Dynamic LCA applied to buildings and urban districts

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Summary

Existing Building LCA tools are based upon a static method, considering yearly average processes and impacts. This paper presents a dynamic method that has been developed to evaluate electricity-related impacts in buildings. Results on case studies show important discrepancy between the static and dynamic methods. This study is a first step towards the introduction of consequential LCA parameters in life-cycle assessment of buildings.

Keywords: Buildings, Electricity production, Dynamic Life-cycle assessment, Consequential life-cycle assessment

Extended Abstract

Most building life cycle assessment tools are based upon a static method, i.e. no temporal variation is considered for processes and corresponding impacts. The present study addresses the validity of such a simplification in the case of buildings. Electric heating, heat pumps and air conditioning induce seasonal demand, during which the production mix may differ from the yearly average. Professional and domestic activities influence weekly and hourly patterns. Local renewable electricity production, e.g. using a photovoltaic system, is also variable.

A dynamic LCA model has been developed to account for such temporal variation, in order to evaluate more precisely the environmental impacts of electricity consumption and production in buildings, which is useful in order to compare e.g. plus energy and standard buildings.

The French electricity grid manager provides hourly production values for nuclear, hydro-electricity, thermal plants, and other types. Based upon these data, the model evaluates the production mix in terms of an average temperature in France and several periodic functions corresponding to variation frequencies identified by a Fourier analysis. In a second step, specific production mixes are derived for different uses: heating, cooling, domestic hot water, domestic appliances and office appliances. This model is then integrated in a building LCA tool. The model requiring hourly energy consumption data, the LCA tool is linked to dynamic thermal simulation.

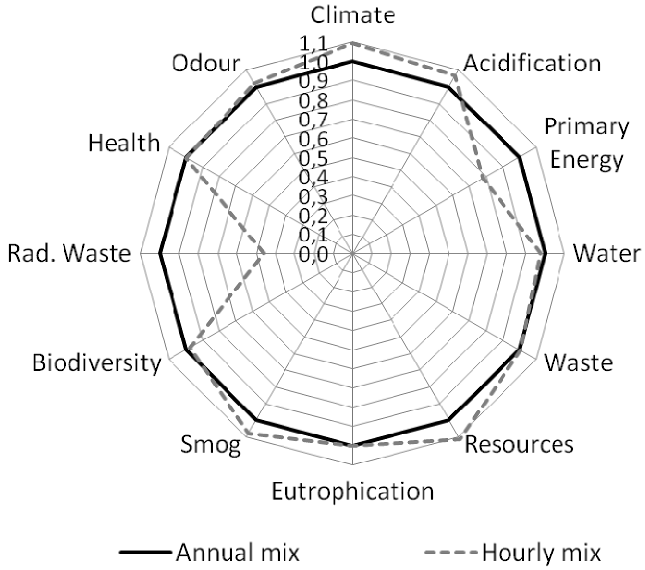

Figure 1: Evaluation of Low-Energy Neighbourhood using the annual and hourly models

Comparative results between the static and the dynamic method show a discrepancy up to 50% for radioactive waste, 22% for cumulative energy demand, 10% for climate and resources. Using a more precise model based upon use-specific hourly mixes instead of a constant annual average is therefore justified.

The Building LCA tool has been extended to the scale of urban districts, integrating several building types as well as streets, public spaces and networks. In order to illustrate the capabilities of this tool, a new project in France has been compared to passive blocks of Quartier Vauban in Freiburg. This allowed the performance of this project to be evaluated against best practice.

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Summary

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1. Introduction

In France in 2011 almost 60% of the total electricity production was consumed in buildings [1]. Electricity consumption is highly time-dependent, from summer to winter, from day to night and from week to week-ends. Production of electricity follows this variability. For instance, electric heating induces a seasonal peak demand in winter with a high dependency to temperature, which is increasing every year [1]. Local production of electricity, e.g. by photovoltaic modules on buildings roofs is also time-dependent. However, standard LCA practice is based on an average annual electricity mix, neglecting this variations. The purpose of the work presented here was to integrate a dynamic electricity mix, disaggregated on different use. After a presentation of the building LCA, the model developed to calculate the electricity mixes is exposed. Then we explain how it was integrated in building LCA. Afterwards we show implications of this modification in terms of environmental impacts of buildings. Finally we discuss limitations of the model and future possible developments.

2. Building LCA

Life cycle assessment was developed in the 70's to evaluate industrial products. This method estimates environmental impacts of a product from "cradle to grave" on a multi-criteria approach. All the value chain of the product is accounted for, from primary resources extraction to end of life treatment. The aim is to prevent displacement of pollution, spatially but also from a life cycle stage to another and between environmental indicators.

This method was first considered too complex for building evaluation, and first application in the late 80's evaluated only energy aspects [2]. The European project REGENER [3] sketched out a common methodology for building LCA. Other following projects like PRESCO [4] and LORE-LCA

[5] have contributed to harmonize the methodology among existing tools and to promote LCA use by building professionals.

Linked to the thermal dynamic simulation tool COMFIE [6], the EQUER tool was developed to model the life-cycle of buildings, from construction to dismantling, through utilization and renovation phase [7], [8]. It considers twelve indicators, mostly from the CML2000 and Ecoindicator 99 methods to get a comprehensive set of environmental impacts (see table 1). It also includes an extension to urban district evaluation [9].

Table 1: Environmental indicators in EQUER

Impact indicator	Unit	Legend
Cumulative Energy Demand	GJ	Primary Energy
Water consumption	m^3	Water
Abiotic Depletion Potential	kg Sb-eq	Resources
Non-radioactive waste creation	t eq	Waste
Radioactive Waste Creation	dm^3	Rad. Waste
Global Warming Potential	t CO_2-eq	Climate
Acidification Potential	kg SO_2-eq	Acidification
Eutrophication Potential	kg PO_4^{3-}-eq	Eutrophisation
Damage caused by the ecotoxic emissions to ecosystems	$PDF.m^2.yr$	Biodiversity
Damage to human health	DALY	Health
Photochemical Oxidant Formation Potential (smog)	kg C_2H_4-eq	Smog
Odour	Mm^3	Odour

3. Construction of hourly and use specific electricity mixes

3.1 Modeling the production of electricity thanks to Fourier analysis

The French electricity grid manager (RTE) provides hourly production values for nuclear, hydroelectricity, gas & coal, and fuel thermal plants. At time of study, data was available from 2007 to 2009. Our model has been based upon 2008 data because this year fits the most with a typical climate (lowest temperature discrepancy compared to the average 1971-2000, according to MeteoFrance).

The electricity production changes according to the seasonal, weekly and daily variation of the consumption. Fourier analysis allows the different frequencies composing a signal to be identified. This method has therefore been applied. The main frequencies correspond to 12 h, 24 h, 48 h, 168 h (i.e. one week), 4392 h (half a year, 2008 being bissextile), and 8784 h (one year). The electricity production is then expressed as a sum of periodic functions corresponding to the identified frequencies (daily, weekly, seasonal and yearly variations). Due to the importance of the heating use, the production also depends on climatic conditions, and mainly external temperatures. As production data is available on a national scale, a reference temperature has been evaluated as an average between several locations (MeteoFrance data), weighted according to the corresponding population. The production P is then expressed as a function of this average temperature T_{av} and of time t:

$$P(t, T_{av}) = \sum(X_i(T_{av}) * \cos(w_i * t + Y_i)) + Z(T_{av}) \qquad (1)$$

Where w_i are the identified frequencies.

Parameters $Xi(T_{av})$, Yi and $Z(T_{av})$ are identified by a least square method (quasi-Newton algorithm) in order to minimize the discrepancy between calculated and measured production values. Yi are assumed constant.

The average discrepancy between calculated and measured production is 4%. The discrepancy is higher (11%) when comparing the year 2009 values (see the discussion session).

A part of the consumed electricity (around 6% of production) is imported. RTE data include hourly imported quantities from different countries: Germany, Switzerland, Spain, Italy, UK and Belgium. This has been integrated to the model, so that a complete electricity production mix is derived.

3.2 Impact Allocation model

The total impacts of electricity production can be evaluated at each hour using the model presented above. But electricity is used for several purposes: lighting, domestic appliances, cooling, heating, tertiary uses, domestic hot water production etc. These different uses can be regarded as co-products, and different allocation methods can be applied. If electricity is consumed during a winter night both for heating and hot water, considering the same production mix would lead to account for high CO_2 emissions also for electric hot water production, though these high emissions are due to the seasonal peak induced mainly by heating. It seems therefore more precise to differentiate the production mix according to the different uses. Assuming that the weekly minimum consumption (week-end nights) is related to heating, cooling and hot water, these 52 weekly values are used in a first step to identify production mixes for these three uses. A yearly constant mix is first identified according to the yearly minimum values of nuclear and hydro-power production.

This mix is used to evaluate the environmental impacts related to hot water production, the solar hot water contribution being marginal at the moment. The production values defining the mix also include other consumption types (industrial uses …), not relevant in our study, but in a first approach a unique category is considered for all that is supposed to be “yearly” constant. Subtracting the yearly minimal production from the weekly minimal production allows a mix to be identified for heating and cooling. This mix is evaluated for each week. A correction based upon a linear approximation is applied at each hour to account for climatic variation within a week [10]. The weekly minimum production is then subtracted to the hourly production values in order to study other domestic and professional uses (i.e. other than heating, cooling and hot water). Week-end production is assumed, by approximation, to correspond to domestic uses. This allows the domestic and professional contributions to be identified. This process is applied to each production type (nuclear, hydro-power, thermal plants) so that hourly electricity production mixes are evaluated for each use type. The same grid efficiency (9% losses) is considered for all production types.

4. Integration in Building LCA

The model thus provides five reference mixes. In a first approach, uses have been associated to their major variation scheme:

1. Seasonal consumption : Heating and cooling
2. Base load : Domestic hot water
3. Daily consumption : Domestic appliances
4. Weekly consumption : Professional appliances
5. Average hourly mix (not disaggregated by use), e.g. For a local electricity production

Figure 3 shows example of the model results aggregated on a hourly basis. The base load mix is constituted of nuclear and hydraulic (run-of river turbine) which are the main base load technologies feeding the French grid. The seasonal mix is based on nuclear and thermal plants: nuclear plants are seasonally adjusted to cover the overall increase of electricity demand in winter, but the climatic dependency is covered by coal and gas mainly. The share of hydraulic production is higher in appliances-related mixes. This corresponds to hydroelectricity from dams which is the most reactive technology available. However, the production is not sufficient to cover the whole demand so that thermal plants fill the gap.

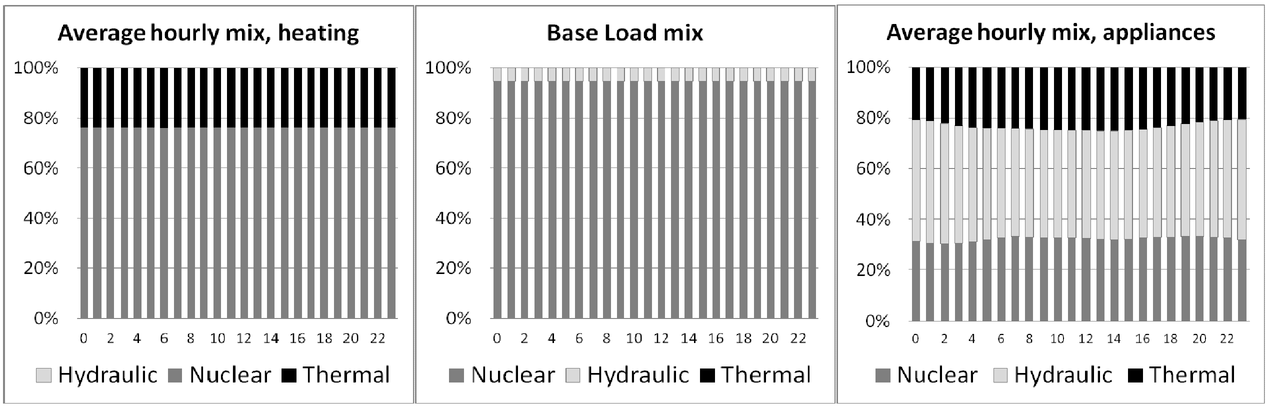

Figure 2: Results of the model presented as aggregated daily mixes

To be integrated in the building LCA tool EQUER, the model has been recalibrated on a typical year (mean temperature over twenty years), so that it is compatible with the simulation tool COMFIE, in terms of temperature used to evaluate the heating and cooling loads, provided as hourly values. The energy consumed for appliances generally contributes to heat the building, and this heat gain is defined in an hourly scenario in COMFIE. The EQUER interface allows the user to account for an additional electric consumption on an annual aggregated basis. This additional consumption is dispatched on hours of the day according to the hourly scenario provided by COMFIE.

Local electricity production is firstly consumed in the building. The allocation to each use is proportional to its share in total electricity consumption at each hour. Residual production is then evaluated as exported to the grid and corresponds to an avoided grid production evaluated using the general hourly mix at the same hour. The corresponding avoided impacts are subtracted from the total impacts of the building. Impacts linked with the production of equipments (Production and transport of photovoltaic modules for instance) are entirely allocated to the building.

5. Case study

The model presented above has been applied on a settlement inspired from the eco-district Vauban in Freiburg (Germany) [11] , named here “low energy neighborhood” (LEN) representing best practice. The results were then compared to results obtained on a new project in the greater Paris area, the Descartes City.

5.1 Settlements description

The LEN settlement include dwellings, a tertiary building, an elementary school and a parking lot of four levels including a supermarket in its ground floor and a small photovoltaic system on the roof. In order to use this best practice project as a reference for a comparison with the Descartes City, it is contextualized in the model, e.g. using climatic data for Paris and the French electricity mix. Size and number of occupants have also been adapted to allow results to be compared on the basis of the same functional unit: a neighborhood with 887 inhabitants, 734 offices occupants, 432 shops occupants and 240 school occupants, situated in Paris region, on a 80 years lifespan.

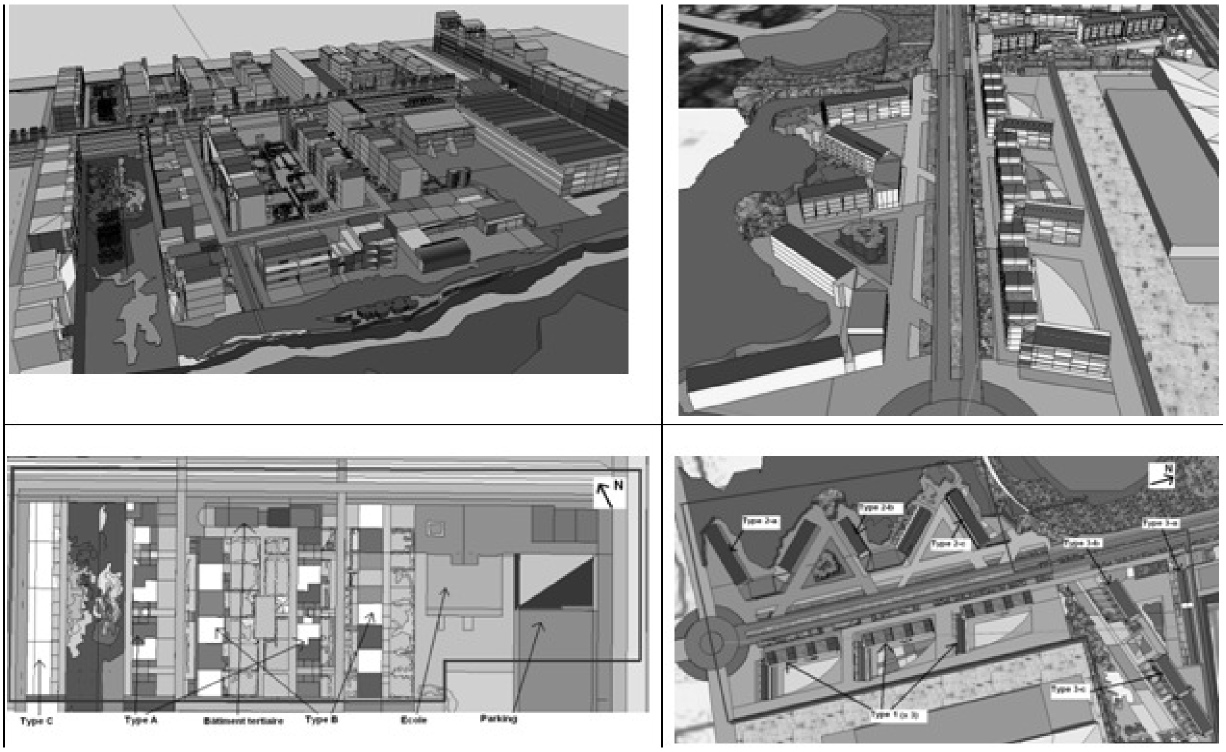

Figure 3: Overview of the settlements Vauban (LEN, left side) and Descartes (right side)

Table 2: Results of thermal dynamic simulation

In kWh/m²	Heating load	Cooling load	Hot water	Internal heat gains
LEN	11,4	1,2	6,3	24,7
Cité Descartes	9,4	0,8	6,1	25,2

5.2 Common LCA parameters

Buildings are heated by district heating, the source being a cogeneration plant using 20% of natural gas and 80% of wood with an efficiency of 26% for electric production and 61% for heat production. The domestic hot water is produced 50% by this plant and 50% by a solar system (410 m² of south oriented collectors for both settlements). For dwellings, an additional electricity consumption of 500 Wh/person/day is accounted for to integrate washing machines, dishwasher and similar appliances contributing only partly in internal heat gains.

The French electricity production mix is considered as the reference annual mix (78% nuclear, 14% hydroelectric or renewable, 4% gas and 4% coal) with 9% losses in the network. Demolition waste is considered treated as inert waste, except metals that are recycled. Fabrication of materials is evaluated considering a 5% surplus added in order to account for on-site processes, broken elements and purchased quantities. An average 100 km transport distance by truck is considered from the factories to the building site, 20 km from the building site to incineration facilities and 2 km to landfill. Life spans considered are 10 years for building finishes, 30 years for windows and doors and 80 years for the other elements and buildings. The photovoltaic system has been evaluated with a 25 years lifespan and the thermal solar collectors with a 20 years lifespan. There is two times more photovoltaic modules per equivalent-occupant on the Descartes City roof than on the Low-Energy-Neighborhood roof.

We also define the cold and hot water consumption in litre per day per person, as well as the characteristics of the public spaces (type, composition, surface, needs of lighting and water, imperviousness), and of the heating, drinking water and sewage networks (length, composition, maintenance…). Because the objective is to compare electricity related impacts and urban choices, the study does not account for domestic waste and choice of home-work transport.

6. Results

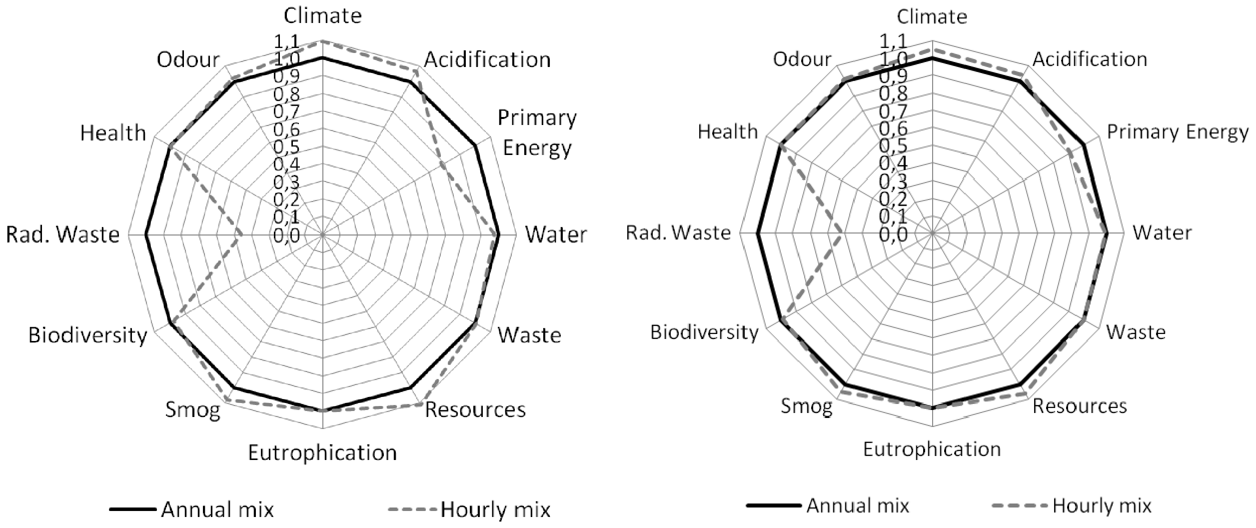

Figure 4: The LEN (right) and the Descartes City (Left) LCA using the annual and the hourly model

Using the hourly mix method increases environmental impacts related to thermal electricity generation technologies (Climate and Resources for instance) up to 10% for the low-energy neighborhood and decreases environmental impacts related to nuclear production (Primary Energy demand and Radioactive waste). The main uses of electricity are cooling and specific electricity (the district heating providing heat and hot water). Results indicate that the amount of thermal technologies used to generate this electricity is higher than what is suggested using an annual mix.

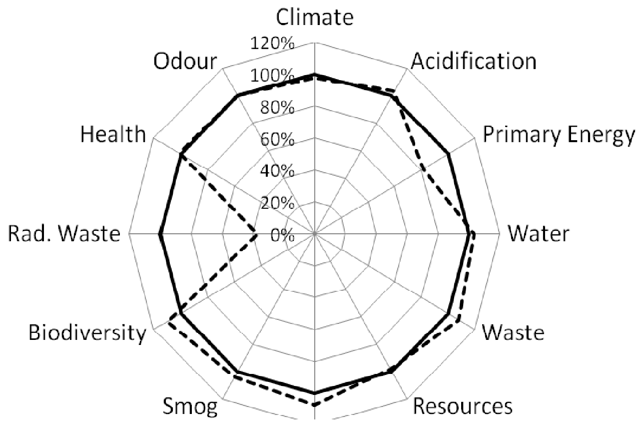

Figure 5: Comparison of LEN and Descartes evaluated using an annual mix and the hourly mix model

On fig. 5, the Descartes City has been compared to the reference settlement. The ranking between the Descartes City and the reference settlement is not affected by the type of mix used, except a small difference regarding climate and resources. Both settlements have comparable results except regarding cumulative energy demand and radioactive waste production. This is mainly due to the larger amount of photovoltaic modules installed on the Descartes City. Differences between the two settlements are smaller using the hourly mix model. Radioactive waste is related to electricity generated from nuclear energy. The amount of nuclear electricity avoided by photovoltaic modules is smaller when considering an hourly mix.

7. Discussion

The results show how important it is to consider time-variation in energy consumption and production. We can see differences up to 50% for radioactive waste, 22% for cumulative energy demand, 10% for climate and resources in case studies. Using a model based upon use-specific hourly mixes instead of constant annual average is therefore justified. The use of electricity in the two settlements is quite reduced, as neither heating nor hot water needs are satisfied by an electric system. Other case studies on plus-energy buildings and buildings using heat pumps or electric hot water systems are being investigated and a larger discrepancy between the annual and the hourly mix model is expected.

The model has been calibrated on the year 2008 and tested on 2008 and 2009. At the time of development, it was the only years for which detailed data were available. Collecting data on a longer time period would improve robustness of the model. Moreover, economic parameters are not included. As an example, in 2009 in France, the economic crisis has had a large influence on electricity consumed by industry. The decrease of electricity consumption from industry has made nuclear capacity available for other uses. This is one explanation of the high discrepancy between results of the model and measured electricity production in 2009. A larger period of study may reduce discrepancy due to economic variations.

The model has shown difficulties to treat extreme weather events and intermediate season when dependency to temperature is lower. Furthermore it only takes into account temperature but it would be useful to integrate a solar radiation parameter. The model is based on two main parameters: temperatures and frequencies of uses. However, these two parameters are not completely independent, which means that a part of variation linked with temperatures is allocated to frequencies. The reference temperature is calculated on the basis of three meteorological locations in France. This number could be increased, e.g. the grid manager (RTE) uses 32 locations in its model. Holidays are not taken into account. This introduces singularity neglected by the model. Associating uses with temporal variation patterns could be refined, e.g. stand by consumption could be associated to a yearly constant mix instead of domestic or professional patterns.

Future evolution of the mix (planned closing of obsolete plants for instance, planned construction of new capacities) has not been taken into account. This is of importance considering that average lifespan of buildings is around 80 years but is also very uncertain. Therefore LCA results are more reliable for short term periods, e.g. dividing the total impacts by the duration of the period provides yearly impacts and this value is more reliable for the next years than for a far future.

Consequential LCA is defined as a modeling technique aiming at evaluating consequences of a decision (Earles et Halog 2011; Ekvall et Weidema 2004; [12]. This method is of great interest when feedback loops of important magnitude occur between the studied system (here a building or urban settlement) and background processes (e.g. Electricity production). The study performed is a first step towards integration of consequential parameters in life cycle assessment of buildings. Providing an hourly production mix can still be classified as attributional LCA. However, allocating impacts to each use implies to relate a use to a specific technology implying that the mix is a consequence of the use. This is a point of view similar to the marginal technology concept, which is at the basis of the consequential approach [13], [14]. After increasing the robustness of the model, further steps may include feedback loops such as modification of the general mix because of the influence of buildings (short-term, utilization of installed capacities), scenarios integration (mid or long-term, influence on investment on new capacities), and economic parameters (electricity market merit order, elasticity).

8. Conclusion

Choosing an hourly production mix model to perform building life cycle assessment has a large influence on impact evaluation. Technologies such as photovoltaic modules, heat pumps, cogeneration, solar domestic hot water systems, or new control strategies influence the electricity consumption over time. Thus, environmental benefit from new building-related technologies or impacts related to energy in buildings consumption cannot be evaluated on an annual average basis. Life-cycle simulation is therefore adapted in such cases.

Consequential LCA method could be further developed to better understand feedback loops mechanisms between the building sector and the overall electricity production system. Economic mechanisms, resources constraints or scenarios may be added. This would allow a better understanding of short and long-term environmental consequences of electricity consumption.

9. Acknowledgements

This work follows research initiated by Gregory Herfray during his PHD thesis and was performed in the frame of the research Chair ParisTech VINCI “Ecodesign of buildings and infrastructure”.

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