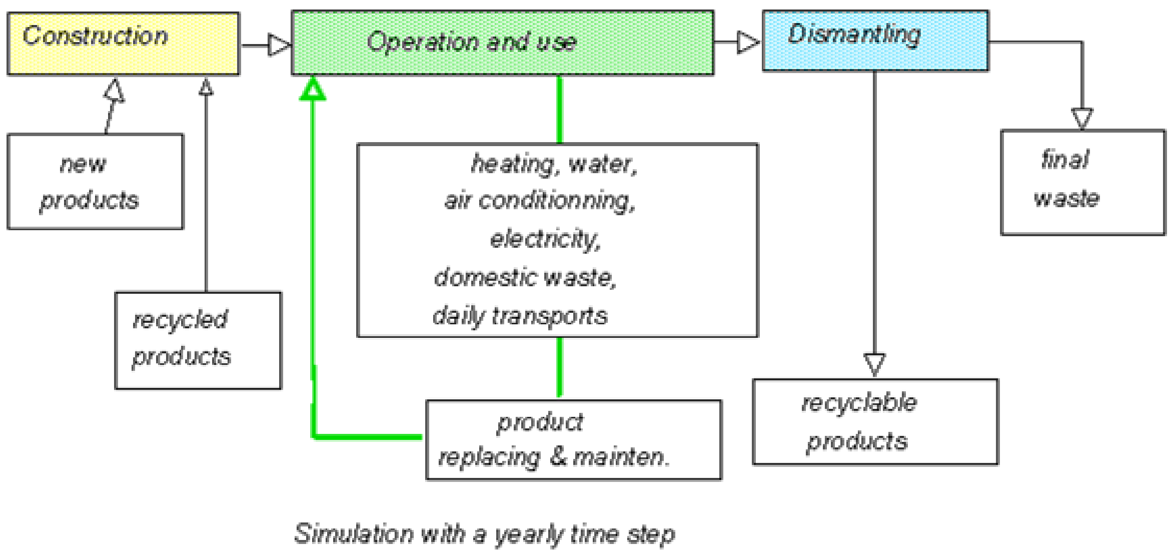

Figure 4: Principle of life cycle simulation

A set of environmental indicators is evaluated, according to the list given in the table hereunder, indicating also the unit and legend in the figures showing the results obtained in the case study (see § 4).

Table 1: List of the impact indicators evaluated by EQUER

Impact indicator	Unit	Legend
Cumulative Energy Demand	GJ	ENERGY
Water consumption	m^3	WATER
Abiotic Depletion Potential	kg Sb-eq	RESOURCE
Non-radioactive waste creation	t eq	WASTE
Radioactive waste creation	dm^3	RADWASTE
Global Warming Potential at 100 years (GWP_{100})	t CO_2-eq	GWP_{100}
Acidification Potential	kg SO_2-eq	ACIDIF.
Eutrophication Potential	kg PO_4^{3-}-eq	EUTROPH.
Damage caused by the ecotoxic emissions to ecosystems	PDF.m^2.yr	BIODIVERSITY
Damage to human health	DALY	HUMAN HEALTH
Photochemical Oxidant Formation Potential (Smog)	kg C_2H_4-eq	O_3-SMOG
Odour	Mm^3	ODOUR

4. CASE STUDY

In order to illustrate the possible application of the methodology described previously, three urban morphologies are compared on the basis of the environmental indicators listed above. The functional unit is “a residential settlement located in Paris, over 80 years”. In order to compare settlements including different numbers of inhabitants, the impacts will be expressed per inhabitant. Therefore the reference flow relates to one inhabitant.

The first type considered is composed of 8 stories high apartment buildings, each construction having a width of 10 m, a length of 50 m, being south oriented and including 2 elevators. The buildings are separated by 10 m on the east-west axis, and by 20 m in the north-south axis. 1300 m² of streets and 100 m² of roads are added to each building.

We consider then the case of 130 m² single houses, at street level, surrounded each by 200 m² of garden, associated with 120 m² of street and 20 m² of walking pathway.

The last type considered here is inspired from the Vauban settlement in Freiburg [11], see Fig 5. The part of the settlement considered here is composed of 3 levels buildings with a high glazing area on the south façade and solar protections. The roof is equipped with PV modules producing electricity, so that the primary energy balance of the buildings is positive. In order to study the morphology of the whole settlement, five types of buildings are considered, and a total of 1000 m² of roads, 100 m² of roads, 1800 m² of walking pathways and 5000 m² of gardens are added.

The other parameters of the simulations are the same for all cases, in order to only assess the influence of the buildings morphology. We consider settlements located in Paris (2406 heating degree days). Natural gas is used for heating and hot water, with a production and distribution efficiency of 87 %. The French yearly average electricity production mix is considered: 78 % nuclear, 14 % hydroelectricity, 4% natural gas, 4 % coal). The inhabitants consume 100 l of cold water and 40 l of hot water per day, 330 days in a year, and 2000 Wh electricity per day.

Figure 5: Plus-energy neighbourhood in Freiburg, Architect Rolf Disch

In a first step, domestic waste and commuting transport are not included in the studied system. The thermal characteristics of the envelope are also supposed to be the same in each case: U-values are 0.16 for walls and floors, 0.11 for roofs and 0.87 for windows.

The number of inhabitants is evaluated according to the dwelling area, assuming 33,3 m^2 per person. The thermostat set point is 19°C, except on working days when the persons are supposed to be absent, and the heating is reduced (16°C). There is no cooling system, and the ventilation rate is as low as 0.3 air change per hour thanks to a careful limitation of air infiltration.

The open spaces are characterized by the compositions and hypothesis defined in table 2.

Table 2: open spaces characteristics

	Road	Street	Pathway, parking	Permeable pavement	Garden, green spaces
Imperviousness	95%	90%	85%	60%	40%
Shearing	-	-	-	-	5 per year
Lighting	4,8 kWh/m²/year	4,8 kWh/m²/year	4,8 kWh/m²/year	0	0
Water use	10 l/m²/year	9 l/m²/year	9 l/m²/year	3 l/m²/year	60 l/m²/year

The different morphologies are modelled and in a first step, dynamic thermal simulation is used to evaluate the heating load, which is higher for single family houses (32 kWh/m^2/year) than for the more compact apartment buildings (10 kWh/m^2/year) and for the solar oriented positive energy buildings (10 kWh/m^2/year). LCA is then applied to each building type, and finally urban infrastructure is included.

Comparing the positive energy settlement to the single houses, the primary energy consumption indicator is reduced by around 90 %, but the biodiversity impact indicator is multiplied by 2. Actually the absolute impact of the neighbourhoods on biodiversity is very small compared to their primary energy demand. Therefore priority should be given to this energy indicator. To be comparable, absolute values have to be expressed in the same unit. This is achieved using normalization. Indicator values are divided by the average indicator value per person and per year in France, e.g. 8.68 ton CO_2, 48,670 kWh primary energy, 339 m^3 water, 10.4 tons of waste etc. The common unit is therefore the year-inhabitant equivalent. European average values are considered for human health, biodiversity and resources.

The results obtained are presented in the figure hereunder, per inhabitant. The reference 100% value corresponds to 80 year-inhabitant equivalent, because the life span considered in the functional unit is 80 years. Relative values are derived for each indicator value, e.g. water consumption related to the neighbourhood corresponds to around 25% of the average water consumption in France for all human activities. The positive energy settlement avoids the production of electricity, which would have been provided mainly by nuclear plants. The consequence is a negative radioactive waste indicator.

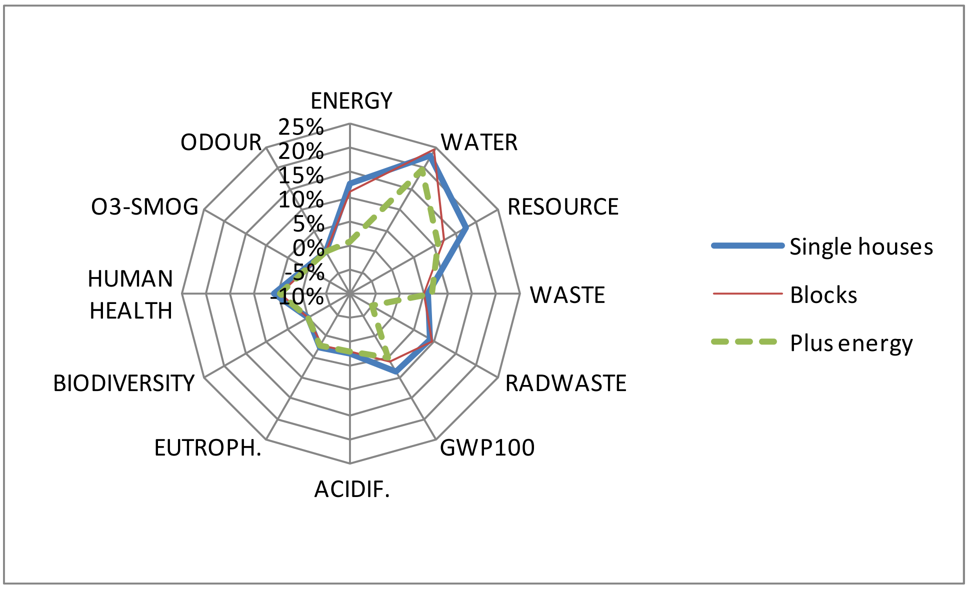

Figure 6: comparative LCA results for the three urban morphologies

Sensitivity studies have been performed regarding inhabitants behaviour, e.g. the choice of heating thermostat set point and ventilation flow rates. The building life span can also be varied.

Transport related impacts are accounted for in a second step. In this illustrative case study, a very simple assumption is considered: the density of the single house type is low so that public transport is not frequent for economic reasons. As a consequence the commuting transport is made by car. Train is used in the other morphologies, the following data is considered. The average distance between house and work is 14 km, and 80 % of inhabitants do this route every day. In such a case, transport related impacts contribute to amplify the differences between the single houses and the other alternatives compared.

5. CONCLUSIONS

The developed LCA model can be applied in order to help urban designers and architects in a decision making process at a local level. A first prototype tool has been realized, and used in several case studies. A dynamic LCA model has been developed in order to account for the seasonal, weekly and hourly variation of the electricity mix. This allows a more precise impact evaluation of electricity consumption and production, which is useful to compare e.g. plus energy and standard alternatives. Perspectives for improving the method have been identified e.g. in the LORE LCA European coordination action [12]. Further activities aim at modelling more precisely the users' behaviour, which has a large influence on environmental performance.

ACKNOWLEDGEMENTS

This research work has been supported by the Chair ParisTech-VINCI "Ecodesign of buildings and infrastructure" and by ANR (Project ACV Quartiers).

REFERENCES

[1] Stupka and Kennedy, Impact of Neighborhood Density on Building Energy Demand and Potential Supply via the Urban Metabolism, ACEEE conference on Energy Efficiency in Buildings, 2010

[2] Robinson D. et al., CITYSIM: comprehensive micro-simulation of resource flows for sustainable urban planning, 11th international IBPSA Conference, Glasgow, 2009

[3] Kohler N., Analyse énergétique de la construction de l'utilisation et de la démolition de bâtiments, thèse de doctorat, Ecole Polytechnique Fédérale de Lausanne, 1986

[4] Mak J., Anink D., Kortman J. et al., ECO-QUANTUM, design of an LCA based method on building level, W/E Consultants sustainable building / IVAM Environmental research, Gouda / Amsterdam (in Dutch), March 1996

[5] Polster B., Contribution à l'étude de l'impact environnemental des bâtiments par analyse de cycle de vie, thèse de doctorat. Ecole des Mines de Paris, December 1995

[6] Peuportier B., Kellenberger D., Anink D., Mötzl H., Anderson J., Vares S., Chevalier J., and König H., Inter-comparison and benchmarking of LCA-based environmental assessment and design tools, Sustainable Building 2004 Conference, Varsovie, October 2004

[7] Brentrup F., Kfisters J., Lammel J. and Kuhlmann H., Life Cycle Impact Assessment of Land Use Based on the Hemeroby Concept, International Journal of LCA, 7 (6) (2002) 339 - 348

[8] www.inies.fr, accessed 03/11/2011

[9] www.ecoinvent.ch , accessed 03/11/2011

[10] Peuportier B. and Blanc Sommereux I., Simulation tool with its expert interface for the thermal design of multizone buildings, International Journal of Solar Energy, 8 (1990) 109-120

[11] Heinze1 M. and Voss K., Goal: zero energy building, Exemplary Experience Based on the Solar Estate Solarsiedlung Freiburg am Schlierberg, Journal of green building, 4 (4) (2009) 93-10

[12] Peuportier B., Herfray G., Malmqvist T., Zabalza I., Staller H., Tritthart W., Wetzel C. and Szalay Z., Life cycle assessment methodologies in the construction sector: the contribution of the European LORE-LCA project, Sustainable Building Conference, Helsinki, October 2011