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Spatialization in LCA

Interests, feasibility and limits of eco-design

EcoSD Annual Workshop 2017

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Lynda Aissani

Opening ceremony

As President of IFP Energies Nouvelles (IFPEN), I am pleased to welcome you to this workshop dedicated to Life Cycle Assessment (LCA).

IFPEN is a major French research player in the field of energy and transport. Innovation is at the heart of our action. A good innovation is an innovation that makes economic and environmental sense. We therefore attach particular importance to the environmental assessment of the solutions we develop. Within the Economy and Watch Department, a team is dedicated to the LCA activity. Whether in the context of national projects such as BioTfueL or Futurol (which aims to develop second-generation biofuels), European programs such as WideMob or Scelectra (focused on electric vehicles and mobility), or at the request of partner companies, public authorities or for research purposes within the IFPEN Group, this team is regularly asked to carry out various environmental assessments: biofuels, plant chemistry, hybrid vehicles, wind power offshore, etc.

We are also committed to advancing research in the field of LCA. At IFPEN, basic research accounts for 25% of our research budget. It is structured in the form of nine scientific issues. It is an essential part of our activity in support of IFPEN's innovation programs and strategic ambitions. One of these issues is dedicated to evaluation of economic and environmental impacts of energy-transition innovations. LCA is part of these issues, and a recent result has been the development of so-called consequential and prospective approaches. These new approaches combine LCA with energy and economic scenarios. These advanced approaches can be applied to all types of technologies for various geographical perimeters. LCA is becoming a valuable decision-support tool for quantifying environmental impacts of large-scale political and industrial decisions.

To enrich our research as well, IFPEN is involved in specialized collaborative networks such as SCORELCA and EcoSD, and regularly hosts or co-organizes events that are supported by scientific communities positioned on key disciplines of its research, in connection with its scientific issues. We thus organize, several times a year, under the auspices of the Academy of Sciences, the IFPEN Scientific Meeting, allowing the players of fundamental research and industrial research to present their work in a particular field and to discuss progress, possible applications, and challenges.

The present workshop is part of the IFPEN Scientific Meeting, and we are happy to organize this Annual Workshop for EcoSD jointly with IRSTEA, INRA and the Ecole des Métiers de l'Environnement. The topic of this workshop is "Spatialization in LCA - Interests, feasibility and limits of eco-design". The integration of spatial information into LCA is a real challenge, particularly for the assessment of the environmental performance of agricultural and industrial production systems and rural and urban development projects. You will discover and exchange around a new essential approach to LCA, through case studies and examples.

Didier Houssin

President of IFPEN

Foreword

As president of EcoSD (Eco-design of Systems for sustainable Development), I am very proud to present EcoSD, the association which organizes and financially supports this annual workshop and its associated publication since 2013.

The EcoSD network is a French association whose main objective is to encourage collaboration between academic and industrial researchers so they may create and spread advanced and multidisciplinary knowledge in the eco-design fields at national and international levels. EcoSD proposes several actions with the support of the French Environment and Energy Management Agency (ADEME), the French Ministry of Higher Education and Research, and the French Ministry of Industry:

- Structuring EcoSD research activities in France to take advantage of the expertise of more than 200 members of this research network
- Developing knowledge among researchers in the eco-design fields, particularly better training of Ph.D. students, by organizing relevant training courses for different themes in eco-design
- Developing new methods, tools and databases to achieve complex systems design, compatible with the principle of sustainable development
- Initiating the "EcoSD label" to acknowledge the quality and inclusion of sustainable development in training, research programs, research projects and symposiums
- Helping interactive collaboration between researchers and industrial partners by organizing quarterly research seminars in Paris and an annual workshop

Approximately 100 researchers from industry, academia and government institutions participated in the 2017 workshop on "Spatialization in LCA" and had the opportunity to exchange with experts. The associated publication contains a synthesis of the main contributions presented during this workshop.

I am very grateful to the coordinators (Lynda Aissani from IRSTEA-Rennes and Cécile Querleu and Pierre Collet from IFPEN) for the perfect organization of this workshop held in Rueil-Malmaison in March 2017. I also thank all the speakers for the quality of their oral presentations and the fruitful exchanges they allow.

Dominique Millet

President of EcoSD

Introduction to the workshop

Why spatialize LCA?

Lynda AISSANI[1]

1 IRSTEA, Rennes, France

TOWARDS THE USE OF LCA FOR REGIONAL SCENARIOS

The use of Life Cycle Assessment (LCA) methodology for environmental assessment of increasingly varied systems has been growing for several years despite its limitations. Since LCA was clearly developed for products, it has limits to how much its scope can be extended to urban projects or agricultural production. Its holistic nature makes it a promising tool to assess prospective regional scenarios for renewable energy production, waste management, urban projects and agricultural production. Using LCA for environmental assessment of such systems appears to be a strong challenge.

WHAT IS SPATIALIZATION IN LCA?

One of the greatest limits to applying LCA to these systems is its lack of spatialization which is the ability to place a studied system in its spatial context (i.e., surroundings) if this context strongly interacts with the system. Since many different terms exist to describe spatialization in LCA, it is necessary to define specific terms for this seminar:

- Spatialization/contextualization/spatial differentiation:
    - considering spatial information when studying a system
    - placing the studied system in its spatial context
- Space/context:
    - From workstation to workshop
    - From workshop to factory
    - From a factory to its local or administrative surroundings (watershed, territory, local authority, etc.)

Spatialization in LCA consists, in part, of integrating spatial information throughout LCA methodology to define the system, collect local data, estimate system impacts and represent the results.

Why should one spatialize?

Spatialization in LCA aims to increase the relevance of environmental assessment by introducing spatial information on which the studied system depends. Indeed, ignoring spatial information may weaken the sense and robustness of LCA results for some systems. In particular, spatialization must be performed for renewable energy production, agricultural production and urban projects to highlight the modifications of their geometry, operating and dynamics due to their interactions with the context.

This seminar aimed to identify the utility, practicality and limits of spatialization in LCA for eco-design for around 100 researchers from industry, academia and government institutions. It was an opportunity to:

- present an overview of existing tools to perform spatialization in LCA
- explore new advanced tools, approaches and initiatives
- identify successful case studies
- become open to other concepts, such as industrial ecology

At the end of this seminar, we tried to take a global view by asking about the need of a framework for spatialization in LCA and potential links with industrial ecology.

Part I

Existing and advanced tools

Introduction to Part I

Anne Ventura[1]

1 IFSTTAR, Nantes, France

Once a substance has been emitted to the environment, it can spread to a variety of compartments and geographical areas to various degrees depending on characteristics of both the substance emitted and the emission location, as well as on the persistence of the substance emitted. Figure 1 represents geographical and temporal scales generally found for current environmental impact categories in LCA. The scales are related to one another: the more persistent a pollutant, the wider the geographical spread. Spread also depends on the emission compartment: the more mobile the fluid of the emission compartment, the wider the spread of pollutants (through advection). Indeed, one expects a wider spread of substances emitted to the air than those emitted to water, which itself is more mobile than soil.

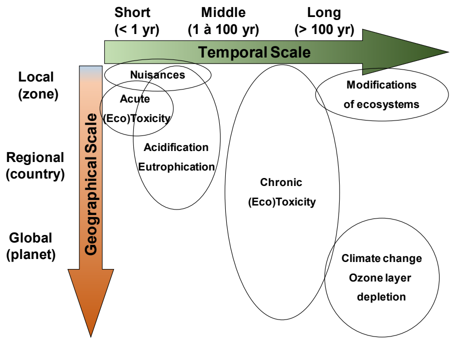


Figure 1. Spatial and temporal scales for environmental impacts

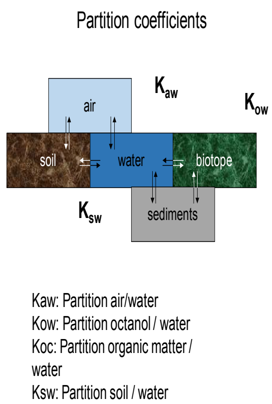


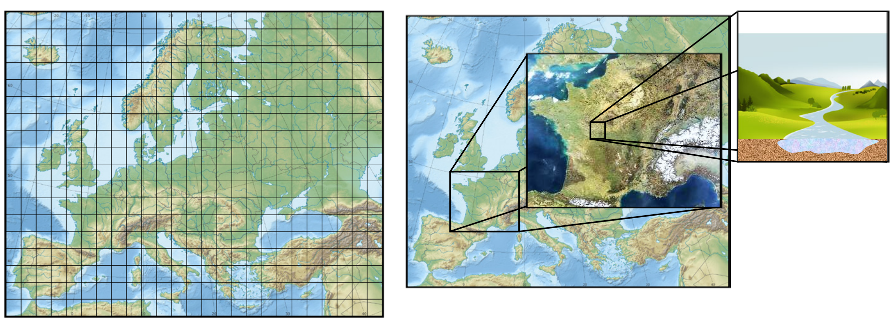
Figure 2. Multi-compartment partition models

In the 1990s multi-compartment modeling tools based on equilibrium partition laws (Figure 2) were developed, such as CalTOX (McKone, 1993), aiming to predict which receiving compartment(s) of a given area would accumulate toxic pollutants once they were emitted in a given emission compartment. For example, it was shown that persistent organic pollutants are widely spread in sediments of the Pacific Ocean (Wania and MacKay, 1996), even though they are emitted in small but regular amounts at distant continental spots. Multi-compartment models were initially applied to toxicological risk assessments for specific locations concerned by toxic pollutants. They were then adapted and are still in use for LCA, especially for toxicity and eco-toxicity indicators, setting the basis for chemical fate factors (Pennington et al., 2006). The path from toxicological risk assessment to LCA was a path from specific local situations to generic values for emissions of a toxic substance. Indeed, considering the life cycle of product requires considering many emission spots along all life cycle steps, and thus requires a harmonized impact assessment method for a given substance wherever it is emitted. To reach this goal, multi-compartment models are used for given volumes of environments called **boxes.** In Life Cycle Impact Assessment (LCIA) models, each compartment has a volume within each box, and substances can spread between compartments and boxes. Two main structures can be used to consider several boxes:

- Meshed adjacent boxes (Figure 3a): each box represents a specific region of the Earth
- Nested boxes (Figure 3b): each box represents an archetype of the environment (e.g. urban, sub-continental, continent, Earth)

Chemical fate factors are not restricted to toxic impacts; they are now also used for other impact categories.

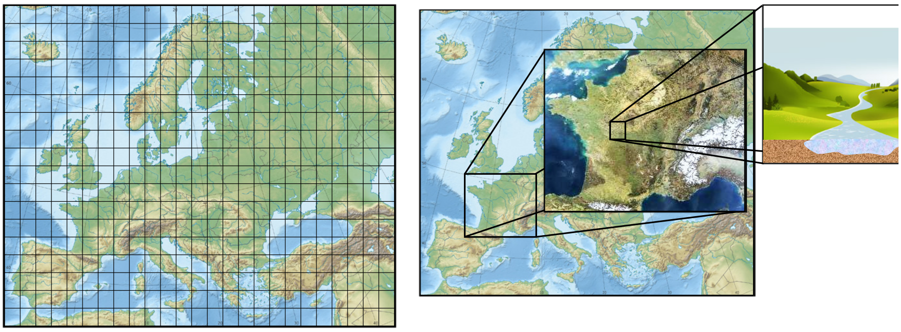
Meshed adjacent boxes



a) Meshed adjacent boxes *b) Nested boxes*

Figure 3a:. each box represents a specific region of the Earth

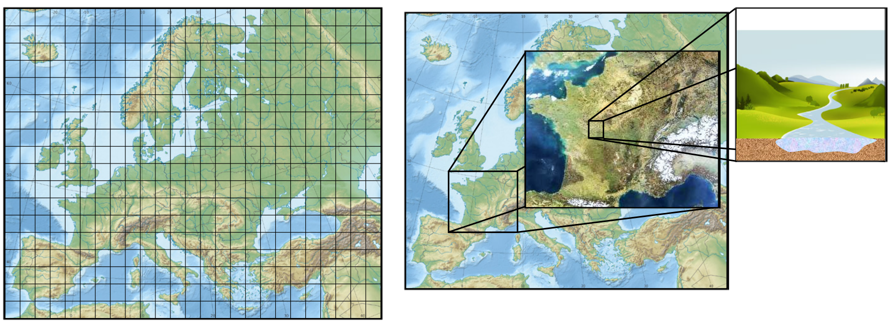
Nested boxes



a) Meshed adjacent boxes *b) Nested boxes*

Figure 3b.: each box represents an archetype of the environment (e.g. urban, sub-continental, continent, Earth)

Chemical fate factors are not restricted to toxic impacts; they are now also used for other impact categories.



a) Meshed adjacent boxes *b) Nested boxes*

Figure 3. Types of box structures for LCA chemical fate factors

Finally, spatializing LCIA can appear to return to initial risk assessment methods, so this scientific issue leads to different questions:

- Why may it be relevant to spatialize LCIA indicators?
- Does it, or should it, concern inventory data (i.e. spatializing emissions) and/or characterization factors? What do they represent, and what are the current methodological issues?
- Are spatialized approaches compatible with life cycle modeling in which emissions occur at different locations and times?

In this session, individuals presented several existing methods. I used these presentations as a basis to contribute to these general thoughts.

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Methods and tools to integrate the spatial dimension in LCA

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Introduction

Life Cycle Assessment (LCA) did not initially consider the spatial (or temporal) dimension, mainly because it was designed to prevent global pollution rather than assess site-specific risks. Spatial differentiation in Life Cycle Impact Assessment (LCIA) has recently received growing interest, since addressing geographic aspects in LCA appears to be a promising avenue for increasing the representativeness and reliability of its results. The objective of this study is first to review the current state of the integration of the spatial dimension in LCA, based on the SCORELCA study entitled "Considering geographic aspects in LCA: benefit and implementation". Major concepts for integrating the spatial dimension in LCA are provided with each step and their relevance and potential uses are assessed. This study was performed through an extensive literature review of current LCA standards and emerging approaches such as territorial LCA. The integration of geographic aspects in Life Cycle Inventory (LCI) databases, LCA tools and software developments was also analyzed.

This study places special emphasis on coupling LCA with Geographic Information System (GIS) tools, based on another SCORELCA study entitled "Interest and implementation of coupling GIS and LCA". GIS is a tool to capture, store, manipulate, analyze, manage, and present spatial or geographic data from many sources. The use of GIS databases and software tools can support the regionalization of LCA, both for the LCI and LCIA. The study aims to evaluate the utility and feasibility of coupling LCA with GIS, based on a literature review and on two case studies performed by the Luxembourg Institute of Science and Technology (LIST), to draw recommendations for LCA practitioners.

Defining terms related to the spatial dimension in LCA

Based on the literature review (67 references), we provide a glossary for the following terms:

- *Geographic vs. Spatial*: both adjectives are used synonymously
- *Region/territory*: geographic area, delimited by boundaries, with homogeneous parameters
- *Spatial coverage*: area of geographic validity of an inventory dataset or impact assessment method
- *Regionalization*: describes representation of processes and phenomena for a given region
- *Spatialization:* assigns a location to something, e.g. an environmental flow (EF)
- *Inventory regionalization:* improving the geographical representativeness of inventory data
- *Inventory spatialization:* assigning to an EF a geographic location, which is necessary for using regionalized characterization factors (CFs).
- *Impact regionalization:* calculating regionalized CFs to assess spatialized EFs representative of specific geographic areas. LCIA method developers determine the optimal spatial scale, called the native resolution, for a given impact category.
- *Archetype:* used to regionalize LCIA methods by accounting for the most influential parameters and impact mechanisms without needing a specific geographic location
- *Regional impact calculation*: calculating impacts using spatialized EFs and regionalized CFs
- *Receiving environment*: the place where environmental interventions occur

Critical analysis of the methods reviewed to consider the spatial dimension in LCA

Integrating the spatial dimension in the goal and scope

In most LCA studies, spatial coverage is described in the goal and scope when specifying the study objectives and/or functional unit. A territorial LCA approach should be adopted (Loiseau et al 2012; Loiseau et al 2013)methods for environmental assessment of human activities are urgently needed. In particular in the case of assessment of land planning scenarios, there is presently no consensual and widely adopted method although it is strongly required by the European Directive (2001/42/EC when the scope is a territory. Laurent (2015) developed an approach for territorial LCA to use spatial information to better define the goal and scope. Nitschelm *et al.* (2015) developed an LCA framework to capture the spatial variability of potential impacts in a given territory.

Integrating the spatial dimension into the LCI

The spatial dimension can be integrated into the LCI in two ways: regionalization and spatialization. Inventory regionalization improves the geographical representativeness of LCI data (both economic flows and EFs) since many parameters (e.g. yields, operation conditions) depend on their location (Ciroth and Hagelüken 2002). Two approaches to inventory regionalization coexist (Lesage and Samson 2013): process recontextualization (adapting a process to be more representative of a given geographic area) and adaptation of quantitative data. The ecoinvent v3 database (Weidema B P et al 2012) represents countries that are the main producers of a given technology. Recent studies (Yang, 2016; Yang and Heijungs, 2017) developed a general framework and computational structure to deal with the spatial dimension in LCA.

In inventory spatialization, geographical information is given to an EF. Different types of geographical information can be added to spatialize an EF. Textual information about the geographical zone of the EF can be added, for example, in the way that water EFs have been spatialized in ecoinvent v3 (Pfister et al 2016)comprehensive databases fulfilling the requirements for addressing these issues have been lacking and are necessary to facilitate efficient and consistent assessments of products and services. To this purpose, ecoinvent focused on integrating appropriate water use data into version 3, since previously water use data has been inconsistently reported and some essential flows were missing. This paper describes the structure of the water use data in ecoinvent, how the data has been compiled and the way it can be used for water footprinting. Methods: The main changes required for proper assessment of water use are the addition of environmental and product flows in order to allow a water balance over each process. This is in accordance with the strict paradigm in ecoinvent 3 to focus on mass balances, which requires the inclusion of water contents of all products (also for e.g. waste water flows. Another option is to associate archetypes with the EF, which is a current practice for the toxicity impact category (Humbert 2009). Finally, geographical coordinates can be used to localize the EF. This approach is the most practical, and it is increasingly integrated in LCA software, such as Brightway and OpenLCA (Mutel 2014; Rodríguez and Greve 2016).

Integrating the spatial dimension in impact assessment

Regionalization in LCIA methods captures the spatial variability of the receiving environment by developing CFs that are valid for a defined region. Two approaches exist to define regionalized CFs: archetypes and spatial differentiation. In the archetype approach, the parameters on which the archetype is based are not directly linked to their geographic position. For example, an archetype based on population density is used to distinguish the impact of fine particulate emissions on human health between urban and rural areas (Humbert 2009). For the spatial differentiation approach, two types of models are used: site-dependent or site-specific.

Several regionalized LCIA methods exist, but only a few of them are regionalized in a consistent way. For example, IMPACT World+ (Bulle et al 2017) has global coverage and provides CFs at different scales (native, country, continent and global level) for spatially differentiated impact categories. In contrast, LIME 2 was developed for Japan (Itsubo and Inaba 2012). Its CFs are regionalized at a fine native resolution and then aggregated for the whole of Japan. Unlike IMPACT World+, LIME 2 has national coverage.

Interpretation

OpenLCA can generate maps showing impacts according to the geographical origin of the EF but not the regions affected by the impacts (Rodríguez and Greve 2016). Liu *et al.* (2014) developed an approach to visualize the regions affected the impacts by tracking EF fate, exposure and effect. This approach improves the interpretation phase but is difficult to apply with existing tools, since it requires GIS skills to implement.

Most common LCA software (SimaPro and GaBi) can include textual geographic information in the description of a process. EFs are identified by their name, compartment and sub-compartment. Therefore, this software can support regionalized LCIA methods if EFs are adequately defined, i.e. named with the required geographical information (emission by country for example). Consequently, the number of EFs can increase greatly when integrating a regionalized LCIA method with these types of software; thus, software without GIS is not appropriate for performing regionalized LCA.

OpenLCA and Brightway can include GIS data. Brightway is dedicated mainly to research, while OpenLCA is more user-friendly, with a large community of users. Therefore, OpenLCA is currently the most appropriate tool for LCA practitioners to deal with the spatial dimension in LCA.

Concluding remarks on the critical analysis

Table 1 summarizes the approaches selected and assesses their relevance, level of development and level of operationalization.

Table 1. Analysis of the approaches identified. Each "+" or "-" corresponds to a qualitative estimate of the issue analyzed. EF = emission factor

Question	Approach definition	Relevance	Level of development	Level of operationalization
Goal & Scope				
Does the scope of the study refer to a territory?	Territorial LCA approach	+++	++	+
How to define the spatial requirements of the LCA study?	Description of the spatial coverage in the goal of the study or functional unit	+++	++	++
Inventory				
How to regionalize the inventory?	Adaptation of quantitative data to better fit the spatial coverage	++	+++	++
	Process recontextualization	++	+++	++
How can spatialization be performed?	Use the geographical information from the inventory regionalization	++	+	+
	Spatialize the EF without inventory regionalization: Description of the geographical distribution of the EF within the spatial coverage of its related process	+++	++	+(++)
Impact regionalization				
How can impact assessment be regionalized?	Archetype-based LCIA model	++	+++	+++
	Spatially differentiated approach	++(+)	+++	+++
Which impact assessment method should be used?	IMPACT World+	+++	+	+
	LIME 2 – spatial coverage: Japan	++	+	-
How can uncertainty related to spatial variability be assessed?	Quantification of uncertainty due to the spatial variability for aggregated CFs	+++	+	+
How can regionalized impact assessment be implemented?	Differentiation of EF names	+(++)	++	-(++)
	Geographical information handled with a GIS	+++	++	+

Interpretation				
How should impacts be visualized?	Results integrated over space (no regionalized results)	++	+++	+++
	Maps showing impacts according to geographical origin of the EF	+++	++	++
	Maps showing resulting impact locations	+++	-	--

Coupling LCA and GIS

Utility and application context of GIS in LCA

In the literature, GIS has been used to refine the geographical representativeness of both the LCI and LCIA since 2010. The degree of relevance of LCA-GIS coupling depends on the objectives and scope of the study. Concerning the type of application, the most appropriate use is to support political strategic development (type B decision context according to the ILCD Handbook), due to the vast scope and scale of the results. Even at a smaller scale (type A decision context according to the ILCD Handbook), GIS can avoid biased conclusions caused by poor geographical representation (Mutel et al., 2012). The utility of coupling can also be high to prepare a report of large-scale impacts (balances for a country, a product category, etc.) or for model development. Regarding the audience, visualization of results as maps may have greater utility when the target audience is a wide public, not specialized in LCA (more easily understandable and greater impact). Based on the literature review, using GIS for LCI data is relevant for regional LCA and sectors with high geographic sensitivity, such as agriculture, transport and logistics, infrastructure and energy. The definition of the functional unit (FU) may include geographical features that increase the utility of GIS. Finally, regarding the choice of the impacts considered, (eco)toxicity, noise and odor are sensitive to geographic variability. Other impacts also have a strong regional aspect, such as eutrophication, acidification, particulate pollution, ionizing radiation, photochemical ozone creation and use of natural resources (land and water). The impacts of climate change, ozone depletion and use of fossil and mineral resources have a more global scope and do not require a geographic refinement. The impacts on human health and ecosystem endpoints depend on regional parameters.

Using GIS information for LCI modeling is particularly useful for supporting regional strategies (e.g. Loiseau et al., 2012; Geyer et al., 2013) due to the collection of large amounts of data for the area studied (via databases or provided by competent authorities). In product or process LCAs, GIS information about agronomic and climate data can be used as input data for the LCI in agricultural studies (e.g. Ooba et al., 2015); transportation network layers can ease calculation of distances for logistic scenarios (e.g. Newell et al., 2011); building or material maps can be used to model infrastructure impacts (e.g. Nichols and Kockelman, 2014); and network and agricultural modeling with GIS can support assessment of energy production (Delivand et al., 2015; Saner et al., 2014).

To estimate impacts, LCA-GIS coupling has been performed for acidification based on deposition and soil sensitivity models (Roy et al., 2014), for eutrophication based on water and sediment cycles (Helmes et al., 2012), for toxic impacts based on environmental parameters (Kounina et al., 2014), for land use based on data such as soil characteristics (de Baan et al., 2013), for water resources based on hydrologic data (Pfister et al., 2009) and for noise-related impacts based on geographical parameters such as topographic elements (Cucurachi and Heijungs, 2014).

Coupling LCA and GIS

In computer science, "coupling" describes the automatic exchange of information between software components. In this study, three types of coupling were distinguished. "No coupling" consists of manually adding GIS data to an LCA model. This can be practical when GIS and computing skills are low, but only a small amount of data can be shared, and replicability of this approach is limited. "Weak coupling" allows for automated exchange between the two components of a larger number of data. The workload and skills required depend on the complexity. If computing skills are advanced, "strong coupling" is possible to completely automate the interaction between GIS and LCA in a common interface (LCA software or "connector" software). Strong coupling has been performed to solve spatial optimization problems (Delivand et al., 2015; Saner et al., 2014). To generate spatialized characterization factors (CFs), some studies have used only GIS data or models to differentiate CFs by region or archetype (table form), while others developed georeferenced CFs. This latter approach provides better resolution and coupling with georeferenced LCI data. Only a few studies have integrated GIS models for both LCI and LCIA (i.e. Pfister et al., 2011; Rodriguez et al., 2014).

Focusing on the coupling ability of LCA software and databases, only OpenLCA and Brightway2 (open-source) among LCA software can treat GIS data. OpenLCA can add geographic coordinates to a process and visualize regional contributions to final impacts on a map. Brightway2 has a plugin to spatialize LCIs and CFs, and to export contribution maps. In contrast, the files used by GaBi or SimaPro cannot store detailed geographic information. Among LCA databases, only ecoinvent v3, via the ecoSpold 2 format, can store geographic coordinates of activities.

Case studies performed by LIST have helped to understand practical aspects and limitations of weak and strong coupling. For a simplified LCA of automotive fuel, strong coupling was performed between QGIS and Brightway2 (using Python scripts). A QGIS plugin was developed with the following functions: automatic GIS data treatment, input data selection, choice of impact assessment method, LCA calculation and visualization of results on maps. A second case study estimated environmental impacts of residential buildings at the city scale (Rotterdam). Weak coupling was implemented using a connector based on the open-source software R, linking the open-source software GRASS-GIS with SimaPro 7.3.3. The foreground LCI was spatialized by automatic GIS treatment, while impacts of reference elements of buildings (including their retrofitting and end of life) were calculated per unit area (i.e. $m^{2)}$ and further aggregated at the city scale. For these two case studies, GIS allowed for increased data availability, generation of new LCI data (layer superimposition, distance calculation, spatial differentiation of flows), use of regionalized CFs, higher quality of foreground processes and visualization of results on maps. The constraints identified were large-scale data availability and accuracy, background process characterization, and the GIS skills required for data management, treatment and visualization.

To provide practical recommendations, a decision tree was developed (Figure 1), determining the type of coupling to use depending on the study context and skills of the LCA team. First, if the LCA is used as to support decisions, the relevance of coupling is increased, in particular for regional or industrial strategies with geographic resolution of results. Strong coupling is necessary for spatial optimization (basic GIS skills are mandatory). The choice between weak or strong coupling is guided by the computing skills of the team. For large-scale assessment or a sector sensitive to geography, spatialized LCI data can be used. The recommended coupling depends on the amount of data to be treated, time available and skills of the LCA team. Finally, if there is low geographic sensitivity of the LCI, coupling has little use. Finally, if only regionalized impacts are considered, CFs can be implemented in LCA software in tabular form (no coupling).

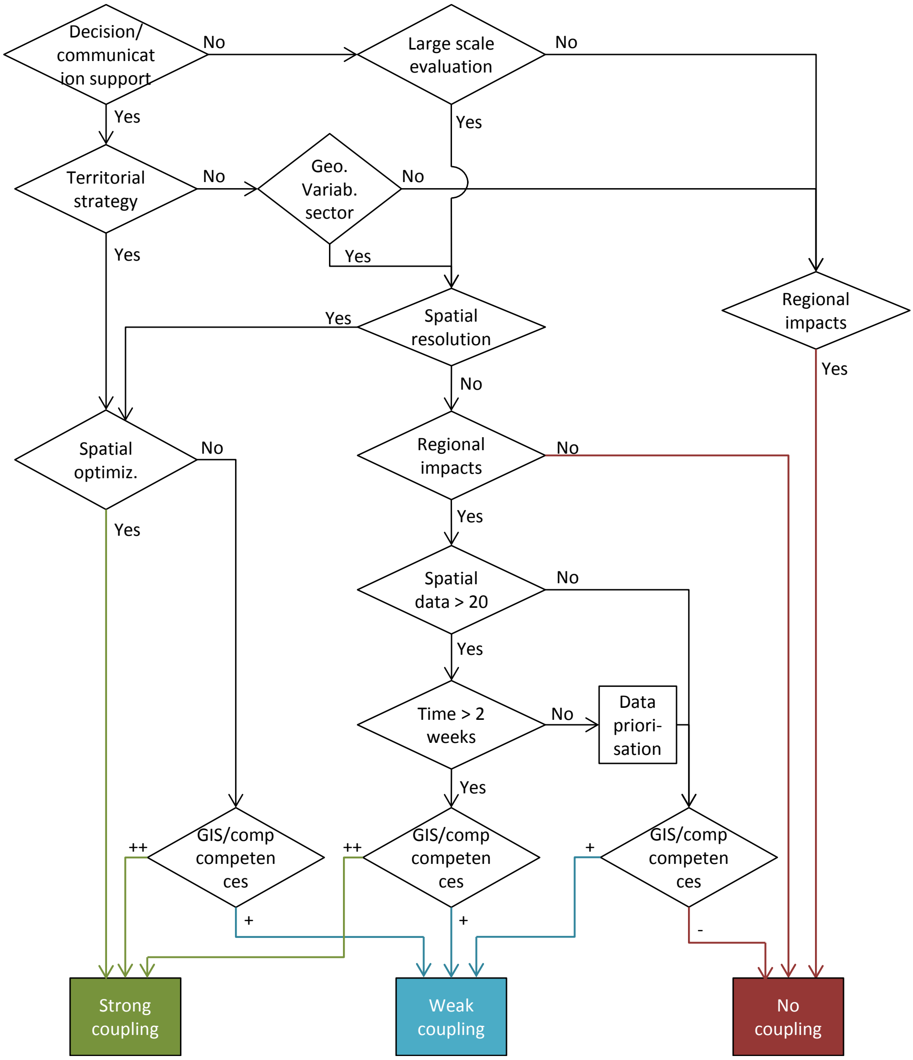

Figure 1. Decision tree for types of coupling of LCA and GIS

DISCUSSION AND CONCLUSION

This study provides common definitions of terms related to the spatial dimension in LCA and also a critical review of the relevance of considering the spatial dimension in LCA. Main approaches available in the literature were analyzed for each LCA step (goal and scope, LCI, LCIA and interpretation). The results of this study are an initial attempt to optimize regionalization efforts performed by LCA practitioners.

Even if the use of GIS seems pertinent, LCA practitioners can be confronted with several obstacles to coupling them. First, LCI or LCIA spatialized data are not always available. For example, many ecoinvent v3 datasets still have the code "Rest of the World (RoW)", which differs by activity. To compensate for the lack of data, GIS treatment and skills are required to generate new spatialized data and harmonize layers. In addition, coupling needs basic computing skills because common LCA software tools lack GIS functions. Finally, depending on the complexity and amount of data, the additional workload and budget do not facilitate coupling, particularly in private companies. Regarding usage precautions, as emphasized by Mutel *et al.* (2012), uncertainties in impact assessment methods can decrease with finer geographical representation, but the multiplication of CFs generates additional variability, sometimes unjustified. LCA practitioners need to be careful about the validity of the spatial resolution. Heijungs (2012) also warns about misinterpreting results, which can be minimized by comparing results with and without regionalization, and an incompatibility of resolution between LCI and LCIA methods. This confirms the need for GIS skills to spatialize LCA to make good choices when coupling and analyze results that have relevance.

In conclusion, the use of GIS for LCA has expanded over the past few years, and we can expect many developments in the future to facilitate this coupling. First, several authors (Mutel et al., 2012; Cucurachi and Heijungs, 2014; Kounina *et al.* 2014) highlighted the importance of evaluating the validity of spatialized CFs to provide practitioners with a relevant scale for each category. Databases will be also refined to ensure consistency of regionalized results between foreground and background processes. This trend has already started with ecoinvent v3, but the consistency and reliability of data still need to be improved. Finally, the spatialization of impact assessment methods and LCI databases should encourage the implementation of GIS functions in LCA software. Some developers, in particular GreenDelta GmbH for OpenLCA, have already displayed this intention.

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How to select the life cycle steps to be spatialized?

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Introduction

Regionalization in Life Cycle Assessment (LCA) is one way to reduce uncertainty in overall results by focusing on uncertainty due to spatial variability. Regionalization can form part of each step of LCA methodology (Patouillard et al., 2017). Life Cycle Inventory (LCI) regionalization deals with increasing the geographic representativeness modelled in the LCI. Life Cycle Impact Assessment (LCIA) regionalization deals with regionalized impact characterization that accounts for the spatial variability of the receiving environment. Regionalized characterization factors (CFs) apply to spatialized elementary flows (EFs), called LCI spatialization. However, regionalization and spatialization require additional effort by LCA practitioners to collect regional data (Baitz et al., 2012). As stated by (Heijungs, 1996), these efforts should focus on the data that are most uncertain and contribute most to LCA results, i.e. those that have the highest potential to decrease the uncertainty.

This study develops an operational method to guide LCA practitioners to prioritize regional data collection to reduce the overall uncertainty in LCA impact scores. It is based on uncertainty contribution analysis, which aims to identify impact categories, unit processes and EFs that need further regional data collection. Among other things, it allows practitioners to prioritize effort between LCI regionalization (if LCI uncertainty dominates) or LCI spatialization (if LCIA uncertainty dominates). Its relevance and applicability is illustrated by a case study with the ecoinvent v3 database and the IMPACT World+ LCIA methodology.

Prioritize data collection in a regionalization context

The method developed is designed to help LCA practitioners prioritize regional data collection. Its four steps are iterative (Figure 1).

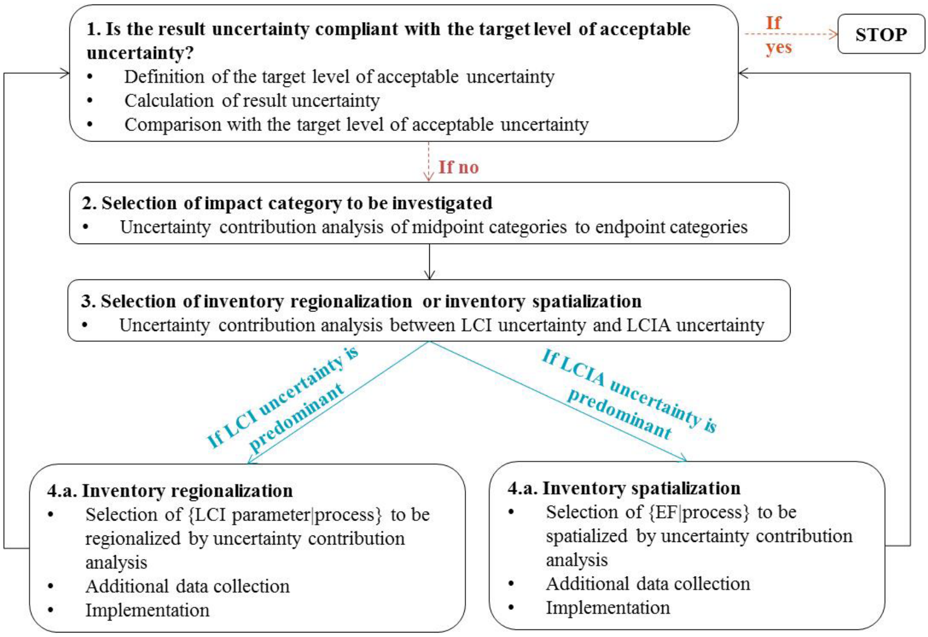

Figure 1. Decision tree for LCA practitioners to prioritize data collection for regionalization purposes

The first step consists of deciding whether the uncertainty in results of the study are acceptable, to determine if additional data collection is needed. First, the decision maker who will use the results should define the level of acceptable uncertainty, i.e. the level at which there is enough confidence in the LCA results to make a decision. For comparison purposes, the target level of acceptable uncertainty could be the probability that environmental impacts of product system A differ from those of product system B. The target level of acceptable uncertainty could also be set for a specific product system by specifying the maximum value of a statistic measuring the dispersion of LCA results, such as the standard deviation or the coefficient of variation (CV). Next, the uncertainty in the results should be estimated for the preliminary LCA model, built with available data. This uncertainty assessment should include uncertainty inputs from the LCI data and from the LCIA. The actual level of uncertainty is then compared to the target level of acceptable uncertainty to determine whether additional data need to be collected or not.

The second step is to select the impact categories to investigate first. If the purpose is to reduce uncertainty, impact categories that contribute most to the overall uncertainty should be selected. To do so, uncertainty contribution analysis is performed for each endpoint category to identify the contribution of midpoint impact categories.

The impact categories selected have two sources of uncertainty: the LCI and the LCIA (i.e. uncertainty from the CFs). The actions LCA practitioners can take to reduce the uncertainty due to spatial variability depend on the source(s) of uncertainty. To reduce LCI uncertainty, additional data should be collected to regionalize the LCI. To reduce LCIA uncertainty, additional data should be collected to spatialize the EFs to use more regionalized CFs. Therefore, the main source (LCI or LCIA uncertainty) should be determined in the third step, with uncertainty contribution analysis helping LCA practitioners take appropriate actions to reduce the uncertainty.

Depending on the result of the third step, LCA practitioners regionalize or spatialize the LCI. In both cases, they need to select the {LCI parameter|process} pair to be regionalized or the {EF|process} pair to be spatialized first by performing an uncertainty contribution analysis. After collecting additional data and including it, LCA practitioners should iterate the steps to check whether the target level of uncertainty has been reached. If not, they can repeat the procedure.

This method aims to identify the sources of uncertainty that contribute most to the overall uncertainty of LCA results and that need further data collection. Global sensitivity analysis (GSA) tools serve this purpose. However, some GSA tools such as variance-based methods (e.g. Sobol indices) require much computational time when dealing with many uncertain parameters, such as in LCA product systems (Wei et al., 2015). Therefore, the GSA tools used here were selected based on a trade-off between accuracy and application in an operational context by LCA practitioners. For uncertainty contribution analysis, Monte Carlo simulations are used to calculate the Contribution To Variance (CTV) based on Spearman rank correlation between impact scores and each contributor at different levels of the LCA model (midpoint contribution to endpoint, process contribution, EF contribution) (Mutel et al., 2013). To analyze the relative contributions of LCI and LCIA to overall uncertainty, uncertainty metrics such as CVs are compared, as in our case study. Once the most sensitive processes are identified (if the LCI dominates), they can be investigated in more depth to identify their most influential uncertain parameters (e.g. quantity of economic flows and EFs) using GSA tools such as elementary effects combined with regression techniques (Saltelli and Annoni, 2010).

Application to a simplified case study

The method developed was applied to an ecoinvent v3.2 process (soybean production in the USA) to identify where regional data collection should be strengthened for this product system (Weidema B P et al., 2012). The IMPACT World+ LCIA method was selected since it provides regionalized CFs for certain impact categories, along with their associated spatial variability (Bulle et al., 2017). Therefore, uncertainty could be assessed by including uncertainty sources from both the LCI and the LCIA. Uncertainty sources from the LCI were quantified using the distributions provided by ecoinvent v3.2 (Ciroth et al., 2013).

For this example, we focused on the endpoint category "impact on human health", whose only contributing impact category for which spatial variability was available is "water use impacts on human health". Therefore, we focused analysis on this impact category (Boulay et al., 2011).

First, the target level of acceptable uncertainty was defined. Using the CV as the metric, we chose the arbitrary value of 0.12 as the target. Next, the CV of the existing product system was calculated using Monte Carlo simulation that included all uncertainty sources. CFs were aggregated at the global level. The CV of impact on human health (0.33) was higher than the target, indicating that additional regional data collection was needed.

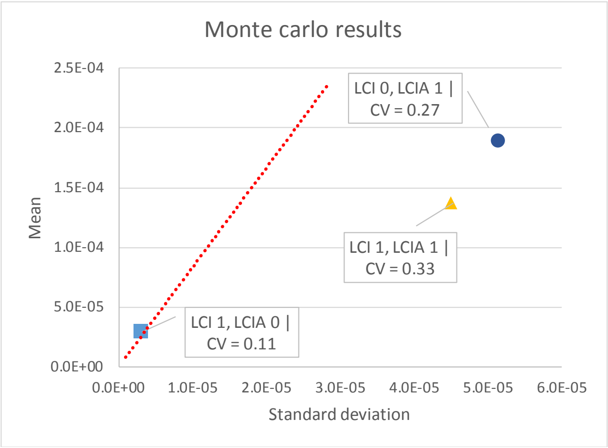

Figure 2. Monte Carlo results (mean and standard deviation) for the score of impact on human health (in DALY) with LCI uncertainty sources only (square), LCIA uncertainty sources only (circle) and both uncertainty sources (triangle). The dotted line represents the target of acceptable uncertainty (i.e. coefficient of variation (CV) = 0.12).

Next, the relative contributions of LCI and LCIA uncertainties (CVs) to overall uncertainty were compared by examining LCI and LCIA uncertainty separately. The CV of uncertain LCI parameters alone was 0.11, while that of uncertain LCIA parameters alone was 0.27 (Figure 2). Therefore, data collection efforts should focus on spatializing water EFs to be able to use less aggregated CFs, e.g. country-level CFs, which have lower spatial variability.

The {EF|process} pair in most need of spatialization was identified from its CTV of the resulting impact score. The pair was then spatialized by using the geographical location of the process defined by ecoinvent (country or continent). The corresponding CF was then used to calculate a new impact score. This process was iterated until the CV of the impact score reached the target level of uncertainty. Five iterations were necessary, reducing uncertainty in the overall impact score by 88% by spatializing less than 1% of the EFs (Figure 3).

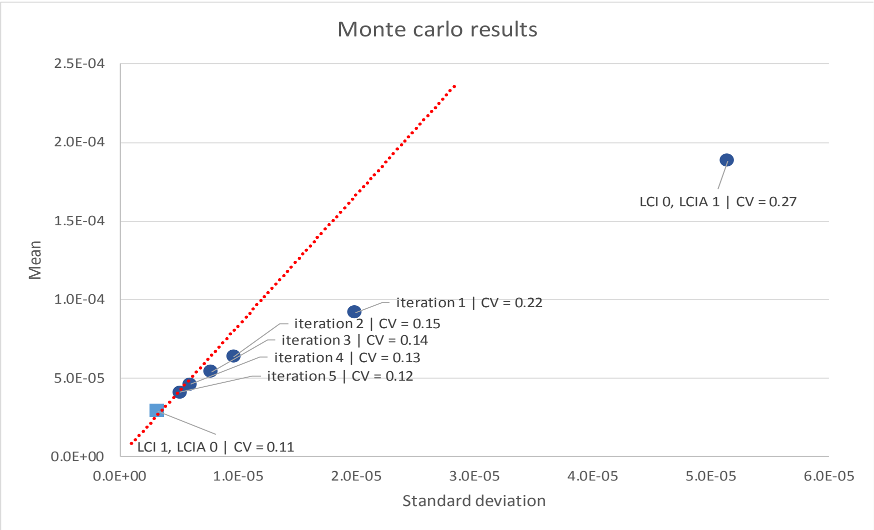

Figure 3. Change in Monte Carlo results (mean and standard deviation) for the score of impact on human health (in DALY) after each iteration of data collection. The dotted line represents the target of acceptable uncertainty (i.e. coefficient of variation (CV) = 0.12).

We compared this method of prioritization based on uncertainty contribution analysis to the common method, impact contribution analysis. First, the ranking of {EF|process} pairs by contribution differed by method: the greatest contributor to uncertainty was not the greatest contributor to impact. The uncertainty in impact decreased by 70% after 2 iterations when using uncertainty contribution but by only about 20% when using impact contribution. Consequently, using uncertainty contribution reduced uncertainty more effectively in this case study. Both methods of prioritization reduced uncertainty in impact by the same amount after 4 iterations.

Discussion

The overall procedure is based on uncertainty analysis. Therefore, the way that uncertain inputs are defined can influence the results. Distributions used in the LCI are those set by ecoinvent, determined with the pedigree matrix (Muller et al., 2014). They reflect uncertainty in the representativeness of quantitative data. For the LCIA, we accounted for uncertainty in the spatial variability of aggregated CFs as calculated by IMPACT World+. In the case study, variability in CFs was represented by a triangular distribution, with the minimum and maximum equal to those observed among the native CFs in the aggregated region, and the mode equal to the mean CF weighted as a function of the quantity of EFs in each native region. Other distributions, however, such as a generalized beta distribution, could have been chosen. The influence of the chosen distribution on the results should be investigated.

In the case study, the CV was chosen as the metric of uncertainty. Its main advantage is that it is dimensionless and easy to calculate. Its use is limited, however, when the mean tends to zero and when impact scores can be positive and negative (as for water use). In addition, the CV is not a robust indicator since it is sensitive to outliers. Consequently, other metrics to measure uncertainty need to be tested, in particular those based on percentiles, which are more robust.

Results of the case study show that ranking by uncertainty contribution decreases uncertainty in impacts faster than ranking by impact contribution. This should be investigated for an entire LCI database, however, to confirm that prioritization based on uncertainty contribution analysis is needed.

The procedure to determine the target of acceptable uncertainty still needs to be investigated. Indeed, efforts to decrease uncertainty will depend on factors such as the study goal, product system assessed, time and financial means for the study, knowledge of LCA practitioners, and data availability (Herrmann et al., 2014). In addition, some uncertainties are difficult or nearly impossible to decrease (Weidema and Wesnæs, 1996). Thus, the target of acceptable uncertainty should be realistic. Further developments are needed to help set the target of acceptable uncertainty and quantifying the effort required to reach it. In the meantime, the target of acceptable uncertainty can at least be estimated qualitatively. In the early stages of an LCA study, LCA practitioners and decision makers should clearly identify the study's intended audience and data-quality requirements. LCA practitioners should remain transparent about study limitations, especially of regionalization issues. It implies that practitioners should be aware of regionalization issues.

Conclusion

This study allows LCA practitioners to prioritize efforts to improve the robustness of LCA results by identifying which data have the highest potential to reduce the overall uncertainty in an LCA result. Furthermore, opportunities for improvement are identified at both the LCI and LCIA level, and LCA practitioners may decide to invest effort in inventory regionalization or inventory spatialization, which cannot be done with traditional impact contribution analysis. In addition, the method also integrates decision-maker requirements by determining an acceptable level of uncertainty that matches the study's data-quality requirements. This method is described for regionalization purposes but could be further adapted to prioritize overall data collection.

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How to spatialize the inventory?

Coupling LCA and GIS for environmental assessment of buildings at the urban scale

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Introduction

Cities increasingly assume a key role in carbon mitigation since the rate of urbanization is growing worldwide, reaching 78% in more developed countries (United Nations, 2012). Local authorities have the opportunity to develop policies to make cities more sustainable; however, they need quantitative data to assess effects of policies on the environmental performance of urban systems. While a number of studies focused on estimating the operational energy linked to urban energy systems (Kavgic et al., 2010; Swan and Ugursal, 2009), an extension to life-cycle based approaches is recommended for more holistic evaluation of environmental impacts.

Life Cycle Assessment (LCA) is a widely accepted methodology to assess environmental impacts of products and services (International Organization for Standardization, 2006). Recent developments have upscaled LCA for environmental assessment of neighborhoods, cities and territories for policy support (Loiseau et al., 2014; Lotteau et al., 2015). Nevertheless, the complexity of such systems requires operational developments to adapt LCA to large scales.

Coupling LCA and Geographical Information Systems (GIS) was recently recommended to consider spatial aspects explicitly in multiple stages of LCA for different sectors (Geyer et al., 2010). Such coupling is highly relevant to the study of urban systems; however, only a few applications are currently available for the environmental assessment of buildings at the urban scale to support sustainable urban planning (Saner et al., 2013; Reyna and Chester, 2014; Mastrucci et al., 2017;). Application to urban buildings is particularly important since buildings represent 36% of greenhouse gas emissions in Europe (European Parliament, 2010) and offer potential for carbon mitigation by retrofitting. The integration of LCA and GIS is promising for the refinement and spatialization of the Life

Cycle Inventory (LCI); however, hurdles still exist due to the lack of commonly accepted methods.

This study aims to develop a method for coupling LCA and GIS in the environmental assessment of buildings at the urban scale. After describing the generic method for spatializing the LCI, a case study evaluating house retrofitting in Rotterdam (Netherlands) is presented. Results are discussed to highlight advantages and disadvantages of the spatially explicit method and the potential to support decision making in sustainable urban planning.

Methodology

The method consists of the following steps (Figure 1):

- Characterize the buildings. Spatial input data are processed by GIS to generate the foreground LCI. Geometric and construction characteristics, as well as energy profiles, are estimated for each building in the case study.
- Perform LCA. Environmental impacts related to their retrofitting and end-of-life are calculated per dimensional unit (e.g. m^2 of building area, building envelope). For the use phase, energy-related impacts are calculated per unit of energy.
- Extrapolate the results. LCA-GIS coupling is necessary to associate calculated impacts with real buildings across the city and aggregate the results. A connector (soft coupling) is developed for this goal.

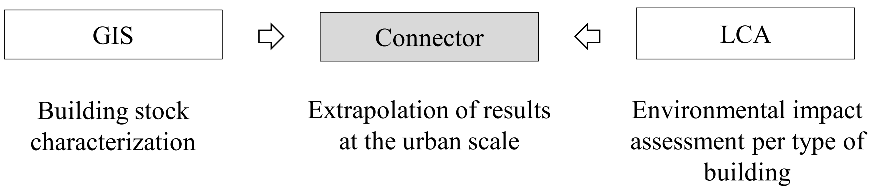

Figure 1. Coupling LCA and GIS for environmental assessment of urban buildings

Case study

Residential buildings of Rotterdam (Netherlands) were used as a case study. The city has approximately 600,000 inhabitants and 290,000 residential buildings. The city provided a detailed GIS database for buildings that contained the following data:

- Digital elevation model obtained from LiDAR, a remote sensing technology using laser beams to acquire data and survey topography. This raster layer contains elevation data at a spatial resolution of 50 cm × 50 cm.
- Vector footprint of buildings (polygons). The layer contains attributes such as the year of construction and the function of each building.

- Vector layer of addresses (points). The layer contains attributes such as the floor area and the number of inhabitants in each house.
- Vector layer of neighborhoods (polygons).

Previous studies conducted to characterize the city's residential buildings and energy consumption served as the basis for this study (Mastrucci et al., 2014). The residential park was characterized on the basis of housing typologies (e.g. single-family houses, apartments) and periods of construction. This approach makes it possible to group buildings with similar characteristics and describe them appropriately.

We used the free software tools GRASS-GIS and QGIS for GIS analysis and processing, the proprietary software SimaPro 7.3.3 for LCA calculations and the free software R for the development of the connector. The software R was chosen for its ability to import, process and export spatialized data.

Building characterization

The available GIS dataset was processed to generate new inventory data using GRASS GIS and QGIS software, including building height, volume, floor area, and external wall area.

Mean height of the buildings was generated by intersecting the elevation raster layer and the building footprint vector layer. Building volume was estimated as the footprint area times the mean height of the buildings. Residential floor area of buildings was available from the address point file provided by the municipality and then aggregated to the scale of buildings (Figure 2).

Specific algorithms were developed to process building footprint data and distinguish the portion of the perimeter facing outside from that in common between two buildings. The area of the outer walls was then estimated by multiplying the length of the outer perimeter by the mean height. Similar algorithms were used to estimate building type (detached, semi-detached or row-house) by calculating the number of buildings (i.e. polygons) adjacent to each building (Figure 3).

Housing types (e.g. detached, row-house, multi-family) were subsequently obtained based on building function and number of units in the building.

The GIS dataset was supplemented with information about typical construction and technological characteristics of residential buildings in the Netherlands, per type and period of construction (Agentschap NL - Ministerie van Economische Zaken, 2011).

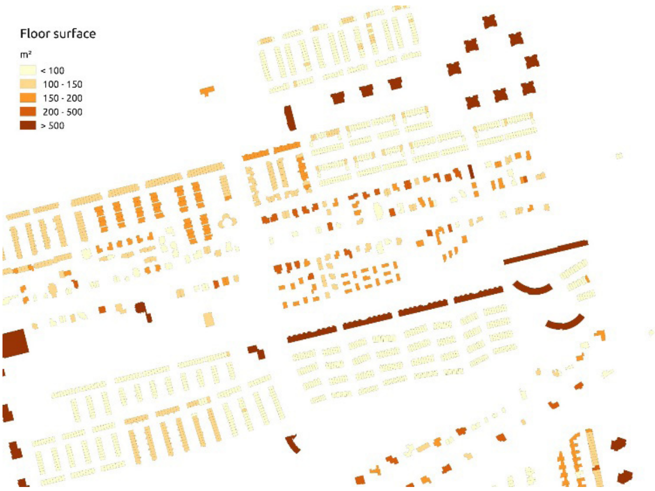

Figure 2. Map of floor area of buildings in Rotterdam

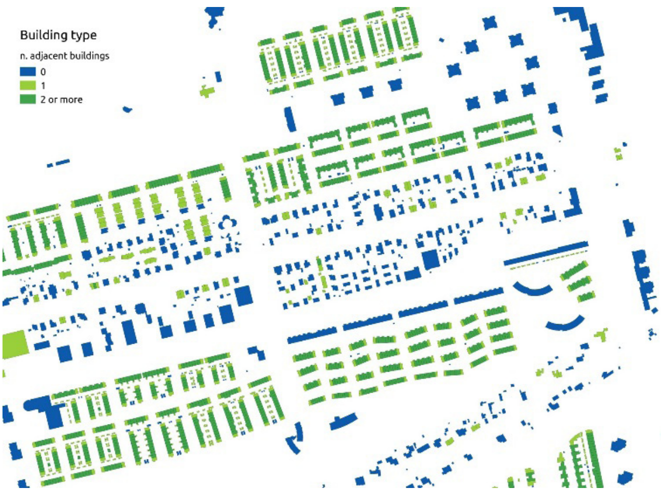

Figure 3. Map of building types for Rotterdam based on adjacency: isolated buildings, one wall in common with another building, walls in common with two or more buildings.

Life Cycle Assessment

We considered the use and retrofitting life-cycle phases of buildings. The ecoinvent database v2.2 was used for the background inventory.

For the use phase, energy consumption for heating and hot water and electricity consumption were allocated on the basis of the results of a previously developed statistical model (Mastrucci et al., 2014). The energy for heating and domestic hot water was determined at the building level according to floor area, the type of house and the period of construction; electricity use was calculated based on floor area, the number of occupants and the type of house.

A set of components and systems representative of each combination of housing typology and period of construction was identified, and impacts related to the retrofitting phase were estimated. The operations considered for building retrofitting were insulation of external walls, the roof and ground floor; replacement of windows; and replacement of the heating system.

Construction characteristics of building components and retrofitting operations were obtained from national reports and standards. Material production and transport were included in the Life Cycle Impact Assessment (LCIA).

LCIA was performed using the CML 2-baseline 2000 method, and results were reported for the Global Warming Potential (GWP) impact category. For the use phase, impacts were calculated per m^2 of floor area. For the retrofitting phase, impacts related to building envelope measurements were calculated per dimensional unit (i.e. m^2 of wall insulated or window replaced).

Extrapolation of results

Real buildings across the city and their impacts were associated automatically using the geometry estimated by the GIS, the typology and the period of construction through the connector developed in R. LCIA results were exported from SimaPro as tables and subsequently imported into R. The GIS layer for buildings was also imported into R after GIS processing. Correspondence between the LCIA results and individual buildings in the city was established based on the typology and period of construction. Total impacts were then calculated for each building by multiplying the unit impact by the respective dimension. For example, the impact of retrofitting external walls was calculated by multiplying the impact per m^2 of wall by the total area of external walls of each building obtained from GIS. A residual lifespan as a function of housing type and construction period was taken into account and used to normalize results on a yearly basis. Finally, the results generated for each building were introduced as attributes in the building layer and directly exported to GIS (e.g. as a shapefile).

The GWP of buildings in Rotterdam was calculated in two scenarios: without or with retrofitting of buildings. The use of natural gas for heating and domestic hot water as well as the retrofitting phase (only for the second scenario) were taken into account to generate the results.

Results

The GWP of buildings without retrofitting (Figure 4) was significantly higher than that with retrofitting (Figure 5).

Figure 4. Map of Global Warming Potential (GWP) sources at the building level without retrofitting in Rotterdam

Figure 5. Map of Global Warming Potential (GWP) sources at the building level with retrofitting in Rotterdam

GIS can be also used to aggregate the results, e.g. at the neighborhood level, and to show the results for the entire city (Figure 6). This type of representation can be useful for communicating results and supporting decisions for sustainable urban planning.

Figure 6. Map of Global Warming Potential (GWP) associated with residential buildings at the neighborhood level for Rotterdam

Discussion

Coupling LCA and GIS to spatialize the LCI offers advantages compared to traditional LCA. First, GIS datasets represent an opportunity to enrich and refine the LCI for buildings at the urban scale. For example, building geometry, such as building footprint polygons, can be obtained directly from GIS processing of vector data.

Georeferencing building-related data further makes it possible to include the spatial dimension in the LCI explicitly. Once the position of the building is defined, spatial and local constraints can be identified easily. For example, old buildings in the historic center can be distinguished from the others, and limitations to conservation and permitted interventions can be explicitly included in future scenario development. Similarly, constraints of existing infrastructure and networks can be included. Transportation distances of construction and demolition materials can also be calculated using GIS, once the potential origin and destination sites are identified. Finally, GIS allows visualizing LCI data and results (e.g. sources of impact) as maps for hotspot identification and enhanced communication with stakeholders and decision makers.

Current limitations to the spatialization of LCIs include a lack of consensus on how to implement LCA-GIS coupling and the need for methodological developments (Geyer et al., 2010). Only a few of the currently available LCA software tools are suitable for GIS data import and use, further limiting the ability of practitioners to spatialize LCIs. In addition, the quality and format of GIS data might depend strongly on the data provider and potentially hamper the applicability of generic methods for treating the data. Using GIS requires more skills and potentially more work than non-spatialized analyses.

Nevertheless, the increased availability of GIS data may encourage using them for the LCA of buildings. The 3D CityGML standard for three-dimensional semantic urban models is particularly promising for LCA applications to provide enriched data on buildings and infrastructure. This standard has already been used to estimate energy demand of buildings (Nouvel et al., 2017), but LCA applications are currently lacking. Recent developments in free LCA software (e.g. OpenLCA) focused on introducing import and treatment functions for GIS data may also facilitate spatialization of LCI and accessibility to a wider audience.

Conclusion

This study presented a method for coupling LCA and GIS to assess environmental impacts of buildings at the urban scale. Application to the case study of Rotterdam showed that GIS can be successfully used to generate spatialized LCI and evaluate the carbon mitigation potential of retrofitting actions.

Advantages of coupling GIS lie in the refinement and spatialization of the LCI, leading to more accurate and spatially differentiated results. The location of impact sources and visualization of impacts as a map are also possible. The limitations of GIS and LCA coupling identified are the availability of accurate and complete datasets, the validation of GIS analysis results and the knowledge of GIS required for data processing and visualization.

Future research on LCA-GIS coupling is encouraged to overcome current operational barriers and develop simplified tools for improved interaction with stakeholders and decision support in sustainable urban planning.

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How to spatialize impact assessment?

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Introduction

One of the main research topics in Life Cycle Assessment (LCA) is the development of models to quantify potential environmental impacts, also called "impact characterization". This profusion of studies is due mainly to the shortage of consensus on how to quantify potential impacts, especially local (toxicity, biodiversity) and regional ones (acidification, eutrophication). Among these impacts, eutrophication is one of the most studied impacts in the scientific literature: a search for publications with the keyword "eutrophication" from 1991-2010 identified an increase in the number of such publications in the past 20 years, with a number four times as high in 2008, 2009 and 2010 as in 1991 (Yi and Jie 2011). The two topics for which this keyword is most often associated are the European Union Water Framework Directive and LCA, which are therefore the two identifiable mainstream research topics relating to eutrophication since the early 2000s. In current LCA practice, eutrophication is one of the impacts requiring the most spatial differentiation for quantification since its occurrence and intensity depend strongly on characteristics of the impacted environment (Finnveden and Potting 1999). Many models exist, but they still do not meet the challenge of relevant and achievable spatial differentiation for LCA practitioners. This article analyzes the literature on models quantifying eutrophication in LCA to assess spatial differentiation of this impact category. Two new methods for spatializing eutrophication are briefly presented and then compared to determine their advantages and disadvantages.

Need for spatial differentiation of eutrophication

To understand the need for spatial differentiation of eutrophication in LCA, a literature review and an analysis of existing models were performed. To analyze models developed in the literature, this study described the substances considered, their receiving compartment, the type of eutrophication considered, the consideration of fate and effect factors, the spatial and temporal resolution required, the concept of a limiting factor, and consideration of uncertainties or sensitivities.

Calculation principle

In LCA, the equation for calculating an impact indicator is relatively simple, as described in ISO 14040 (ISO 2006a, b):

$I_i = m_i \cdot CF_i$

where Ii is the contribution of substance (i) to the impact, mi is the mass of substance (i) and CF_i is the characterization factor of substance (i).

Quantification of eutrophication is based on the CF, which can be defined as the eutrophication potential of a substance relative to a reference substance, which is usually phosphorus in freshwater systems and nitrogen in marine systems. This relationship is most commonly based on the Redfield ratio (Redfield *et al.* 1963).

The eutrophication CF can also be defined in a more complex and refined way to assess the eutrophication potential of a substance as finely as possible (Finnveden and Potting 1999). In this case, the CF can be written as the product of a fate factor (FF) and an effect factor (EF) (EC-JRC 2010):

$$CF_{i,m,r} = FF \cdot EF = f_{i,mr} \cdot \beta_{dose\text{-}response}$$

where $f_{i,m,r}$ is the FF (dimensionless $kg.kg^{-1}$) describing the transport of substance (i) in compartment (m) (air or water) and its transfer to a receiving compartment (r), and βdose-response is the EF expressing the response of an ecosystem to the change in nutrient concentration (unit impact.$kg^{-}_{1N\ ou\ P}$ released or dimensionless).

This latter approach is the most relevant because it aims to illustrate the cause-and-effect chain of an impact by using different models.

Model description

The models are described by focusing on the nitrogen and phosphorus emissions considered, the concept of a limiting element, the FFs and EFs, the spatial and temporal resolution and uncertainties.

Nitrogen and phosphorus flows and limiting elements

Some authors include both nitrogen and phosphorus emissions to freshwater and the air (Huijbregts and Seppala 2001, Norris 2003, Seppala *et al.* 2004, Gallego *et al.* 2010). Others authors focus only on atmospheric emissions such as $NH_{3\ a}$nd NOx (Huijbregts *et al.* 2001, Karrman and Jonsson 2001, Seppala *et al.* 2006, Posch *et al.* 2008, Roy *et al.* 2012). Some authors consider only phosphorus emissions to freshwater (Struijs *et al.* 2011, Helmes *et al.* 2012, Azevedo *et al.* 2013, Scherer and Pfister 2015). Finally, a few authors focus on nitrates (Basset-Mens *et al.* 2006) and the response of marine ecosystems to nitrogen supply (Cosme *et al.* 2015).

Some authors explicitly mention their position on the concept of limiting elements by conforming to the consensual position that nitrogen is considered limiting for marine eutrophication and phosphorus is considered limiting for freshwater eutrophication (Karrman and Jonsson 2001, Norris 2003, Seppala *et al.* 2004, Basset-Mens *et al.* 2006, Gallego *et al.* 2010, Struijs *et al.* 2011, Scherer and Pfister 2015). Most of them concede that this necessary simplification can sometimes be wrong (Finnveden and Potting 1999). Some authors explain the use of the Redfield ratio in their methods and also mention that the ratio may change by chemical species, even if it does not do so in their study (Karrman and Jonsson 2001, Norris 2003, Seppala *et al.* 2004, Gallego *et al.* 2010). Helmes *et al.* (2012) and Azevedo *et al.* (2013) implicitly use the limiting nature of phosphorus for freshwater eutrophication by studying exclusively this flow and its impact on freshwater.

Fate factor

"Fate" is used to quantify potential impact by considering transport, dispersion, degradation and deposition of the released substances. The aim of the FF is that impact assessment better represents reality by considering the resulting concentration of the released substance in different media. Most authors have developed or used agro-hydrological or atmospheric fate models: EMEP (Seppala *et al.* 2004, Seppala *et al.* 2006, Posch *et al.* 2008), CARMEN (Gallego *et al.* 2010, Struijs *et al.* 2011), RAINS-LCA (Huijbregts *et al.* 2001), GEOS-CHEM (Roy *et al.* 2012), ASTRAP (Norris 2003) and INCA (Basset-Mens *et al.* 2006).

Some grid models exist that predict phosphorus fate from freshwater to sea outlets (Helmes *et al.* 2012, Azevedo *et al.* 2013, Scherer and Pfister 2015). Before using this type of model in agricultural LCA, it is also possible to use inventory models to predict the amount of phosphorus lost after organic or mineral fertilizer spreading by coupling two models: USLE (Universal Soil Loss Equation) and SALCA-P (Swiss Agricultural Life Cycle Assessment) (Scherer and Pfister 2015).

Effect factor

The EF expresses the ecosystem response to the change in nutrient concentration. One concept comes up regularly in the literature: the critical load (Huijbregts *et al.* 2001, Seppala *et al.* 2006, Posch *et al.* 2008). Critical load is a simple description of ecosystem sensitivity at steady state and widely used in policies aiming to reduce nitrogen emissions. Critical load is sometimes associated with the concept of accumulated exceedance (AE), which represents the potential production of phytoplankton biomass per unit mass of released compound relative to phosphate (Huijbregts and Seppala 2001). AE and critical load are used only in the above approach (i.e. assuming a kind of threshold effect corresponding to environmental conditions).

Geographical scale

Since most articles study fate, they mention the geographical scale required and used. Most models used are grid models with different geographical scales.

The choice of the geographical scale depends entirely on data availability; consequently, the geographical scale chosen is often not as relevant as possible. These geographical scales correspond to the grid size of the model and are expressed in a variety of units or rely on objects:

- Degrees: 0.5° × 0.5° (1° = 111,319 km at the Equator) at the European scale (Azevedo *et al.* 2013), the world scale (Helmes *et al.* 2012) or at 0.5 arcminutes (Scherer and Pfister 2015)
- Area: 50 km² × 50 km² (Posch *et al.* 2008) and 150 km² × 150 km² (Huijbregts *et al.* 2001, Seppala *et al.* 2006) at the European scale
- Watersheds (Seppala *et al.* 2004, Basset-Mens *et al.* 2006)
- Business sectors (Seppala *et al.* 2004)
- European regions or countries (Huijbregts and Seppala 2001) or a specific region such as the coast of Galicia, Spain (Gallego *et al.* 2010)

The concept of "archetype" is evoked to improve the geographical scale, and the choice of archetype can be based on the cumulative distribution of EFs or FFs by using a proxy, such as population density (Helmes *et al.* 2012).

Uncertainty and variability

These models to quantify eutrophication using FFs and EFs have some uncertainties. Most authors are aware of this uncertainty and have developed uncertainty and sensitivity analyses of the models developed. These analyses have a variety of subjects, but many of them focus on the spatial issue:

- Spatial variability: FFs and EFs (Azevedo *et al.* 2013), latitude (Cosme *et al.* 2015), geographical scale (Roy *et al.* 2012), CFs (Scherer and Pfister 2015) and primary production (Cosme *et al.* 2015)
- Environmental characteristics: meteorological data (Almroth and Skogen 2010), soil erosion and background phosphorus concentration (Scherer and Pfister 2015), volume of freshwater reservoir (Helmes *et al.* 2012)
- Emissions: dependence on atmospheric emissions (NO_2, NH_3) to identify the sensitivity of CFs to small decreases in emission (Seppala *et al.* 2006) and the deposition rate (Gallego *et al.* 2010)
- Model variability: change of the fate model used (Roy *et al.* 2012)

Results

This overview of methodological developments for assessing eutrophication has highlighted the use of FFs and EFs. These developments, however, are not yet consensual or stabilized; different models and approaches coexist. As often in LCA, applying these developments and adapting them to case studies will improve FFs at the appropriate scale (the watershed) and EFs based on the critical load. The final challenge is to achieve refined and relevant spatialization of FFs and EFs.

One shortcoming identified is thus small-scale spatialization of environmental sensitivity to eutrophication, which could be considered as EFs. Environmental sensitivity could be assessed according to two new methods: *ex-ante* and *ex-post*. The *ex-ante* method aims to understand environmental sensitivity by considering characteristics known to favor eutrophication. The *ex-post* method aims to understand environmental sensitivity by identifying the frequency of eutrophication in the past in the environment studied. These two methods have the same main objective but significant differences. LCA practitioners can apply either method according to their objectives and means.

PRESENTATION AND COMPARISON OF TWO NEW METHODS TO ESTIMATE SPATIALLY DISTRIBUTED EUTROPHICATION

In our opinion, the two main issues for spatially distributed eutrophication assessment are:

- spatial variability in FFs
- differentiating the sensitivity of surrounding environments (e.g., different regions) when assessing alternative systems

To reach this goal, we developed a simple approach of spatial differentiation to estimate eutrophication impact by introducing a sensitivity factor (SF), which is a corrective coefficient of the CF that integrates spatial differentiation. To build this SF, ranking the processes and parameters involved in eutrophication is not relevant, because the combination of an increase in nutrient concentration and required environmental conditions is necessary to observe eutrophication (Le Gall 2012), even though some mechanistic methods do exist (Cosme *et al.* 2015).

Therefore, two methods were developed to define SFs of the surrounding environment to eutrophication: *ex-ante* and *ex-post*. The *ex-ante* method needs a set of regional parameters (e.g. water flow, topography) that may contribute to the future occurrence of eutrophication. It aims to predict eutrophication by considering biophysical parameters that influence future eutrophication. In contrast, the *ex-post* method needs only one parameter representing the current occurrence of eutrophication. It aims to predict eutrophication by using a key parameter: evidence of current eutrophication. The main assumption is that currently observed eutrophication implies a sensitive environment and thus the potential for future eutrophication, all else being equal. The fundamental difference between the methods is the level of accuracy expected of spatialized eutrophication assessment. Depending on the goal of the LCA and the nature of the system studied, the degree of accuracy needed for estimates of eutrophication impact will differ; thus, LCA practitioners can choose whether to use the *ex-ante* or *ex-post* method. The next section describes both methods and presents a virtual case study for each.

Presentation of the *ex-ante* and *ex-post* methods

Ex-ante method

In the *ex-ante* method (Nitschelm, 2016), a CF is calculated for each compound responsible for freshwater and marine eutrophication using both the fate of the compound and the sensitivity of the surroundings (both determined using biophysical parameters such as slope, soil type and climate):

$$CF_{i,d} = EP_i \times FF_i \times SF_d$$

where CFi,d is the CF of compound *i* in environmental compartment *d* (e.g., lake, river, bay), EPi is the eutrophication potential according to the CML-IA method of compound *i* (EP_{NO3-} = 0.10 and $EPP_{O4}{}^{3}$- = 3.06), FFi is the FF of compound i and SFd is the SF of environmental compartment *d* to the eutrophication impact. EP can be understood as an EF.

This method has many advantages. Compound fate and sensitivity of the surroundings are considered when calculating the CF. It can be used for small (100 km²) to larger (10,000 km²) territories. Fate and sensitivity are differentiated at the watershed scale. Field data are not required since spatial data necessary for determining fate and sensitivity can be collected from national or European databases, from the regional to the European scale (e.g., TOPO and LITTO databases from the French National Geographic Institute (IGN)).

Ex-post method

Although it is difficult to predict local eutrophication, its symptoms can be monitored (Caspers, 1984; Kitsiou and Karydis, 2011). Eutrophication is currently monitored by measuring photosynthetic pigment concentration in waterbodies and other parameters such as pH or oxygen concentration. These types of monitoring data exist and can be used to build a simple method to predict spatially distributed eutrophication potential in LCA. Sensitivity to eutrophication can be defined as the propensity for eutrophication to occur in a specific region due to a given emission.

Unlike the *ex-ante* method, the *ex-post* method calculates CFs by considering only SFs:

$$CF_{i,d} = EP_i . SF_d$$

To respect the limiting-element concept of eutrophication, the spatialized CFs for nitrogen flows equal 0 for freshwater eutrophication and those for phosphorus flows equal 0 for marine eutrophication. The difference with the *ex-ante* method results from how the SFs are calculated. In the *ex-post* method, only one key parameter is used: photosynthetic pigment (chlorophyll *a*) and pheopigment concentration concentration in freshwater and marine water.

The EPi for both methods comes from the CML-IA characterization method (Guinée et al., 2002) because of its simplicity and ability to ensure that regional and local conditions are not considered in a redundant manner.

Comparison of the two methods

The two methods are compared to help LCA practitioners who wish to estimate spatialized eutrophication at a small scale to choose between them (Table 1).

Table 1. Comparison of the *ex-ante* and *ex-post* methods to predict spatially distributed eutrophication

Characteristic	*Ex-ante* method	*Ex-post* method
Differentiates between marine and freshwater	Yes	Yes
Limiting nutrient	N: marine P: freshwater	N: marine P: freshwater
Native spatial scale	Watershed	Hydrographic sub-sector
Spatial scale available in LCA software	Watershed	Hydrographic sector
Type of input data	Pollutant quantities, morphology/ hydrology	Pigment concentration
Amount of data necessary (per watershed or hydrographic sector)	Fate factors: Nitrogen and phosphorus surplus in soil Mean NO3 concentration in water Base Flow Index* Daily precipitation Wetlands Water bodies River network Sensitivity factors: DTM resolution 100×100 m BDTOPO© database resolution (1:10,000)	Sensitivity factors: Monthly concentration of chlorophyll a and pheopigments over 10 years
Explicit fate factor	For NO3 and phosphorus compounds	No
Sensitivity factor for freshwater and marine	Yes	Yes
Model use	Nutting-N and -P for fate (Dupas et al., 2015)	No
GIS use	For the sensitivity factor	

* The BFI can be considered a measure of the proportion of river runoff that derives from stored sources; the more permeable the rock, shallow deposits and soils in a watershed, the higher the baseflow and the more sustained the river's flow during periods of dry weather. Thus, the BFI is an effective means of indexing watershed geology. For example, rivers draining impervious clay watersheds (with minimal lake or reservoir storage) typically have baseflow indices of 0.15-0.35, while most chalk streams have a BFI > 0.9 due to the high groundwater component in river discharge.

Characteristics common to both methods:

- SFs are defined, and GIS is used to do so
- Freshwater and marine water eutrophication are distinguished

Differences between the methods:

- Fate factors: the *ex-ante* method explicitly includes FFs (i.e. fate will change depending on the pollutant). The *ex-post* method does not define FFs, but they are implicitly included by considering chlorophyll *a* and pheopigment concentrations, which results from FFs and EFs. The *ex-ante* method appears more relevant for prospective assessment (at least for the FFs).
- Geographical scale: the *ex-ante* method is developed at the watershed scale, while the *ex-post* method is developed at the hydrographical sector scale

- Input data: the *ex-ante* method is based mostly on morphological and hydrological data, while the *ex-post* method is based on historical data of chlorophyll *a* and pheopigment concentrations
- Model use: the *ex-ante* method must use models to calculate FFs

Drawbacks of the *ex-ante* method:

- Requires more data than the *ex-post* method, which needs only chlorophyll *a* and pheopigment concentrations
- Requires more time to implement
- Uses a model with more uncertainties

Drawbacks of the *ex-post* method:

- Lacks an explicit FF (only implicit)
- Needs to be updated every 5 years or so, because chlorophyll *a* and pheopigment concentrations change over time. (In contrast, the *ex-ante* method does not need to be updated, since it is based on morphological and hydrological data, which can be assumed to remain constant over time.)

Recommendations:

- The *ex-post* method can be implemented easily for the whole of France. We therefore recommend this method for LCA practitioners who want to add spatial differentiation to their LCA results.
- The *ex-ante* method is more difficult to implement but may be useful for prospective scenarios in a region/territory since FFs are calculated (e.g., different pollutant concentrations will result in different CFs for each scenario).

Conclusion

Eutrophication corresponds to an unusual increase in the biomass produced in an aquatic ecosystem. This increase is due to the combination of biological, physical and chemical processes that interact with each other and the surrounding environment. To assess eutrophication potential in a relevant manner using LCA, the assessment must be spatialized. The literature contains many developments highlighting the needs and issues of spatialization. The fate of eutrophying substances and environmental sensitivity appear as the two main spatialization issues for eutrophication assessment. The question that remains is what is the relevant geographical scale for this assessment?

To resolve the lack of spatial variability in eutrophication impact assessment at local and regional scales simply, two new methods were developed. Using both, we assessed spatialized eutrophication with spatialized FFs for the *ex-ante* method and spatialized SFs for the *ex-ante* and *ex-post* methods.

The *ex-ante* method considers environmental characteristics to estimate FFs and SFs for freshwater and marine eutrophication potentials at the watershed scale. Indeed, FFs are calculated for nutrient pollutants, while SFs characterize water systems. The *ex-post* method is a retrospective and monitoring-based method to determine local sensitivity to eutrophication by using photosynthetic pigment and pheopigment concentration data.

Each method can be used differently. The *ex-ante* method produces local FFs and SFs to mitigate local eutrophication. The *ex-post* method produces regional (at the hydrographic sector scale) SFs to mitigate regional eutrophication. The method to use depends on the spatial accuracy needed by LCA practitioners. The two methods will be compared in a future study.

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Conclusion of Part I

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When is it relevant to spatialize LCIA indicators?

All of the presentations in this session showed that spatializing LCA requires a huge amount of additional data and model development. From a practical viewpoint, why would it be worth spending this extra time? From a scientific viewpoint, as explained in the introduction of this session, tremendous research efforts have focused on extrapolating local toxicological risk-assessment models to global LCIA ones. So why return to localized approaches?

Concerning the practice of LCA, the presentations in this session show that all studies must make a decision about location. In the first example, concerning buildings, Mastrucci *et al.* mapped climate change indicators at the scale of individual buildings in an urban neighborhood. Greenhouse gas (GHG) inventories were predicted from building characteristics, which were then used to calculate climate change indicators (using non-spatialized characterization factors). Their results provide useful information about future city planning, especially for setting priorities for retrofitting buildings.

Spatialization is thus relevant mainly when decisions based on the LCA study include choices about location.

Concerning scientific justification, it is obvious that an identical amount of a substance is likely to provoke different magnitudes of the same impact when emitted at different locations and/or times. This relies upon two main rationales:

- First, as explained in the introduction to this session, if the Earth is modeled using meshed adjacent boxes (Figure 3a in the introduction), each box has characteristics particular to its compartment and sub-compartments. Thus, there is no particular reason that the chemical fate of a substance would be the same for all boxes.
- Second, in a given geographical area of the Earth, the magnitude of an environmental impact can vary according to the sensitivity of the area to the impact category. This is due, for example, to the capacity of the environment to react to, adapt to and resist environmental burdens.

Providing spatialized values of LCIA indicators may thus better reflect actual environmental impacts.

Does spatialization always concern both inventory data and characterization factors?

In the first example, Mastrucci *et al.* spatialized GHG inventories of individual buildings in Rotterdam. The city map shows the climate change indicator calculated for each building. In this example, characterization factors for climate change indicators are not spatialized. The fact that climate change does not depend on the location of GHG emission (Figure 1 in the introduction) justifies keeping a global indicator.

Table 1. Archetypes of impacted areas by emission compartment and sub-compartment (Ventura, 2011)

Emission compartment	Type of emission location	Physical unit for considering the impacted zone	Order of magnitude of the impacted zone (depends on the time horizon)
Air	Other	Area	1 km^2
	Stack		10-1,000 km^2
Water	Rainwater		10-1,000 km^2
	Still water		m^2 to km^2
	Watercourses	Downstream length	1-100 km
	Ocean	Area	1-100 km^2
Soil (point source)	Permeable	Depth	m
	Impermeable	Area	m^2
Soil (non-point source)	Permeable Depth per unit area		m^3
	Impermeable	Area	m^2

In the second example, Aissani and Nitschelm provide both spatialized inventory data and characterization factors for eutrophication. In this case, spatialization throughout the causal chain of environmental impact is justified since eutrophication depends on local conditions concerning both emissions and impacts (Figure 1 in the introduction). They compare results of two methods for estimating characterization factors. The first method, called *ex-ante*, is based on local chemical fate and effect factors based on biophysical parameters (e.g. slope, soil type, climate). The second method, called *ex-post*, does not calculate fate factors, but introduces sensitivity factors of local media to eutrophication, based on local observations. Both methods assume that emissions and impacts are located in the same geographical area, the watershed. As presented in the introduction to this session, this assumption is not always valid, especially when substances are emitted to the air, where substances spread geographically largely due to transport by advection. This simplifying assumption could be the cause of the different results of the two methods. Freshwater eutrophication was provoked mainly by emissions to water. In this case, emission and impact were assumed to occur in the watershed. In contrast, emissions generated outside the studied geographical area may contribute to marine eutrophication inside the studied watershed.

From a more general perspective, spatialization can be limited to the inventory for global and long-term impacts, such as climate change or ozone layer depletion (Figure 1 in the introduction). For local/regional impacts, methods for spatializing characterization factors are expected to produce LCIA indicators more representative of actual impacts; however, further developments are still required. One key issue is how the spread of substances can be represented. This issue is particularly important for persistent substances (organic or metallic), which spread in the environment for long periods. Table 1 summarizes archetypes of impacted zones according to emission compartments described in previous literature (Ventura, 2011 .

Are spatialized indicators compatible with life cycle modeling?

Results of Mastrucci *et al.* combine two types of inventories: those associated with buildings (construction life-cycle step) and those associated with building heating (use life-cycle step). The two inventories do differ: GHG emissions from construction occurred in the past and in places besides Rotterdam, while GHG emissions from heating occurred in Rotterdam. Aggregation of the two inventories represents past and global contribution (construction life cycle step) combined with present and local contribution (use life cycle step) of each building to climate change. In other words, spatialization focuses only on the use phase of the building, taken as a foreground system, while the background system is not spatialized.

Indeed, the foreground system is defined as a collection of "processes which are under control of the decision maker for which a LCA is carried out" and the background system as a collection of "processes on which no or, at best, indirect influence may be exercised by the decision maker for which a LCA is carried out" (Frischknecht, 1998). For this case study, decisions related to urban planning and setting priorities for building retrofitting are due mainly to current heating energy consumption of buildings, because GHG emissions due to construction occurred in the past and cannot be changed. The effort thus focuses on spatializing GHG from heating energy. One could think that it may not be necessary to conduct an LCA at all. Indeed, techniques such as infrared photography can easily analyze thermal losses of a city for each building and set priorities for retrofitting to decrease heating energy consumption. However, LCA adds additional information: it can first estimate contributions to climate change that vary by the energy source used to heat buildings, and it can compare magnitudes of climate change impact of the two life cycle steps, construction and use.

The lack of detailed information about background processes does not allow spatialized indicators to be compared to global indicators. This is prejudicial to the life-cycle approach because contributions of foreground systems cannot be positioned within the complete life cycle. Furthermore, if they are not connected to the complete life cycle, are LCA results more relevant than local environmental risk assessments?

The examples presented in this session clearly highlight that indicators cannot be easily spatialized in complete life cycle systems. In their presentation, Patouillard *et al.* recommended focusing on particular processes or sub-systems in the product's life cycle for which the effort is worthwhile: those that contribute most to the uncertainty in results and whose uncertainties can be reduced considerably.

General perspectives

This interesting session showed that spatialized LCAs are possible; however, they face research challenges. The first challenge concerns the relationship between impacted areas and the emission compartment, especially for persistent substances. While existing models can predict the spread of these substances, it appears difficult to attribute a characterization factor to each area of spread. However, estimating the mass of substance that exits the area under study is possible. Environmental impacts of this mass should not be calculated with spatialized characterization factors but with global ones. This is possible and is related to the second challenge, detailed below. The purpose of LCIA is to provide environmental impact indicators of a product's life cycle, which means that emissions of substances can occur at different locations and different times, corresponding to different production processes and different life cycle steps. The second challenge of LCIA is thus to be able to produce indicators that can be comparable regardless of the place and time they represent. This constraint is currently valid for non-spatialized LCIA methods, but should still be kept in mind and applicable to spatialized ones.

In conclusion, spatialized LCIA methods can add important information, especially when decisions concern local actions. However, spatializing an entire product's life cycle system is not possible. It should be restricted to the foreground system and to processes that will decrease uncertainties in results significantly. This restriction requires conserving global indicators that are compatible with local ones. This compatibility could also ensure correctly accounting for the spread of substances outside the area under study.

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Part II

Integrated approach

Introduction to Part II

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Spatialization in LCA still raises many methodological questions and faces many technical challenges (Reap et al., 2008). Therefore, two main approaches are necessary. The first one starts with LCA methodology and questions the place of spatialization in the general framework of life cycle thinking and in the different steps of the LCA method (Aissani and Le Féon, 2015; Nitschelm et al., 2016). The second approach starts with the use of spatialization in LCA and questions its relevance and ability to respond to the needs of potential or existing users. Of course, these two approaches are not separate; they benefit one another through continuous iteration between the LCA framework and questions about its applicability. The second session is dedicated to the second approach: the application of spatialization to LCA case studies. Behind the application of these methods, several points have to be clarified.

The first point is the place of stakeholders throughout the assessment. Who requested the study – regional-managers, a non-governmental organization (NGO), a company, a scientific organization? Who is the audience - co-workers, scientists, citizens, civil servants? Based on the answers to these two questions the type, quality and communicating power of the results must be defined. Who will perform the LCA - someone from a scientific organization, an engineering firm, a civil service, an NGO? Based on the answer to this question, the complexity of the method and the ease of use of tools become essential considerations.

The second point is, as usual in LCA, the goal and scope of the study. The initial questions formulated (and sometimes not formulated) to justify the study are essential. From them, the boundaries of the studied system, the border(s) of the area(s) considered, and the spatial resolution of each part of the studied system have to be defined. System boundaries have a specific meaning when including spatialization in the assessment, since areas are associated with both foreground and background activities. This aspect increases the complexity of identifying and defining these areas. Therefore, the choice of relevant spatial resolution for each sub-system area as a function of the initial question is essential and particularly challenging.

The initial questions also define the functional unit, a critical point in spatialized LCA, and the allocation rules, if any. These two points underlie the presentations of the session, which focuses on three case studies of an integrated approach, each at a different level of organization: an urban project, a territory (with its activities), and an industrial sector. Specific focus is placed on the perception of stakeholders to better understand advantages and disadvantages of the application of spatialization in LCA.

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Using LCA to assess urban projects, a case study

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Introduction

The objective of this study was to help practitioners designing sustainable new construction and renovation urban projects. The models developed by the Center for Energy efficiency of Systems, i.e. the thermal simulation model COMFIE and the Life Cycle Assessment (LCA) tool novaEquer, are disseminated by a software editor, IZUBA Energies, in charge of developing the user interface (e.g. Pleiades), distributing the software and training users. Resulting from this collaboration, Pleiades+COMFIE is the most widely used energy simulation tool in France, with 2,500 users (e.g. engineers, architects, contractors, teachers).

Simulation requires spatial data (e.g. location of buildings and urban morphology), and large-scale projects benefit from new geographic information techniques. This is why R&D activities link energy simulation with graphical and spatial modeling. Spatialization is also used to improve the relevance of impact assessment, particularly regarding human health. This study first presents the method and tools, then provides perspectives on the use of new spatial data sources and spatialization techniques. The method is then applied to a green development case study. Since energy and transport play an important role in the environmental balance of urban projects, this study focused on these aspects.

Presentation of the method and tools

The method has several steps: graphical modeling, possibly performed by an architect or urban designer, followed by energy simulation and quantification of materials and components, which generates input for the final LCA step (Peuportier, 2016).

Graphical modeling

Energy consumption in buildings, which contributes greatly to environmental impacts of urban projects, has to be integrated in the Life Cycle Inventory (LCI) phase. Energy simulation requires information about the geometry of buildings, such as a map of the area for the project and its surroundings (to assess possible shading by other buildings); wall, roof and floor areas, which lose heat; the glazing area, which provides solar gains; and room volumes, related to air flow. A graphical modeler helps greatly during the input phase, particularly for large projects.

A specific tool, Alcyone, has been developed by IZUBA (www.izuba.fr) to provide a description adapted to the needs of the calculation model (Figure 1). An urban area is described by several building types. Several identical buildings can be added using "copy and paste". Buildings are created by level(s) defined by 2D plans, but wall thickness is used to derive a 3D model, which is useful if lighting calculation is needed. Each building type has a set of technical characteristics: wall, roof and floor compositions (including the thickness of insulation and masonry); window types (heat losses, solar gains); and thermal bridges. This last aspect is important in new constructions, which have low one-dimensional heat losses due to high insulation levels. Linear heat losses are therefore described in detail using several values: top, bottom and sides of windows and doors; perimeter of the ground floor, intermediate floors and roof; edges of partition walls; and wall corners. The corresponding heat losses are automatically calculated, avoiding cumbersome estimates of length, and enabling energy efficiency to be taken into account in early design phases. This kind of detail may appear non-essential, but it is much appreciated by designers. Default datasets corresponding to standards (e.g. passive house, basic regulations) are developed to make the input even easier.

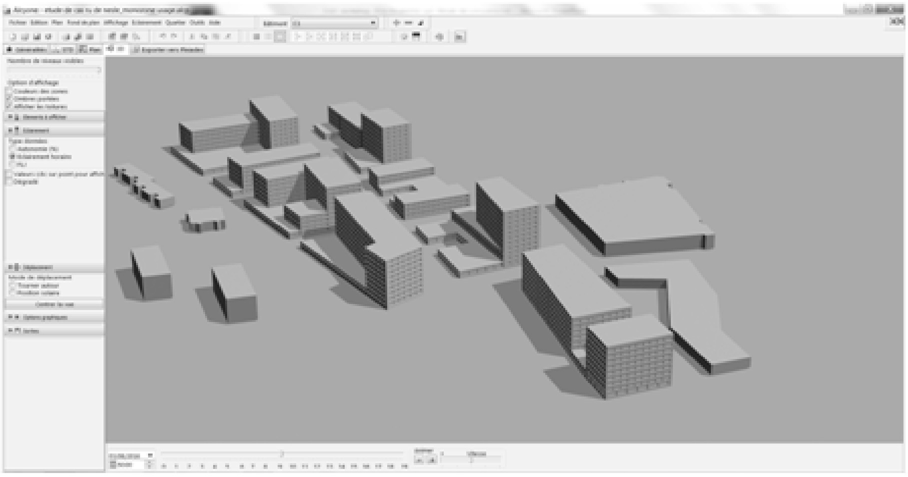

Figure 1. Example view of an urban project using the 3D modeler Alcyone

Buildings can be divided into thermal zones, corresponding to different uses (e.g. shop on the ground floor and apartments above) or solar exposure and orientation. Zones may include several rooms, but a single temperature will be assumed in the calculation. Each zone has a use scenario providing temporal variation for one year (52 weeks, 7 days, 24 hours) of user-related parameters, such as heating/cooling thermostat set point, ventilation air flow rate, use of appliances, and management of solar protection.

Location and climate data are also selected. The graphical modeler identifies shading effects. The entire model, including geometric and semantic attributes, can be exported to the energy simulation tool. Openings can be defined to calculate air flow, which is useful for studying natural ventilation and summer comfort. Daylighting can also be calculated by an automatic link with Radiance software.

Energy simulation tool Pleiades+COMFIE

The data created using Alcyone can be refined, e.g. if the wall composition or glazing type is not the same in all facades. Heating, ventilation and air-conditioning equipment can be added, as well as renewable energy systems (e.g. photovoltaics, solar thermal, micro-cogeneration).

A detailed finite-volume model is automatically created, defining nodes in each zone wall and one node corresponding to the air and furniture within each zone. For each node and at each time step (6-60 minutes), a heat balance is calculated:

$$gains - losses = stored\ energy = thermal\ mass \times temperature\ variation$$

Gains include solar radiation, internal gains and heating from equipment, while losses integrate conductive, convective and radiative transfers.

These equations are combined to form a matrix system. The theoretical knowledge developed at Ecole des Mines about modal analysis has been applied to solve the system in less time (Peuportier and Blanc Sommereux, 1990). The reliability of this model has been studied in several validation studies: experimental validation (comparing simulation results and measurements) and comparison of different model predictions (e.g. BesTest).

Current construction standards have higher insulation levels, and some phenomena such as thermal bridges and air infiltration now play a much more important role. This is why models of passive buildings have been more recently studied at the French National Institute of Solar Energy (INES) (Figure 2, left). Several software tools were compared during the design phase: EnergyPlus developed at the Lawrence Berkeley Laboratory, TRNSYS from the University of Wisconsin, COMFIE, PHPP developed at the Passive House Institute and two other French tools (Codyba and Spark). Heating consumption (C_{chauff}) and maximum heating power (Pmax) for an example house (Figure 2, left) were predicted (Figure 2, right), and experimental validation was performed (Munaretto et al., 2013).

The reduced model COMFIE has an accuracy (mean square error compared to measurements) similar to that of international references such as EnergyPlus or TRNSYS but requires less computation time.

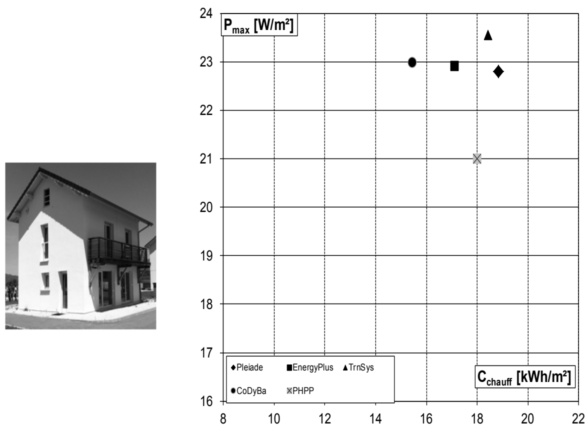

Figure 2. Comparison of heating consumption (Cchauff) and maximum heating power (Pmax) predicted by five models for an example house (source: Brun *et al.* (2009))

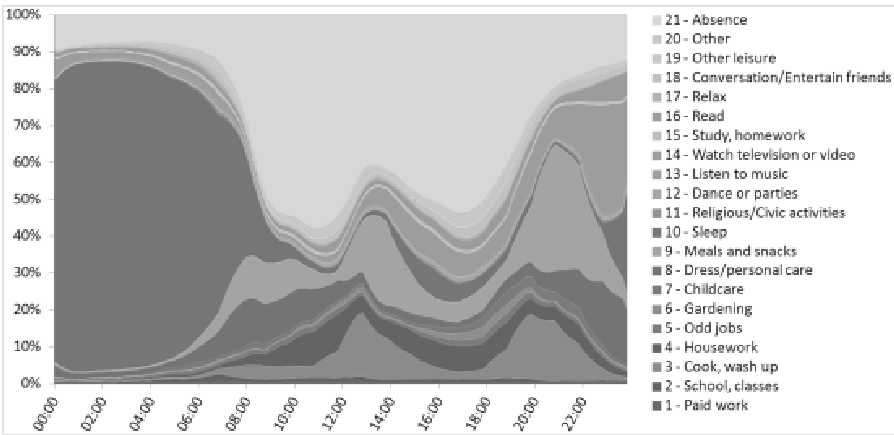

Figure 3. Example data for activities performed on workdays and weekends (source: French National Statistics Institute (INSEE))

A statistical model was developed capture the variability of occupants' behavior (e.g. occupancy periods, thermostat set point, internal gains, window opening, solar protection management). Many characteristics of occupancy depend on the location, creating a need for spatialization. Many scenarios can be created, the probability distribution of parameters depending on the project (e.g. number of persons per m2 in a house), allowing a variety of effects to be studied. This model was based on data obtained from surveys performed by the French National Statistics Institute (Vorger et al., 2014) (Figure 3).

Life cycle assessment tool novaEquer

Energy simulation was linked to LCA to estimate environmental indicators: greenhouse gas emissions, resource (primary energy, water, raw materials) use, human health, biodiversity, waste, etc., using environmental data from the ecoinvent database (Weidema et al., 2013). The Building LCA tool initially developed (Polster et al., 1996) has been expanded to address urban projects (Popovici et al., 2004).

An urban area includes different building types (houses, shops, offices, schools, etc.), public spaces (streets, parking places, green spaces, etc.) and types of utility infrastructure (water distribution, sewage, waste management, district heating, etc.). Besides the elements listed above, LCA at the settlement level should also consider aspects related to occupant behavior (water and energy consumption, transport mode, domestic waste treatment, waste recycling percentage, etc.) and site characteristics (climate, transport networks, electricity production mix, district heating production mix, etc.).

Dynamic LCA can capture temporal variation in e.g. the electricity production mix and related emissions (Figure 4), obtained by Roux *et al.* (2016a) from data provided by Réseau de Transport d'Electricité (www.rte-france.com). Compared to static LCA, which uses yearly averages, dynamic LCA estimates impacts related to seasonal use, such as heating and cooling, more accurately.

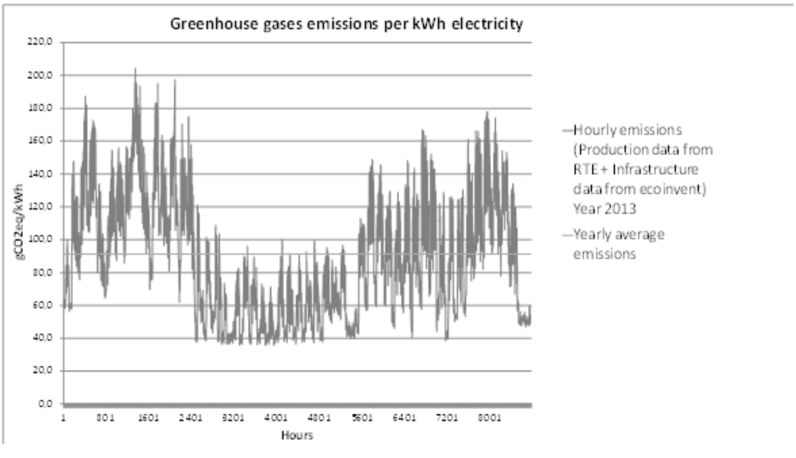

Figure 4. Temporal dynamics of greenhouse gas emissions due to the production of 1 kWh electricity

The software is used mainly to design new construction and renovation projects, at the scale of one building or an urban project of 30-50 buildings. Building archetypes (e.g. typical social housing block, typical office building from the 1980s) can be used for larger projects, possibly considering a statistical distribution of some parameters (e.g. glazing type, if some windows have been replaced in some apartments). Spatialization is useful for defining archetypes and estimating their energy consumption.

Optimization and uncertainty propagation using the AMAPOLA module

A genetic algorithm was implemented in a supplementary module, AMAPOLA (www.kocliko.co), to provide a more efficient design aid. The corresponding module runs several thousands of simulations, but the computation time is reasonable due to the model reduction technique implemented.

This is also the case when performing uncertainty propagation in an energy performance guarantee process. Probability density functions are associated with uncertain parameters (e.g. thermal bridges, management of solar protection by users). Uncertainty propagation using Monte Carlo sampling is used to guarantee estimates of energy consumption with a small margin of error, e.g. 5%. The guaranteed energy consumption can be updated according to parameters of a use scenario: typically the thermostat set point and domestic hot water consumption.

Contractors are beginning to use this approach. If energy savings can be guaranteed by a contract, this is a good signal for investors and helps fund energy retrofit projects.

Research in progress

Several improvement perspectives have been identified, particularly regarding spatial aspects; we address three of them.

Interoperability and standardized data models

Building information standards such gbXML and IFC4 are already integrated in the tools presented previously, at the scale of individual buildings. Importing AutoCAD or Sketchup plans is possible, but their accuracy depends on an architect's practice, and the reliability can be low. It would be interesting to test the CityGML + Application Domain Extension Energy proposal (www.simstadt.eu) to check its feasibility.

Large-scale spatial data

The French National Geographic Institute (IGN) has created a database providing the ground area and height of each building. The French tax administration has developed another database (32 million buildings) describing the use of the buildings (e.g. number of houses), their construction date and characteristics of their renovation. One could use this information to develop a typology (selection and characterization of archetypes) and estimate potential energy savings in a territory by simulating each type (with possible statistical variation in parameters).

Spatialization of emissions

The EcoIndicator 99 method (EI99) (Goedkoop and Spriensma 2000) estimates a toxicity indicator based upon average population density but ignoring the height of emission. Methods have been developed to account for the location of emissions in Life Cycle Impact Assessment. In particular, the impact of toxic atmospheric emissions on human health is related to the population density in the zone where the pollutant is emitted (Humbert et al., 2011). The height of this emission is also important for estimating population exposure, particularly to particulate matter (PM) (van Zelm et al., 2008).

Case study

The aim of the study was to investigate the effect of taking spatialization into account when assessing the impact of PM emitted by transport on human health. The development project studied (Figure 1) is located east of Paris. It includes multi-family houses (33,124 m²), offices (44,758 m²) and shops (3,829 m²) on a total land area of approximately 40,000 m² and has an estimated 1,060 inhabitants, 3,715 office employees and 176 shop employees. Twenty-four percent of the total area will be composed of green spaces.

The set point temperature for heating is 19°C when occupants are inside the buildings and 16°C otherwise. Houses do not have cooling systems. The set point for cooling in offices and shops is set at 26°C during opening hours (and 30°C otherwise). The mean occupancy rate is 0.03 occ.m^{-2} for houses, 0.08 occ.m-2 for offices and 0.14 occ.m-2 for shops. Shading devices and opening of windows (at night in houses) were taken into account to estimate the cooling rate and ensure occupants' comfort.

The LCA of the project was performed considering a 100-year life-span, including transport of district users and domestic waste generation. A mean transport distance by truck of 100 km was assumed from factories to building sites, 20 km from building sites to incineration facilities and 2 km to landfills. The lifespans assumed were 10 years for building finishes, 30 years for windows and doors, 25 years for the photovoltaic system and 100 years for other elements and the building as a whole. Environmental impact due to electricity consumption and production were estimated each hour of a typical meteorological year, following the method of Roux *et al.* (2016a).

To test the influence of emission spatialization, the human health indicator was recalculated for PM emitted by transport. This aspect was chosen because it is the main contributor to health impacts, and the emissions occur in a densely populated area. The CF according to the EI99 method (CFEI99) was compared to a CF adjusted using the intake fraction (IFHumbert adjusted) recommended by Humbert *et al.* (2011) for urban air emissions at ground level, and the same effect factor as in the EI99 method. The population density (DPHumbert) considered was 8300 ind./km², and the linear population density (LDPHumbert) was 130,000 ind./km.

$$CFHumbert\,adjusted = CFE199 \times \frac{IFHumbert\,adjusted}{IFE199}$$

The functional unit used for this comparison was the transport of one person over 1 km using a typical vehicle in the Greater Paris area, starting from or arriving at Cité Descartes (Roux et al., 2016b). The health impact indicator, expressed in DALY, was calculated with and without spatializing the impact of PM (Figure 5, left). Since spatialization had no effect on climate change, the health impact indicator was also compared without including the health impacts of climate change (Figure 5, right).

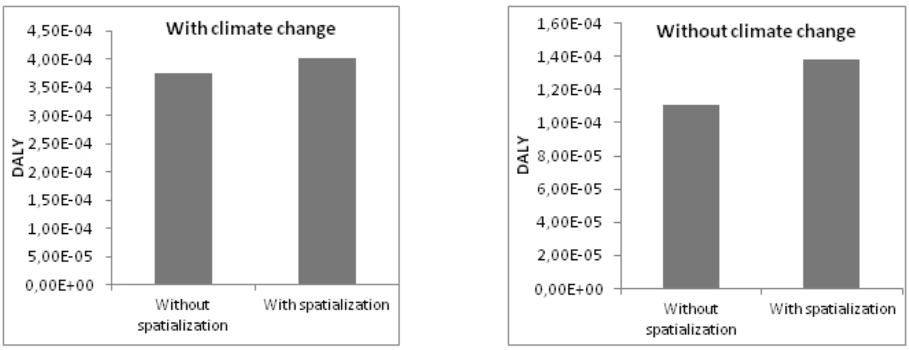

Figure 5. Influence of impact spatialization on the human health indicator for 1 person-km

Because of the high population density of the Greater Paris area, impact spatialization increased values of the human health indicator. In reality, population density is not homogeneous throughout the region. In the example studied, the origin or destination of the travel is Cité Descartes, but the other end and the route are unknown, which leads to uncertainty in the population density. To estimate the range of uncertainty, the human health indicator was estimated assuming high population density (Paris) and low population density (Marne-la-Vallée, the suburban area around Cité Descartes).

The characterization factor (CF) was adjusted according to Humbert *et al.* (2011) using the LDP of Paris (194,981 ind./km), with the DP being used as a proxy for Marne-la-Vallée (1774 ind./km²) because its LDP is unknown. In this case as well, the effect factor considered was the same as that in the EI99 method.

$$CFParis = CFHumbert\,adjusted \times \frac{IFParis}{IFHumbert\,adjusted}$$

$$with\ IFParis = \frac{LDPParis}{LDPHumbert} \times IFHumbert\,adjusted$$

$$CFMarne\,la\,Vallée = CFHumbert\,adjusted \times \frac{IFMarne\,la\,Vallée}{IFHumbert\,adjusted}$$

$$with\ IFMarne\,la\,Vallée = \frac{LDPMarne\,la\,Vallée}{LDPHumbert} \times IFHumbert\,adjusted$$

Uncertainties were calculated (Figure 6) around the human health impacts previously calculated by Humbert *et al.* (2011), the maximum and minimum values corresponding to the population density of Paris and Marne-la-Vallée, respectively. Again, the results were calculated with and without consideration of climate change.

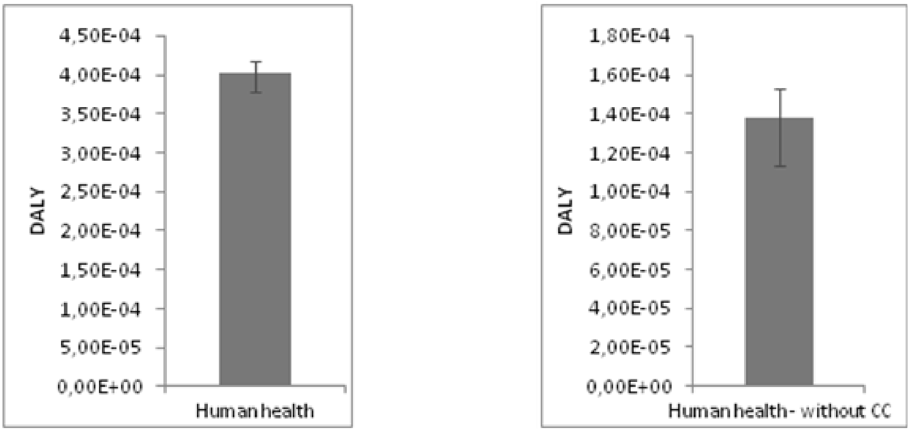

Figure 6. Uncertainty in the human health indicator due to uncertainty in spatialization for 1 person-km. Errors bars correspond to maximum and minimum population densities

Transport-related impacts on human health depend on the population density along the route. Even though this parameter is uncertain, spatialization using an average urban location seems relevant when studying urban projects. This average can be assessed using travel distance as weighting parameter.

Conclusion

Spatialization is essential in urban LCA. First, spatial data are needed to model the buildings, streets, parks, networks, etc. in territories and estimate energy consumption and production. Common standards such as CityGML help facilitate interoperability.

Second, some impacts on human health and biodiversity depend on the location of emissions. It is therefore relevant to improve LCIA methods to consider urban emissions: the case study presented shows that parameters such as population density have a non-negligible influence on human health impacts. A similar study could be performed on the height of emissions. For example, according to Humbert *et al.* (2011), exposure to a pollutant is approximately 66% lower if it is emitted 25 m high (e.g. from a wood-fired heating plant) than at ground level. Spatialization would allow for more accurate estimates of impacts related to transport, and e.g. district heating, particularly if fuel such as wood is used, since wood combustion emits PM and volatile organic compounds (VOCs). Pollutants such as NO_x and VOCs have direct impacts on human health but also indirect impacts (photochemical ozone creation). Climate data on wind and irradiation could also be used to model pollutant dispersion more accurately.

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How to use LCA to assess environmental performances of a territory?

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Introduction

For decades, stakeholders have been strongly encouraged to adopt sustainability principles when defining land planning through voluntary measures such as those defined in United Nations local Agenda 21 plans or regulatory measures such as the European Union Directives on Environmental Impact Assessment or Strategic Environmental Assessment. Regulations state that all plans, programs or projects that can significantly affect the environment should be subject to an *ex-ante* environmental assessment. However, local stakeholders still face a lack of quantitative methods that can assess environmental performances at the territory scale (European Commission, 2009). A "territory", a more precise concept than a "region", can be defined as the interface between a geographical area and a group of stakeholders who use, manage and develop it (Moine, 2006). These stakeholders can be linked together by their belonging to the same administrative unit, e.g., a community of municipalities, or by the need to address an economic, environmental or social issue. Depending on existing links among stakeholders, the goal and scope of the environmental assessment may differ, as may the method required. Although LCA was initially designed to assess environmental impacts of a product or a service, it has been identified as a promising method to assess an entire territory since it is a life cycle, multicriteria and functional approach (Loiseau et al., 2012). These attributes could allow it to identify burden shifting between territories and impact categories. In addition, the functional approach allows assessing the eco-efficiency of the studied system, since the system's environmental impacts are quantified as a function of the services it provides. This study aimed to describe and compare two recent approaches based on the Life Cycle Assessment (LCA) methodological framework: territorial LCA (T-LCA), developed by Loiseau et al., (2013), and spatialized territorial LCA (ST-LCA), developed by Nitschelm et al., (2016). The two approaches are compared based on the four LCA phases as specified in ISO standards (ISO, 2006a, b) and emphasizes their differences, similarities and potential synergies.

Description of the two approaches

Territorial LCA

T-LCA was developed to assess the eco-efficiency of a subnational territory as a whole, i.e. including all production and consumption activities. Seppälä *et al.* (2005) defined regional eco-efficiency as the ratio of indicators of services provided by the territory to indicators of the territory's environmental impacts.

The approach aims to provide quantitative information to support decision-making when defining land-planning strategies. More specifically, T-LCA can be used to provide a sound environmental baseline of a territory as it carries out a global, multicriteria and cross-sectoral analysis, which can determine the main environmental issues at local/regional and global scales and the main driving activities (Loiseau et al., 2014). In addition, T-LCA can be used to compare eco-efficiencies of land-planning scenarios to support the transition of territories towards sustainability.

The T-LCA approach makes four main methodological adaptations to the conventional LCA framework (Loiseau et al., 2013), i.e.:

1. functional unit definition: A territory can be defined as a multi-functional system (e.g. Pérez-Soba *et al.* (2008) determined three main land-use functions: environmental, economic and societal), and no single main function can be determined. To address this issue, the reference flow is now defined by the association of a territory and a spatial planning scenario. The functions provided by the spatial planning scenario become a T-LCA output. The functions of a territory can be assessed by quantifying indicators of services provided (e.g., number of houses, number of jobs, value added generated by all production activities). Two indicators are thus quantified in T-LCA: environmental impacts and services provided.

2. boundary definition: the issue behind boundary definition is territorial responsibility for environmental impacts. The principle of total responsibility defined by Eder and Narodoslawsky (1999) was chosen for T-LCA. This is a conservative principle because it includes all production and consumption activities that occur in the studied territory (direct impacts) and all upstream activities related to these activities (indirect impacts). Only waste management activities are considered for downstream activities (e.g., household waste management that occurs outside of the studied territory).

3. data collection: there is a need to develop hybrid approaches to generate Life Cycle Inventories (LCIs) for all production and consumption activities located in the territory. First, information on the types and the amounts of goods and services produced or consumed in the territory are collected in the form of monetary or physical flows. These flows are then connected to an existing LCI database according to a bottom-up approach (i.e., process LCA) for

physical flows or a top-down approach for monetary flows (i.e., environmental extended input-output LCA (EEIO-LCA)).

4. calculating indicators connected to the local context: calculation of on-site impacts (due to environmental flows occurring directly in the territory) and off-site impacts (due to environmental flows related to upstream processes and occurring beyond the territory borders) aims to identify pollution transfers from the studied territory to other territories.

Spatialized Territorial LCA

ST-LCA estimates environmental impacts of a territory by taking into account the spatial variability of emissions and impacts within it (Nitschelm et al., 2016). ST-LCA was first developed for agricultural territories (areas where agriculture is the main economic activity) because of the strong links between agricultural activities and ecosystems, but it could be applied to other territories as well (e.g. urban area).

The objectives of the ST-LCA approach are to help (1) help decrease impacts within a territory by determining which activities should be developed and where to locate them, and (2) help avoid or minimize impacts of input exchange from other territories and impact transfer between impact categories.

The ST-LCA approach is divided into 6 steps:

1. Define the goal and scope of study with a focus on geographic boundaries and functions of the territory
2. Define typologies of activities (e.g. in agriculture, farm and land-use typologies) and the influence of the biophysical environment on emissions and impacts (e.g. zones of homogenous environmental characteristics)
3. Define the spatialized LCI by combining activity types with environment types (e.g. which agricultural activity on which soil?)
4. Determine environmental impacts for each environment type within the territory. To do so, pollutant fate and the territory's sensitivity to each impact is determined.
5. Map impacts inside and outside the territory
6. Interpret results using contribution, sensitivity and uncertainty analyses

Similarities, differences and synergies of the T-LCA and ST-LCA approaches

Comparison

The two approaches have different starting points, since T-LCA was designed to assess environmental impacts of a land-planning scenario implemented in a given territory, while ST-LCA was initially developed to address specific local environmental issues (e.g. the best locations of activities to minimize environmental impacts). This difference results in two ways of understanding a territory. In T-LCA, the territory is defined by a group of stakeholders linked together by the will to implement a territorial project. In ST-LCA, the territory is defined by the need to address effects of heterogeneity and the causal chain of environmental impacts. Nonetheless, at the end, the territory can still be defined by the association of a group of stakeholders and a geographical area (delimited by administrative, political, environmental, or societal boundaries).

In addition, both approaches consider territorial multi-functionality. In T-LCA, however, this results in adapting the conventional LCA framework to quantify at the end two types of territory indicators: environmental impacts and services provided. In contrast, the conventional LCA framework in ST-LCA recommends defining only one main function of the territory. According to ST-LCA objectives, more emphasis is placed on developing and using site-specific or site-dependent impact assessment models to take the local context into account. This also implies that specific biophysical characteristics should be calculated for ST-LCA and that more data are often required to implement it. In contrast, one T-LCA requirement was to develop an approach that can be reproduced in other territories without spending too much time collecting data. Although this stage is still the most time-consuming, most data can be estimated without field surveys from available online data sources (e.g., the National Institute of Statistics and Economic Studies (INSEE)) and LCI databases (e.g., ecoinvent or Environmental Input-Output databases), and a compromise should be reached between data quality and feasibility.

Table 1. Comparison of the four LCA phases in the T-LCA and ST-LCA methods. LCIA = Life Cycle Impact Assessment

LCA phase		T-LCA	ST-LCA
Goal & scope	Audience	Local stakeholders, decision makers	Local stakeholders, decision makers
	Application	Baseline, scenario comparison	Baseline, scenario comparison
	Decision context	Meso-level decision-support (subnational region)	Meso-level decision-support (subnational region)
	Territory definition	Association of a group of stakeholders and a geographical area	Association of a group of stakeholders and a geographical area delimited by an environmental issue
	Studied system	All production and consumption activities within the territory	For now, a specific sector of activity, e.g. agriculture
	Functional unit (FU)	No FU is defined, but rather a set of indicators of land-use functions and assessed as T-LCA outputs (e.g. 3 main land-use functions: societal, economic and environmental)	Input of ST-LCA, defined with stakeholders and depending on the territorial environmental issue
	Boundary selection	Cradle to the territory gate (except for waste management)	Cradle to the territory gate
	Territory boundaries	Defined by the land-planning scenario (on an administrative unit)	Defined by an environmental issue and/or with stakeholders
	Foreground/ background activities	Territorial foreground/background system	Territorial foreground/background system
	Model use for impact assessment	Available LCIA methods (site-generic or site-dependent)	Fate (e.g., Nutting-N and -P (Dupas et al., 2015)) and sensitivity models (e.g., bay sensitivity to eutrophication (Håkanson, 2008))
Life Cycle Inventory (LCI)	Modeling approach	Hybrid: input-output analysis and process-LCA	Process
	Aggregation level	Activity	Activity
	Data collection	Activity inventory	Activity inventory Biophysical characteristics inventory
	Data quantity	++	+++
	Data accessibility	+++	++
	Emission estimates	Current LCI databases	From models for foreground systems (e.g., Parnaudeau et al., 2012) and current LCI databases for background systems
LCIA	Environmental processes	Generic models	Pollutant fate and territory sensitivity to environmental impacts
	Impact assessment	For now, non-spatialized characterization methods	Spatialized characterization methods for local and regional impacts
Interpretation	Impact location	On-site/off-site burden differentiation	On-site/off-site burden differentiation
	Result representation	Graphs and maps	Graphs and maps capturing spatial variability in the territory

Potential synergies

As explained, T-LCA can provide a comprehensive baseline of a territory. It allows the main environmental issues within and outside the studied territory and the main driving activities to be identified. However, T-LCA is iterative, requiring further analysis for the hotspots identified. For example, while agricultural activities appear to be one of the strongest contributors to the overall impacts of production activities, more investigation could be required to assess these activities in detail. If so, ST-LCA could be used to include spatial variability and improve result accuracy (Figure 1). This potential synergy indicates that the two approaches are complementary: T-LCA can be applied first to screen all territorial activities, followed by ST-LCA to assess in more detail the activities with most impact (Figure 1), depending on the decision scale required. This combination would provide a sound assessment without spending too much time collecting data on activities that do not contribute significantly to the impacts.

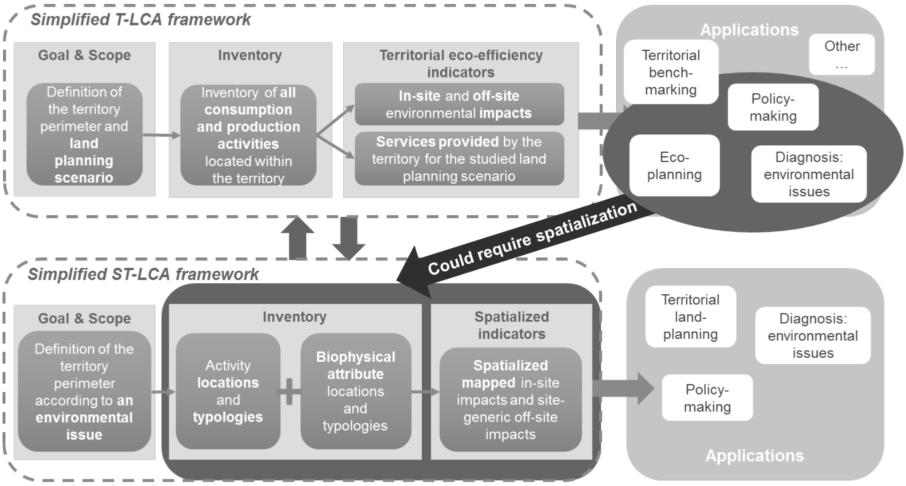

Figure 1. Potential synergies between the T-LCA and ST-LCA approaches: applying ST-LCA to include spatial variability when assessing T-LCA environmental hotspots

Recommendations for use

The choice of using T-LCA or ST-LCA depends on the purpose of the study. T-LCA can provide an environmental baseline of all economic activity in a territory or to help local stakeholders choose between different land-planning alternatives using a quantitative tool. In contrast, if local stakeholders have identified an environmental issue in their territory, ST-LCA can help decrease this environmental impact by determining which activities should be developed and where to locate them.

Conclusion

Currently, few quantitative tools and frameworks have been developed to assess environmental burdens of a territory and support local decision-making. LCA was identified as a promising framework to assess environmental impacts of a territory because of its life-cycle, multicriteria and functional aspects. By adapting the LCA framework, two approaches for assessing territorial environmental impacts were developed: T-LCA and ST-LCA. Although both approaches are based on LCA, they have different purposes. T-LCA was designed to assess environmental impacts of a land-planning scenario implemented in a given a territory, while ST-LCA was initially developed to address a specific local environmental issue. This difference in goal and scope definition implies different methodological developments and results. T-LCA provides two indicators: direct and indirect environmental impacts due to all production and consumption activities located inside territory boundaries and services provided by the territory. In contrast, ST-LCA outputs are site-specific direct environmental impacts (i.e. that take the local environment into account) of a given territorial activity. While ST-LCA has the advantage of calculating local results, it needs more data than T-LCA; therefore, applying it requires more time. Comparison of the two approaches showed that they complement each other. Indeed, T-LCA can provide a comprehensive baseline of a territory and identify the main environmental issues within and outside the studied territory. ST-LCA can then identify site-specific hotspots. In conclusion, both methods need spatial information organized in suitable databases to be applied to various case studies and to be able to address stakeholders' issues.

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How to use LCA to assess an industrial sector within a territory

Centralized biogas production as a case study

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Introduction

Anaerobic digestion plants (also called biogas plants) convert organic matter (e.g. agricultural residues, bio-waste[1], sewage sludge) into a methane (CH_4)-rich biogas that can be used to generate electrical power, heat, or fuel, and a nutrient-rich digestate that can be used to fertilize agricultural land (Figure 1).

Producing biogas by repurposing organic residues in France has been undergoing a remarkable growth for the past 10 years, since 70 new plants emerge every year in the agricultural sector (ADEME, 2016). This growth is supported by regulations and economic incentives that aim to subsidize the agricultural sector, since a biogas plant may contribute to a circular economy within an area. For example, it can recycle bio-waste, producing fertilizers that will return to the soil or a local supply of renewable energy. However, it also emits substances (e.g. CH4, nitrous oxide) directly and indirectly into the environment (like any other industrial process).

Different reasons and different project owners can motivate the development of a biogas plant (ADEME, 2016). For example, upgrading livestock manure storage on a farm to regulatory standards can be funded by the sale of biogas; a local authority may aim to provide a biogas plant to strengthen its area economic attractiveness or mitigate its greenhouse gas emissions; adding a biogas plant within a water treatment plant can improve treatment of sewage sludge without increasing water pricing; etc. Since many of these reasons are connected to environmental concerns, environmental and local impacts need to be assessed to avoid opportunistic development of biogas plants.

1 Bio-waste includes biodegradable garden and park waste; food and kitchen waste from households, restaurants, caterers and retail premises; and similar waste from food processing plants. The definition does not therefore include forestry or agricultural residues, manure, sewage sludge or other biodegradable waste such as natural textiles, paper or processed wood (EU, 2009).

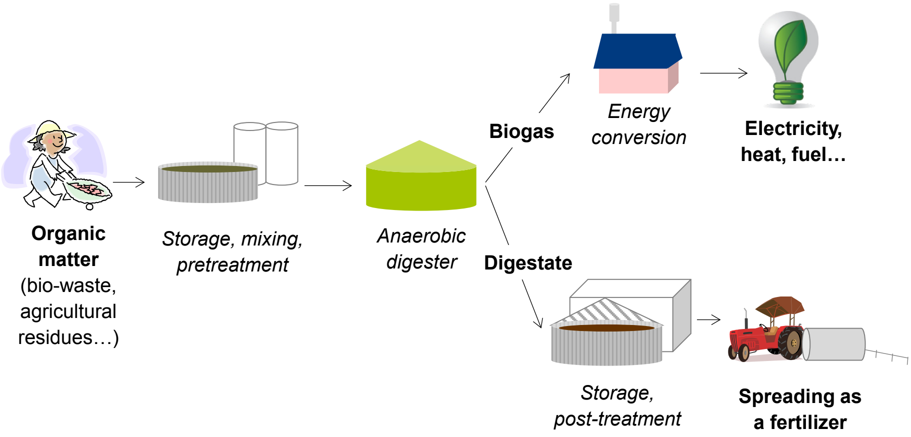

Figure 1. Diagram of a biogas plant

Life Cycle Assessment (LCA) stands as the predominant method in the scientific literature for this purpose (Laurent, 2015). LCA is a quantitative, objective, multicriteria analysis of all stages of a system's life cycle. However, to accurately assess a system that is strongly linked to the area in which it is based, in this case a centralized biogas plant, the method requires spatial considerations. This *contextualization* supports the decision-making process. Assuming that environmental assessment should embed contextualization for certain sectors, the purpose of this study was to develop a spatialized technico-environmental method for assessing centralized biogas plants.

Development of the biogas production sector involves at least three other sectors: energy, agriculture and waste management. Each stock or flow of these sectors (i) has its own spatial dimension,(ii) closely interacts with its environment and (iii) is supervised by human decisions and management. A centralized biogas plant can therefore be considered a complex industrial system, as defined by Cluzel *et al.* (2012), and systemically analyzing its stocks and flows can help resolve issues pertaining to its modeling, prediction or configuration.

This study aimed to systemically analyze patterns of biogas plant entities (i.e. stocks and flows) to capture the function a biogas plant performs in a spatially differentiated manner and to address its multi-functionality. Consequently, environmental assessment using LCA was carried out with the functional unit and scenarios set in keeping with the specific challenges of the study area.

Method

A three-stage method was developed (Figure 2).

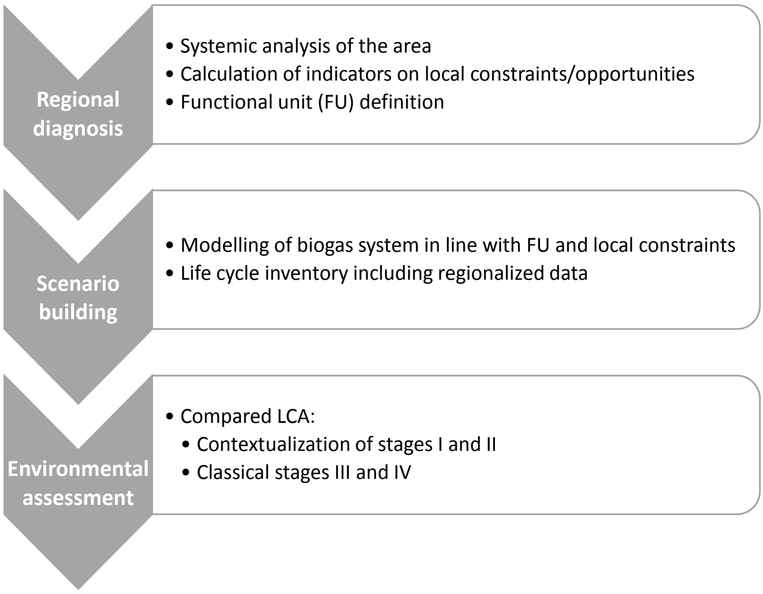

Figure 2. Framework of the three-stage method. Stages I-IV refer the stages of the LCA framework.

Regional assessment

In the first step, systemic needs analysis of the area is performed to answer the following questions: Is development of a biogas sector relevant in this area? If so, what function(s) should it perform? Which biogas production scenarios are suitable for the local context?

Thus, in this first step, local patterns of biogas plant entities are listed, described, quantified, and geo-referenced (e.g., amounts of bio-waste produced, energy distribution networks, roads, waterways) using Geographic Information Systems (GIS) and a database management system. Data are collected from open data sources, national statistics systems and dedicated surveys, endeavoring to ensure that the method can be replicated anywhere in France.

Next, indicators are calculated based on these data to assess local needs that a biogas plant could help meet, such as repurposing organic residues, producing renewable energy and managing nutrients. The indicators include both quantitative technical or regulatory considerations and more subjective, predictive considerations. Indicator scores are compared to rank local needs. The predominant issue corresponds to the main function[2] that a biogas plant should perform, on which the functional unit will be chosen.

2 If several functions stand out as being relevant, one of them is selected as the main function, and secondary functions are considered through substitution. Alternatively, one can conduct a specific LCA for each function.

Scenario building

In the second step, biogas production scenarios are defined by constraints and opportunities of the area, in line with the function(s) identified during the first step. A variety of technical options results from each indicator, revealing important issues for a biogas plant. These options relate to biogas production itself, inputs of organic residues, and outlets for the biogas and digestate. For example, if treatment of bio-waste stands out as a major issue, the local authority must segregate bio-waste collection by source, and the biogas plant should pasteurize the bio-waste. Since different issues may require potentially conflicting options, one can build different alternative scenarios.

During this step of scenario building, results of the preceding systemic analysis are used to define the system boundary, technical options, the baseline scenario, alternative scenarios, allocations, etc. In addition, maps can be created with GIS to support decisions about the location(s) of biogas plant(s) within the study area. Finally, a regionalized Life Cycle Inventory (LCI) is produced using geo-referenced data collected during the first step.

Environmental assessment

In the third step, environmental impacts of these scenarios are assessed using LCA: alternative scenarios are compared to each other and/or the baseline scenario using the functional unit. Most items required for *Goal and scope definition* and *Inventory analysis* are set up using the method developed. Hence, the first and second stages of LCA are spatialized. The later stages of LCA (i.e. *Impact assessment* and *Interpretation*) are conducted in the classic manner. Nonetheless, the interpretation needs to remain consistent with results of the previous regional assessment.

This method was applied to identify relevant biogas production scenarios for a survey area, Rennes Métropole[3] (RM), as part of its plan for managing its bio-waste.

Results

Several indicators were calculated to determine which waste seems most important to process into biogas. For example, green waste (GW) repurposing can be a key issue for local authorities, and it can be achieved by anaerobic digestion. GW flows collected from each of RM's municipalities in 2015 varied from a few hundred t to more than 3840 t (Figure 3).

3 Rennes Métropole is a metropolitan area in the Brittany region, western France, comprising 43 municipalities (440,000 inhabitants in 2014).

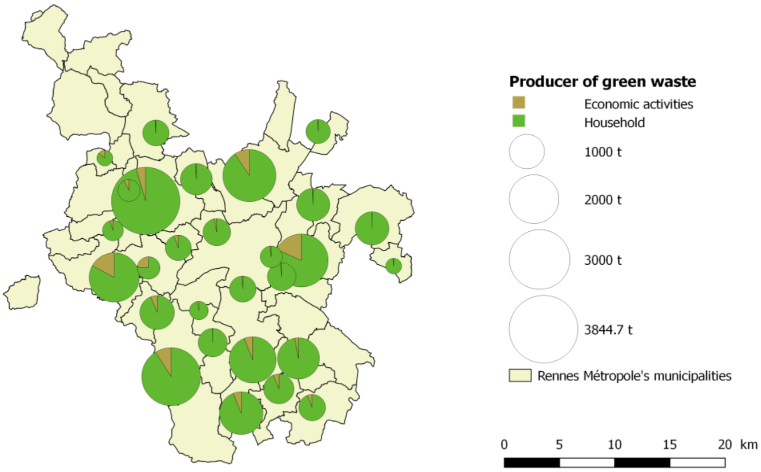

Figure 3. Green waste flows collected in 2015 from municipalities in the Rennes metropolitan area

The indicator reflecting the need to develop new facilities, such as biogas plants, for repurposing GW is based on a quantitative term I(GW), to which is added a qualitative term D(GW).

I(GW) is calculated as follows:

$$I(GW) = \frac{\Sigma dij * \alpha j * qj}{\Sigma qij}$$

with:

- $q_{ij:}$ GW collected at collection site i and repurposed in facility j (t/year)
- dij: distance between collection site i and repurposing facility j (km)
- αj: coefficient for the hierarchy of waste-treatment methods

I(GW) is thus a distance that is transformed to a scale ranging from -5 to +5, setting 0 as the mean distance (26 km) between GW repurposing facilities in France (Table 1).

Table 1. Scale of the quantitative term I(GW) for the indicator of the need to develop new facilities

I(GW) (km)	< 10	[10 ; 14[	[14 ; 18[	[18 ; 22[	[22 ; 26[	26	]26 ; 31]	]31 ; 35]	]35 ; 39]	]39 ; 43]	≥ 43
Score	-5	-4	-3	-2	-1	0	1	2	3	4	5

The higher the distance, the more developing local repurposing facilities is relevant. For RM, I(GW) = 37.5 km, which corresponds to a score of +3.

In contrast, D(GW) is a more subjective score set as a function of foreseeable changes in GW flow and management. The fact that, beginning in 2020, RM's collection sites will no longer accept GW produced by economic activities increases the need to implement new collection and treatment facilities. The local authority's campaign to decrease household bio-waste at the source, however, decreased the GW flow produced by households by 45%, thus decreasing the need for repurposing. As a result, D(GW) was considered to equal 0, yielding a final score of +3 for the indicator pertaining to GW. This score means that RM had great need to implement local facilities for repurposing GW, such as biogas plants.

Two other indicators were developed in the same way for kitchen bio-waste flows from households (HKBW) and from economic activities (KBWEA) (Figure 4).

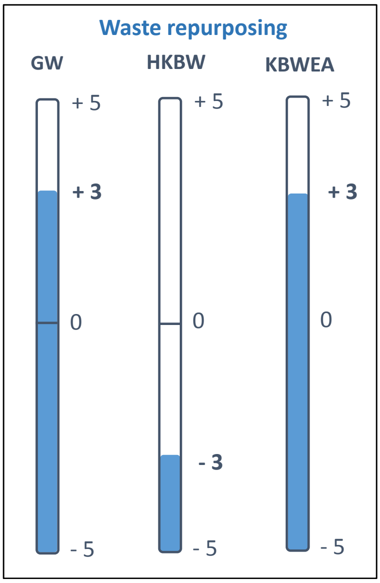

Figure 4. Indicator scores for three bio-waste flows (GW: green waste; HKBW: household kitchen bio-waste; KBWEA: kitchen bio-waste from economic activities) for Rennes Métropole

HKBW is handled locally in RM's incineration plant. Although no material can be recovered from this treatment, RM's HKBW transport distances are much shorter than the French mean. Moreover, this flow has been reduced at the source due to RM's prevention policy. Thus, the indicator had a low score (-3), meaning that concern about HKBW was small.

KBWEA is sent to a centralized biogas plant located quite far from RM (about 70 km from the transfer point). Still, this is less than 60% of the mean distance travelled in France by this kind of waste (about 120 km). The indicator's score was increased by the fact that much of the KBWEA flow is under the responsibility of the local authority and subject to special regulations. The indicator's score reached +3, meaning that KBWEA was a fairly important issue in RM.

Expressing all the indicators on a scale from -5 (lowest concern) to +5 (highest concern) makes it possible to identify which waste to process into biogas first if this sector is developed in the survey area.

Eight other indicators are then calculated, expressing:

- potential to inject biogas into the natural gas network
- potential to develop fueling stations for natural gas vehicles
- nutrient pressures from agricultural sources (nitrogen and phosphorus)
- vulnerability of water quality
- potential to replace mineral fertilizers by processed digestate
- decrease in organic matter in agricultural soils

Comparison of these indicator scores makes it possible to rank issues and thus the functions that a biogas sector should perform for the survey area.

Conclusion

A method was developed to support the decision-making process applied to a centralized biogas sector. This method aims to introduce spatialization into systemic analysis of a complex system strongly linked to the area in which it is based, to address its multi-functionality.

At this stage of the study, regional assessment of the survey area (i.e. Rennes Metropole) yielded several indicators that are used to determine which waste needs to be handled first. These initial results must be supplemented by other indicators assessing the area's needs and potential to produce renewable energy such as biogas, increase the amount of organic residues returned to the soil and export surplus nutrients from agriculture to decrease eutrophication. By ranking these indicators and thus these issues, the main function of a potential biogas sector can be determined, and consequently the functional unit for LCA. The following stages of the method include building biogas production scenarios in line with this function and local constraints, and then assessing their environmental impacts.

Indicators resulting from the regional assessment are meant to offer a scientific, unbiased and interdisciplinary approach to issues addressed by the local authority by the potential construction of biogas plants. They are therefore developed in co-operation with the head of the waste management and energy networks department of RM. Collecting user feedback helped improve the method and ensured that it remained relevant with its concerns (e.g. deal with much spatialized data, adapt its policies).

This contextualization of centralized biogas production is an initial step in considering environmental and local issues during technical development of the sector. Even though decision making remains driven by political concerns more than results of the regional assessment or LCA, this approach can help local authorities arbitrate between several options or request adjustments to emerging projects.

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Acknowledgements

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Conclusion of Part II

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Using spatialization in Life Cycle Assessment (LCA) is a wide field of study that is still in its infancy. The number of challenges to face is large, as seen during the workshop. This text highlights a few items highlighted during the discussion after the presentations. Defining the object of study remains a hotspot in spatialized LCA.

Which scale of the studied system is the most relevant?

The development of territorial LCA implies defining a "territory", which is designed by eco-bio-sociological relationships between society and the environment (Raffestin, 1989). This concept derives from the French *territoire*, which covers three dimensions: organizational, identity and material (Laganier et al., 2002). The territory is a space for governing and managing the resources, activities, organizations and jurisdictions that represent the strategies of territorial development. Despite the significance of the organizational and identity dimensions, considering them in LCA remains a challenge, as shown by the case study of Eléonore Loiseau. Although the physical dimension is a restrictive view of a territory, it can be relevant, as shown by Laure Nitschelm, if the initial question requires it. In this case study, the territory, close to the landscape scale, was defined by the limits of a watershed, since impacts of agricultural practices on water quality lay at the center of the study. Spatial differentiation arises from the spatial dimension of the object of study. As Bruno Peuportier and Christophe Gobin showed for urban planning, both the building and district scales are relevant when assessing environmental impacts, depending on the degrees of interaction considered among the networks of energy supply and consumption, water use and treatment, and transport. The profile of users and population density are therefore relevant parameters to include in the design of urban projects. The spatial dimension associated with the initial question will define the relevant scale for the assessment and eco-design of the studied system.

Which spatial resolution?

Depending on the initial question, the spatial resolution of two main LCA steps - Life Cycle Inventory and Life Cycle Impact Assessment (LCIA) - may differ. Some questions related to biophysical mechanisms may require fine resolution (e.g. the field scale in agriculture) to encompass the variability in local conditions that can influence the quantities of pollutant released. In LCIA, according to a site-dependent approach, impact categories may have different resolutions. The spatial resolution of LCIA is defined by relevant spatial variability (e.g. in local water scarcity) or the spatial dimension of impacts on the targeted ecosystem (e.g. climate change is generally considered at a global scale). In contrast, global scales may be sufficient when the territory is considered as a whole. A single study may use a wide range of spatial resolutions depending on the impact categories assessed. This may raise questions about the transparency of the method and the ability to describe the spatial variability. Using maps to show LCA results for different impact categories at different scales is also challenging.

Is it necessary to relate the subject of study to a function?

The use of space can be multiple and multi-functional. Therefore, defining a functional unit in a spatialized LCA may be difficult. Attributing impacts to different functions can be discussed and determined at the beginning of a study to address this problem. Faustine Laurent suggested this approach for a biogas plant, which can be considered as waste treatment and/or energy production. To determine the function and the functional unit, she performed a systemic territorial analysis that highlighted territorial constraints and needs for a biogas plant. Several case studies seem to have so many functions that a functional unit cannot be defined, as shown by Eléonore Loiseau. Nevertheless, this approach considers the subject of study (i.e. a territory) as the functional unit. The use of area as a functional unit is regularly debated, since doing so helps to assess systems associated with land use (i.e. in agriculture), but several LCA specialists do not consider land use as a function. The increased distance from the ISO standards caused by introducing spatialization in LCA is debated. Is it still LCA? The question of the function, apparent opposition to local differentiation of impacts and the life-cycle vision of LCA seem to push for distinguishing spatialization LCA from classic LCA.

Viewpoints of recipients of spatialized LCA?

Recipients of the results, such as territory governance administrations, private companies, non-governmental organizations, etc., see the potential for using an integrated approach to apply spatialization in LCA. They are waiting for methods that can consider spatial differentiation to better represent local contexts and variabilities. Making decisions according to local and global parameters is an issue for eco-designing products, territories and public policies.

Many controversial points associated with the development of spatialized LCA remain. Although it remains a science in progress, practitioners need stable tools to be defined and uniform and stable standards to be applied. Definition of standards has to go along with creation of datasets with a consistent regional breakdown of global information. Practitioners also await the creation of tools. Model-driven engineering combining Geographic Information Systems (GIS) and LCA may offer opportunities. Therefore, the compatibility and interoperability of tools (GIS, LCA calculators, databases, etc.) become issues for linking them in consistent and operational packages.

Many changes in the combination of LCA and spatialization are to come. The scientific basis has to be strengthened, while operational tools have to be developed for practitioners. Moreover, these trends have to follow changes in LCA, such as the introduction of consequential thinking.

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Part III

Perspectives for spatialization in LCA

Introduction to Part III

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Life Cycle Assessment (LCA) standards such as the ILCD Handbook (EC-JRC, 2010) and ISO (ISO, 2006a, b) take stances about spatialization in LCA. Even though both standards assure that spatialization is an issue for the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) steps, they do not suggest any framework or tools and thus do not prioritize research efforts on this topic:

- According to the ISO:
  - "Depending on the environmental mechanism and the goal and scope, spatial and temporal differentiation of the characterization model relating the LCI results to the category indicator should be considered."
- According to the ILCD Handbook:
  - "Note that LCIA results calculated from non-generic LCIA methods are later to be presented and discussed additionally separately from the default, generic ones".
  - "If aimed at, the use of such non-generic (e.g. spatially or otherwise differentiated) LCIA methods shall be scientifically justified in so far that it results in significantly different LCIA results".
  - "Note that, in case non-generic impact assessment is applied, the characterization step will have to be done on the not aggregated inventory result".
  - "Given however the lack of spatially or temporally differentiated LCI data and especially corresponding LCIA methods, for the time being such differentiation is in practice not or rarely feasible".

This session provided evidence that it is possible and relevant to perform spatialization in LCA with existing and advanced tools, and some integrated case studies. The case studies presented the lack of a conceptual framework to integrate spatial information throughout the steps of LCA. Consequently, the authors encountered both methodological and technical difficulties in developing methods and tools to perform spatialization in their case studies.

First, the methods developed must be approved by the LCA community, which means that they must be placed in the existing LCA framework. The difficulty in aligning them with LCA standards and concepts has slowed down consensual use of these new developments for spatialization in LCA. Second, technical solutions are needed to apply spatialization easily to LCA case studies. To do so, researchers must develop not only methods but also information technology (IT) tools. Current tools are often rough, consisting of existing software with some adaptations. The utility of a rough approach is that LCA practitioners can use it with less effort. One disadvantage, however, is potential incompatibility with other tools such as GIS, which may make spatialization labor-intensive. Some complete tools have been developed as plugins for LCA freeware. The utility of this complete approach is compatibility with other tools such as Geographic Information Systems (GIS) and quantitative models. One disadvantage is the need for in-depth training to use it. In addition, these complete tools increase the time required to perform an LCA.

It is now time to build a framework based on existing studies to overcome these methodological and technical obstacles and help practitioners who want to perform spatialization in LCA. This conceptual framework should define spatialization levels according practitioners' preferences and different pathways to propagate spatial information throughout all LCA steps. To this end, recommendations are required to design specific IT tools.

Beyond these methodological and technical issues, spatialization in LCA raises questions about a variety of concepts, such as the territory, stakeholders and social representation. It is tempting to think that this intersection concerns a circular economy, which is an economic concept (not a scientific field) that promotes environmentally friendly reuse of matter and energy in the technosphere. The scientific field in which the concepts of spatialization in LCA and territory intersect is industrial ecology. Industrial ecology provides an opportunity to spatialize matter, energy, economic or information flows; understand the geometry of the industrial sectors concerned; and question multiscale concepts of flows, stakeholders and area. The case studies presented in the previous session did not consider an industrial ecology perspective, which is the next step in developing spatialization in LCA.

Therefore, this final session had two objectives:

- Developing a conceptual framework to propagate spatial information throughout the steps of LCA
- Opening up new perspectives towards industrial ecology

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How to propagate spatial information in LCA?

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Introduction

Life Cycle Assessment (LCA) is increasingly used to assess environmental impacts of a variety of systems, despite certain methodological limitations. Indeed, LCA was originally designed for products, so adaptations are necessary to assess other systems, such as territories and industrial sectors. Nevertheless, LCA can help decision makers at the local scale due to its holistic perspective. For example, it can help develop renewable energy strategies, waste management systems and agricultural production systems in a territory. LCA has limitations, however, such as the lack of spatial contextualization (i.e. the inability to integrate the surroundings, especially when they interact strongly with the system studied). In LCA, a system is generally seen as location- and context-independent. For some systems (energy, waste, agriculture, building), integrating spatial information is however necessary to ensure contextualization, and this throughout the four steps of LCA: Goal and scope definition (step 1), Life Cycle Inventory (LCI) (step 2), Life Cycle Impact Assessment (LCIA) (step 3) and Results and interpretation (step 4). Indeed, to be relevant for the LCA framework and especially the strong links between steps, spatial information should be homogenously and continuously integrated. In other words, spatial information should propagate from one step to another.

The present study developed a conceptual framework that lays the foundations of such homogenous and continuous integration of spatial information: the continuum of spatialization. Based on a review of the use of spatial information in LCA, strengths, weaknesses and the continuity of existing solutions are briefly presented. Next, the continuum of spatialization concept is described. It is based on existing solutions for each LCA step and links between steps that define pathways to propagate spatial information throughout the LCA framework.

Spatial information in LCA: a review

The review of 152 publications aimed to i) observe current knowledge, developments and ambitions of spatialization in LCA; ii) list existing solutions for each methodological step of LCA and iii) identify studies that develop ways to propagate spatial information from one step to another. This review confronted the continuum of spatialization with existing solutions in order to prioritize future methodological developments. Spatialization is increasingly present in LCA literature, and the number of related publications has constantly increased since the end of the 1990s. At this early date, the need for LCA to include more spatial information was highlighted, starting with the characterization step and its need for spatial differentiation (Krewitt et al., 1998; Potting and Block, 1994). At various levels, each methodological step of LCA is concerned (Figure 1). The objectives of spatialization for step 1 are to fully integrate the local context when defining the system. Inclusion of spatialization in step 1 is rare but becoming more common, notably for territorial systems. For example, Geographic Information Systems (GIS) combined with a territorial systemic analysis can be used to define the functional unit of a multi-functional system (Laurent, 2015). For step 2, the objectives are generally to include location-specific data in LCIs, but they can associate each process with a geographical area or coordinate (Mutel and Hellweg, 2009) or include spatial context information in the LCI (especially for agriculture-related studies). Thus, spatialization is widely used to develop location-specific characterization factors (CFs) and methods. Finally, spatialization is rare in step 4 but offers interesting perspectives to use maps to present and interpret environmental results. This should develop in the future, especially for territorial decision-making. Links between steps in the literature have been examined to understand how some authors propagate spatial information from one step to another (Figure 1). Obviously, if spatial information is included when defining the goal and scope (probably by using GIS), a spatialized LCI is nearly always obtained. However, the methodological question that raises the most discussions and proposals is: how to propagate spatial information from the LCI to the LCIA (Owens, 1997)? Indeed, it could be seen as inconsistent to use spatially differentiated CFs in a generic LCI and, by analogy, to spatialize the LCI then apply a site-generic LCIA. Finally, the link between steps 3 and 4 is quite poor. Despite many spatialized characterization methods, results continue to be presented in a traditional way (i.e. graphs). Only two publications were found that represent a continuum, i.e. that propagate spatial information from steps 1 to 4 (Urban et al., 2012; Nitschelm et al., 2016).

The review provided four main observations about LCA steps:

- LCIA is historically the most concerned by spatialization
- This led to asking questions about LCIs and therefore to the development of spatially differentiated LCIs
- Goal and scope definition tends to consider spatial information, especially when LCA is used for local decision-making

- Results and interpretation are the least concerned by spatialization, despite the appearance of results presented on maps

It also provided two general conclusions:

- For each LCA step, solutions exist to include spatial information in response to unmet needs (e.g. spatial differentiation for LCIA). However, some methods are still lacking or emerging (e.g. multi-functionality in territorial systems).
- Methodological links are lacking to propagate spatial information from one step to another, even though some recent solutions exist (e.g. from LCI to LCIA)

These two points strengthen the interest in developing a new methodological framework that would combine existing and future step-by-step developments with methodological links between steps to include spatial information throughout the LCA when required by the study (e.g. territorial systems).

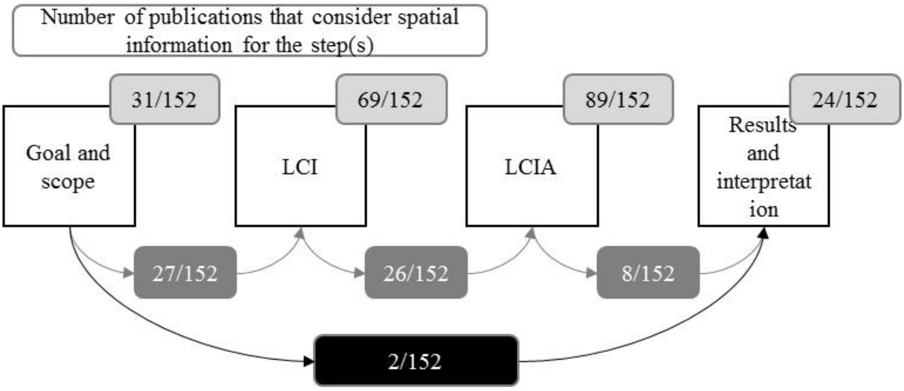

Figure 1. Number of publications that consider spatial information in each LCA step individually, two sequential LCA steps and all four LCA steps

Continuum of spatialization

Definition

Spatialization in LCA generally concerns only part of the study, without thinking about propagating the spatial information. The continuum of spatialization, which aims for this propagation, consists of the following:

- Develop rating scales for spatialization in each LCA step
- Determine methodological links between steps and related pathways
- Identify methodological and/or technical needs for the future

Levels of spatialization

For each LCA step, existing solutions have been used to define levels of spatialization (in ascending order).

Goal and scope definition

1. Spatial homogeneity of the system: spatial relevance is ensured by, for example, choosing the correct electricity mix. This basic level is the minimum recommended by LCA standards, but it is not always verified in studies.
2. Integrating spatial/local characteristics/conditions to design the system: contextualizing the system in this way can be considered trivial, but it may require additional tools such as GIS that add a degree of complexity to the previous solution.
3. Differentiating fixed and mobile sources: distinguishing emission sources is appropriate for studying transport modes, especially comparing electric vehicles – whose emissions are located mainly at the power station – and conventional ones – whose emissions are mobile throughout the journey.
4. Completely integrating the system in its surroundings: the geographical context is considered crucial for the system studied. All interactions between the system and its surroundings are modeled and useful for defining the goal and scope or the functional unit. It is particularly recommended for systems that depend greatly on the local context – decisional, environmental, economic – such as waste, energy or agricultural management systems. At this level, the LCA is applied to a pair composed of a system and a geographical area (e.g. biogas plant in urban area A or electric vehicle in city C).

Life Cycle Inventory

1. LCI separated by location: strictly speaking, differentiating foreground and background processes is not spatial differentiation. For certain systems (e.g. agricultural), however, foreground activities are located in a specific area. This separation can help in spatializing other steps by allowing spatialized CF to be applied or providing on-site and off-site LCA results.
2. Collecting location-specific data: LCA standards recommend using geographically relevant data in the LCI. In some cases, these data are location-specific and can be collected using GIS, especially for foreground processes. This level is attributed to studies that use uncommon efforts to collect local data. In some cases – notably agricultural systems – the local context is accurately represented using emission models.
3. Spatialized LCI: including spatial information in the LCI adds new information: the location of each process and thus each input and output flow. It can

be geographical coordinates, the name of the geographical area (country, watershed, etc.) or a type of area (urban, rural, etc.). This level, which assumes that information is added to traditional LCIs, is often reached to be able to apply spatialized CFs.

Life Cycle Impact Assessment

1. Impact assessment by location: while not strictly a spatialized LCIA, this level follows directly from a geographical separation of the LCI. If the LCI is separated, the LCIA can be separated (e.g. on-farm/off-farm activities), which can be crucial when decision makers wish to know what proportion of local or regional impacts occur on their territory. If spatially-differentiated CFs are not used, this level cannot spatially differentiate the overall impacts of two scenarios that have different proportions of the same process located on-site.
2. Site-dependent CFs: using site-dependent CFs, at least for foreground processes, is a good way to differentiate scenarios that occur in different places without calculating CFs for each geographical coordinate. They should be used for waste or energy management at the local scale (e.g. to differentiate impacts of an incineration plant).
3. Site-specific CFs: using site-specific CFs, which are calculated for specific geographical coordinates, is particularly relevant for impact categories that can have high spatial variability in a specific context, such as urban or agricultural areas. For example, it can be useful to examine noise pollution within a city when differentiation between urban and rural areas is not sufficient.

Results and interpretation

1. Graph results by location: following separation of the LCI and LCIA, results can be presented as a function of location (e.g. on-farm vs. off-farm impacts). While this format is relatively simple, it is not widely used in LCA even though it can provide new information with which to interpret results. Graphing is not innovative, however, since it is a common way to present LCA results.
2. Results on a map: it presents non-spatialized LCIA results on a map. For example, it can be a map showing climate change scores of farms in a region or environmental impacts of different scenarios for the location of a waste treatment plant.
3. Mapped results: location-specific results on a map can be based on spatialized LCI (representing the contribution of each location to the total result) or on spatialized LCIA (representing the spread of impacts in the study area). Examples are rare in literature but can be of great help in decision making at the local scale.

Pathways for the continuum

Starting from the end

The main idea of the continuum of spatialization is that it is not possible or relevant to provide spatialized results in step 4 without integrating spatial information in the previous steps. In a decision-making context, the first step is thus to answer the question: what level of spatialization is required to provide LCA results that are useful for the system studied? The level of spatialization desired for results will determine the level required for the LCIA and each previous step. The level of spatialization desired for results depends on multiple parameters (e.g. nature of the system, choices of decision makers), which are not discussed in this study.

Pathways

Following the concept of the continuum, each later step (2-4) depends on the previous step. Consequently, (i) minimum, (ii) minimum and recommended and (iii) recommended levels of step (n-1) to reach level X of step n were determined (Figure 2). The minimum pathway represents the minimum level of spatialization that step (n-1) should have to reach the desired level for step n, while the recommended pathway is the relevant level. By determining these pathways for each pair of steps, continuous pathways were drawn through the four steps of the continuum. For example, if LCA practitioners want results on a map (level 2 of step 4), they should use site-dependent CFs, integrate some spatial information into the LCI and precisely contextualize the system into its surroundings. At a minimum, they must separate foreground and background processes (if spatially relevant) in the LCI and LCIA. Two levels are never followed since they are neither minimum nor recommended.

Technical and practical feasibility

The feasibility of the continuum and inherent development needs are important considerations. Since spatialization is not a pillar of LCA, some adaptations are necessary, especially from a software perspective. In a way, it seems indispensable to link LCA with GIS, since they have already been associated for years (Bengtsson et al., 1998). They can be connected in two ways: including GIS in the LCA framework (Figure 3) or including LCA in GIS (Figure 4). In either case, connecting tools (e.g. Database Management Systems) need to be used (not shown in figures).

In the first solution, the methodological framework of LCA is used as a basis. For each step, spatialization developments, such as spatialized CFs for LCIA, exist and can be provided by GIS. GIS thus becomes an external tool that adds spatial information to the LCA framework. To ensure propagation of spatial information from one step to another, at least three additional necessary steps were identified: (1) spatially classify system processes as a function of location, (2) include spatial information (archetype and/or coordinates) into the LCI and (3) spatially aggregate input and output flows that occur at the same location. For the last step, several aggregations are necessary, since the geographical scale differs by impact category. For example, pollutants emitted in locations A and B could remain disaggregated for eutrophication but be aggregated for acidification. This approach seems LCA-friendly since it uses the LCA framework as a basis, which allows LCA practitioners to adopt it easily. It requires several exchanges between tools (LCA, GIS, databases) but not necessarily a strong knowledge of GIS.

The second approach uses GIS as a basis and then rebuilds the LCA framework into GIS tools. GIS software is thus the main tool in which each LCA step is modeled. Consequently, the system is modeled in a GIS that can include spatial information in the goal and scope definition, define a spatialized system and then generate a spatialized LCI. The LCI maps generated are combined with spatialized CF maps to obtain environmental impact maps as a result. The spatial information is stored in GIS databases in the form of attribute tables that can be combined for calculations. This solution's main advantage is that it is all-in-one software, but it requires considerable development before becoming operational. At the moment, some maps of CFs are available, but no LCIs have been mapped, since that represents a large amount of work. Furthermore, if the target is LCA practitioners, this solution probably requires learning too much GIS.

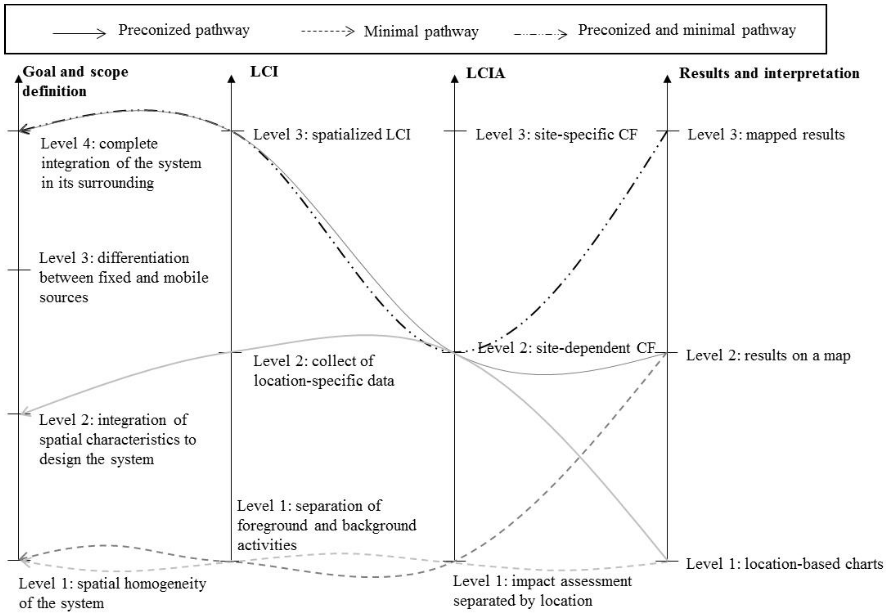

Figure 2. Minimum and/or recommended levels of spatialization at each LCA step to achieve a given level of spatialization at the Results and interpretation step

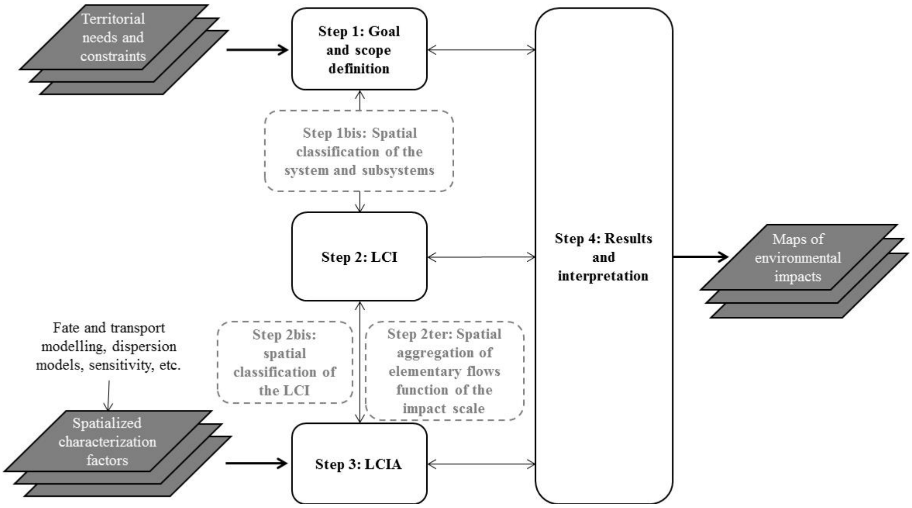

Figure 3. Geographic Information System in Life Cycle Assessment. Connecting tools are not shown.

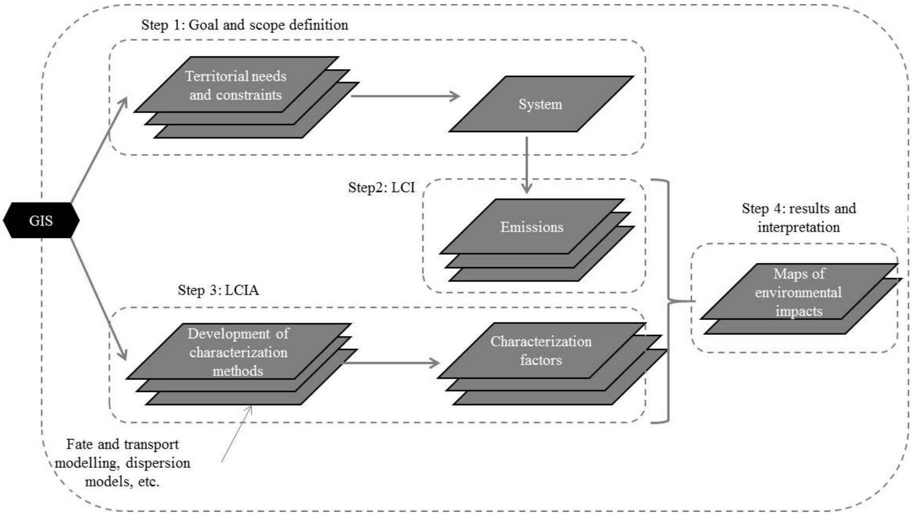

Figure 4. Life Cycle Assessment in a Geographic Information System. Connecting tools are not shown.

Table 1 summarizes main characteristics of the two solutions.

Table 1. Characteritics of each approach to connecting Life Cycle Assessment (LCA) and Geographic Information Systems (GIS)

GIS in LCA	LCA in GIS
LCA software remains the basis	Need to implement inventories (e.g. ecoinvent, ELCD) and characterization methods in GIS
Moderate level of GIS knowledge required	High level of GIS knowledge required
Less complicated for LCA practitioners	Difficulty in modeling parametrized processes
Multiple exchanges between software tools	All-in-one tools

Finally, in addition to conceptual developments, the continuum faces a technical issue: is it possible and relevant to couple LCA and GIS software? This question leads to others: (1) is it preferable to choose software or freeware?, (2) how to ensure the link between LCA and GIS (spreadsheets, additional software)? and (3) what additional tools are necessary (dispersion models, GIS toolboxes, agent-based models)? Preliminary answers to these questions are summarized (Figure 5). For both LCA and GIS, freeware exists and is attracting an increasing number of users. Freeware's main advantage for spatialization is that it is often open-source, providing the ability to develop new modules (especially since most LCA and GIS tools use the same programming language). Its main disadvantage is that it is not widely used by LCA practitioners and lacks user-friendliness. Since LCA and GIS cannot address all spatialization needs, additional tools are necessary. Some examples were identified, such as dispersion models to spatialize pollutant flows more accurately in the LCI, for example in case studies about mobility. It is also necessary to ensure the interface between LCA and GIS. While it can be facilitated by a common programming language, additional tools are also required. A simple one would be a spreadsheet that could, for example, export locations of processes from the GIS to supply LCIs with geographic coordinates.

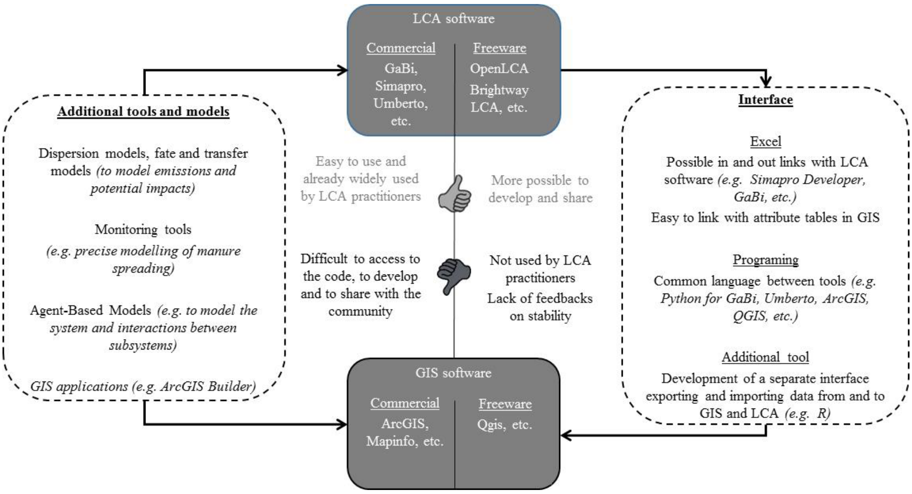

Figure 5. Possible technical choices to apply the continuum of spatialization

Conclusion

Regarding theory, the literature review highlighted some methodological developments for each LCA step, as well as some methodological gaps. Existing and needed methodological links between steps were observed, which led to the definition of different levels of consideration of spatial information for each LCA step. Then, pathways were developed that link LCA steps according to necessary conditions for spatialization. Concretely, the necessary level of spatialization for step (n-1) was defined for each desired level for step n. In a decision-making context, stakeholders and LCA practitioners will choose the desired spatialization level of the results, from which the required level for each LCA step will follow. A complete pathway (linking the four LCA steps) is called a continuum of spatialization. The continuum of spatialization concept developed must be expanded, and new levels should be added for each LCA step. A method to choose the appropriate starting point (e.g. the desired spatialization level of the results) is also lacking. The choice should be made in accordance with decision makers using a decision tree that answers questions such as: how spatially dependent is the system?, how spatially dependent is the issue?, who will see the results and what is their level of understanding?

Regarding practice, the initial lines of thought were explored and elaborated to develop an operational coupling of LCA and GIS. Two options were compared: LCA in GIS software and GIS in LCA software. Each option has different technical, learning and development challenges. Since the main target is LCA practitioners, the second option is preferred, since it uses LCA software as a basis and requires less knowledge of GIS tools. Application questions remain, such as the choice between commercial software and freeware or the need to use other software and models.

Spatialization is far from being a new subject in LCA. However, with the development of new kinds of LCA, notably territorial LCAs, and the objective to use LCA for emerging topics such as spatial planning or local decision-making, there is a need for complete integration of spatial information throughout the LCA framework. Many developments have existed since the early days of LCA, but they cannot propagate spatial information from the goal and scope to the results of an LCA study. This would be possible by developing the continuum of spatialization concept, whose foundations were laid in this study.

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From spatialization of LCA to its application to industrial ecology

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Introduction

The concepts of "territory" and "territorialization" have led to strong debates between geographers since the 1960-1970s. Political, economic and social dimensions of a territory have been discussed and analyzed according different points of view. Among the best known examples, Michaël Storper studied territorialized economic development to understand economic activity depending on territorial resources (Storper 1997), while Claude Raffestin discussed "social space", using an idea of Henri Lefebvre, to designate a "production" that makes a community develop from its surrounding ecosystem. Therefore, a territory is the result of the production of actors (Raffestin and Butler 2012). The present study does not aim to discuss the legitimacy of the term "territory" but to use it to connect industrial ecology to Life Cycle Assessment (LCA).

Industrial ecology and LCA are scientific fields supported by different applications and methods. Industrial ecology aims to understand how to design sustainable industrial systems, while LCA is a method useful for quantifying environmental impacts of a product or service. These issues are important to address according to the territory of implementation, because the sustainability of an industrial system depends on local, urban and regional contexts. This is why these methods probably need to be improved with spatial analysis. How can one implement the territorial dimension using industrial ecology and LCA? How can spatialization of LCA improve its application to industrial ecology?

Industrial ecology, circular economy and the territory

From the territorial dimension in industrial ecology…

Industrial ecology is a scientific field that is structured by analogy to natural ecosystems (Ehrenfeld, 2004) and supported by the International Society of Industrial Ecology (ISIE) and the *Journal of Industrial Ecology*, both created in the 1990s. Industrial ecology requires initiating profound changes in industrial systems towards "ecostructuration strategies" (Bourg, 2002). Suren Erkman identifies the beginning of this concept in the 1960s, with pioneers Robert Ayres and Preston Cloud in the USA, Jacques Vigneron in France and Peter Baccini in

Switzerland, who worked on the relationship between ecology and economy, and the expression of the oxymoron "industrial ecosystem" (Erkman, 2004).

The field of industrial ecology is known to promote implementation of operational projects such as "industrial symbiosis". It aims to close loops of material and energy flows in industrial areas, such as the oft-cited example of the Kalundborg symbiosis, (Christensen, 2006; Jacobsen, 2006). However, industrial ecology cannot be limited to industrial symbiosis and still provide research on several other issues, such: Eco-industrial Development, Socio-Economic Metabolism, Sustainable Urban Systems, Organizing Sustainable Consumption and Production, Environmental Extended Input Output, Life Cycle Sustainability Assessment. All of these are mentioned in the most recent collective report of the ISIE (Clift et Druckman 2016), which shows the variety of social, territorial and economic systems that are studied. While the spatial and social dimensions of these issues can be studied, the concept of territory is not really discussed. According to our review, authors consider the role of a territory as:

- An area with particular characteristics and industrial boundaries, such as an economic activity zones or harbor (Chertow 2007; Mirata et Emtairah 2005; Schiller, Penn, et Basson 2014). In this case, the territory is merely the area where the industrial park is located, but it also provides opportunities for synergy because of the geographical proximity of industrial stakeholders. For some authors, a territory plays a role in synergies as a resource provider or project facilitator (Beaurain et Brullot 2011; Boons, Spekkink, et Mouzakitis 2011).
- An administrative area within which a society's metabolisms can be studied. Therefore, the territory is correlated with spatial planning. Depending on the geographical level, it concerns urban, regional or national plans that aim to optimize circulation of material and energy flows (Billen *et al.* 1983; Fischer-Kowalski and Haberl 2007; Kennedy and Hoornweg 2012; Ferrao and Fernández 2013).
- The location of environmental impacts. These studies are focused on LCA and consumption-based accounting. Hence, emissions and wastes are generated in the territory (Life Cycle Sustainability Assessment approach, e.g. Tom Wiedman in Clift et Druckman (2016)), and they come from an area of resource consumption (Druckman et Jackson 2009).

In France, a new scientific field has emerged involving social and spatial analysis of industrial ecology: "territorial ecology". This concept is defined by Sabine Barles as: "industrial ecology that is considered in a spatial context and that takes into account the stakeholders and, more generally, the agents involved in material flows, questions their management methods and considers the economic and social consequences of these flows" (Barles 2010). This definition leads to the organization of an interdisciplinary field of research (Buclet 2011; Junqua et

Brullot 2015), within which social sciences and land planning have a strong role. We consider that territorial ecology corresponds to Bahers (2014):

- A territorialized approach to flow circulation and stakeholder systems
- Implementation of this "resource-waste" ecology in regional and urban plans

This new field is similar to the "social ecology" of the Institute of Social Ecology in Vienna (Haberl *et al.* 2016), but the latter differs in that it focuses mainly on national areas (e.g. Austria, Germany, India, China) instead of regional or urban areas, as suggested in territorial ecology.

… to the territorialization of circular economy

The new program of circular economy, which is having great success, is supposed to fulfill a renewed vision of resource and waste management. According to the French environmental agency (ADEME), industrial symbiosis, product eco-design, sustainable consumption and the 4R-V (Reduction at source, Reuse of a product, Recovery, Recycling and Valorization of residual material) are the pillars of this political and economic program.

The territorial dimension in the French implementation of circular economy is mentioned because it requires facilitating *the strengthening of cooperation between economic actors at the relevant scale taking into account the principle of proximity (*Translated by ourselves)*,* as laid down in the first regulatory definition in 2014 within the law of "Energetic Transition"[1]. We can see in this definition that there is no indication about at which spatial scale circular economy strategies should be implemented. According to the European Union, the territorial approach disappears completely, since the first target is to promote the efficiency of resource use to maximize economic growth (EC, 2014; 2015).

Therefore, few authors use the territorial approach to study the political program of circular economy. Gregson *et al.* (2015) use spatial distance to criticize initiatives that are unable to reuse all waste at a local scale. The emerging circular economy, according to them, *entails challenges borne of a conjuncture of politically created markets, material properties and morally defined material circuits* (Gregson, 2015). The political action of circular economy depends on local actors adopting the issue. This perspective is also studied by researchers, who talk about "generative spaces" for developing circular economy from citizen engagement (Hobson, 2015). (Ghisellini et al., 2016) consider that the perspectives of circular economy should differ by socio-technical level (providing information to policy makers at the macro level; developing industrial symbiosis at the meso level; and selling, renovating and remanufacturing a service (instead of a product) at the micro level). Nevertheless, the spatial issue is mentioned only at the meso level for eco-industrial parks. Industrial symbiosis thus seems to reveal the territorial dimension of a circular economy. It requires a comprehensive knowledge of the local context to be implemented, especially about local actors' interests.

Industrial symbiosis as a spatialized system

We see industrial symbiosis as the most famous example of the industrial ecology approach, forming a complete system by setting up synergies between economic agents. The best known type of synergy is the recycling of waste or a byproduct of one business into material for another. However, the literature shows other types of synergies: organizational, relational and strategic (Massard, 2011). Another aspect of these synergies is the agreement to exchange materials and protect them from the economic fluctuation of raw material exchange rates. Beyond relationships based on byproduct recycling, industrial symbiosis can be defined through agreements between companies that otherwise would be alone (Jensen, 2012). Establishing agreements can be facilitated by spatial proximity of the agents, allowing for mutual trust (Jensen, 2012; Chertow, 2000). This spatial proximity leads companies to share technical knowledge, best practices and investigations through mutualism, vital for the proper functioning of the symbiosis (Christiansen, 1994, in Ehrenfeld, 1997). Nevertheless, industrial symbiosis is a spatialized system of material and immaterial exchanges, leading agents to create social proximity depending on their motivations and aims, but also to address environmental and territorial constraints (Chertow, 2000). According to several authors (Van Berkel, 2009; Sokka, 2011), however, the legitimacy of industrial symbioses is based on the hypothesis that their synergistic exchanges are greener, which has been demonstrated qualitatively but not quantitatively. To validate this hypothesis, one can consider quantifying environmental benefits of industrial symbioses, as often seen in studies of industrial symbioses. How can environmental evaluation tools quantify environmental benefits of industrial symbiosis, which is a spatialized system? We focus this study on LCA, a robust tool for assessing environmental impacts of complex systems such as industrial symbioses.

LCA AS A TOOL TO QUANTIFY ENVIRONMENTAL BENEFITS OF INDUSTRIAL SYMBIOSIS

LCA is a normalized method to quantify potential environmental issues and environmental impacts through the entire life cycle of a product. LCA is an iterative method composed of four phases: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation of the results of each phase. Much research has been performed to improve LCA methodology in the past two decades, but little has been applied to industrial symbiosis, with methodological issues specific to it (Mattila 2012). The first issue is to quantify environmental benefits by comparison with a reference scenario built to satisfy the same functional unit as that in the symbiotic scenario (Martin, 2015). The functional unit is an essential point for LCAs of industrial symbioses when the aim is to quantify their environmental benefits. Nevertheless, the specific recycling of material flows in industrial symbioses makes the creation of this reference scenario sensitive to methodological assumptions of the LCA practitioner.

The reference scenario used most in the literature is the industrial symbiosis studied without synergies among the companies of the system (van Berkel 2010; Martin 2015). To build a scenario without synergies, LCA practitioners should ask which raw material to consider instead of the non-recycled byproduct and how this non-recycled byproduct should be managed for each synergy of the system. This can be done with system expansion, considering more raw material production and more byproducts to manage than in the symbiotic scenario. However, this method has weaknesses due to the need to make several assumptions (Mattila 2012). Selecting the suitable reference scenario decreases overestimates of environmental benefits of the industrial symbiosis (Mattila 2012).

To consider this sensitivity, different assumptions can be tested by producing several reference scenarios, allowing a sensitivity analysis to be performed (Martin, 2015). Sensitivity of a reference scenario produces a variety of useful reference scenarios and thus variability in their environmental impacts. When comparing the symbiotic scenario to the reference scenarios, the variability in environmental impacts of the latter causes variability in environmental benefits of the industrial symbiosis studied. There is a need to quantify this variability to know whether the industrial symbiosis leads to environmental benefits and to quantify them.

A territorial approach to consider characteristics of industrial symbioses and quantify their environmental benefits

To assess the reference scenario's variability without creating too many reference scenarios, worst-case and best-case reference scenarios can be created to quantify the widest variability in the reference scenario to estimate the range of environmental impacts of the industrial symbiosis. One can assume that all reference scenarios have environmental impacts between the two extremes.

Moreover, environmental impacts of the industrial symbiosis can be compared to those of the best and worst cases.

- If the industrial symbiosis has less environmental impact than the best-case reference scenario, there is a strict environmental benefit of the industrial symbiosis, regardless of the reference scenario chosen.
- If the industrial symbiosis has more environmental impact than the worst-case reference scenario, there is a strict environmental detriment of the industrial symbiosis, regardless of the reference scenario chosen.
- Between these two extremes, relative environmental benefits depend on the reference scenario chosen.

Our literature review revealed two different cases with two different approaches to create the worst-case reference scenario:

- If the territory currently has an industrial symbiosis, the worst-case reference scenario of the industrial symbiosis is created by considering the companies of the industrial symbiosis without recycling linkages (Sokka *et al.* 2011; Eckelman et Chertow 2013; Dong *et al.* 2014; Martin 2015; Daddi, Nucci, et Iraldo 2017)waste material and energy are shared or exchanged among the actors of the system, thereby reducing the consumption of virgin material and energy inputs, and likewise the generation of waste and emissions. In this study, the environmental impacts of an industrial ecosystem centered around a pulp and paper mill and operating as an IS are analyzed using life cycle assessment (LCA.
- If the industrial symbiosis studied is prospective, the worst-case reference scenario is created with average technologies satisfying the same functional unit as the symbiosis (Liu *et al.* 2011; Blengini *et al.* 2012; Ammenberg *et al.* 2015; Mohammed *et al.* 2016)total energy consumption and operation cost. In Jinqiao EIP, Pudong New Area, Shanghai, an industrial symbiosis, based on the energy recovery from municipal sewage sludge and re-refined oil, was proposed in the central heat-supplying company of Jinqiao EIP. It is expected that hot off-gas or part of the steam from the central heat-supplying company could be used for sludge drying and used oil re-refining while the dried sludge and refined oil can be partial substitution for fossil fuel. For the purpose of assessing the environmental performance of this industrial symbiosis, life cycle assessment (LCA. This second option can be followed by reviewing technical solutions used in the territory to consider local technologies satisfying the functional unit chosen.

The reasonably best-case scenario needs to show an improvement compared to the reasonably worst-case scenario. Consideration of processes using marginal technologies (e.g. renewable energy instead of fossil energy) and best available technologies to improve current ones can lead to a best case that replaces worst-case processes, according to our research. Indeed, new industrial processes, spatialized like industrial symbiosis, are implemented considering economic, social and political motivations (Chertow, 2007. The technical improvements assessed should consider local political priorities and regulations (e.g. for waste) and be limited by the availability of raw materials, land availability for facilities, local skills to develop and operate the new technologies but also the social acceptance by the neighborhood.

Interviews with local agents about issues and constraints in the best-case reference scenarios assessed lead to definition of those scenarios that are reasonable. Therefore, one strong approach is to satisfy most strategic goals and needs for technical improvements of local agents. This resulting reference scenario has a reasonable chance to be implemented in the territory if the industrial symbiosis is not developed. The key agents for this evaluation are local politicians, local experts who know the environmental issues of the territory, institutions in charge of waste management and local inhabitants.

Conclusion

1. In conclusion, it appears that a territorial approach is required to assess the environmental benefits of industrial symbiosis. There are many perspectives to improve LCA methodology with spatial, social and political dimensions, according to the territoriality of industrial symbiosis.
2. Therefore, urban and territorial metabolism is a powerful concept that could be interesting to use. It provides keys for understanding socio-ecological dynamics (Bahers 2014, Buclet 2015;) towards better knowledge of the resource space and actors' systems. Territorial metabolism also gives opportunities to examine metabolic links between territories, their environments and their supply and disposal territories as a means to transition towards a circular economy. Analyzing inter-territorial relationships from the viewpoint of metabolic functioning constitutes a preferred opening to reach this perspective.

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Conclusion of Part III

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The objective of this final session was to put the feasibility, uses, utility and limits of spatializing Life Cycle Assessment (LCA) into perspective. In light of these presentations, it is possible to answer two questions.

How can the LCA community increase the applicability of spatialization in LCA?

If the LCA community decides to expand spatialization in LCA, several tasks must be performed. The first is to develop the conceptual framework to propagate spatial information throughout all LCA steps. This conceptual framework is a kind of continuum using the concept of spatialization level and some spatialization pathways, as described by Samuel Le Féon. This framework should be supported by standards to become mainstream. Developing this framework is also an opportunity to question the place of time-related information. Can temporal and spatial information be separated? Integrating time-related information is likely the next step to increase the relevance of LCA results. The issue of spatio-temporal data integration in Life Cycle Inventory (LCI) refers to the matrix structure of LCA, but it is not a technical problem, as mentioned by Pierre Collet. The integration of many data in LCI, however, reflects the question of the accurate use of so much data to perform a LCA. So the question becomes: How can "big data" help improve LCA practices and results? The big data concept is also a challenge outside of the LCA community, since the issue is not collecting the data but organizing and using it in a relevant manner.

Based on a new conceptual framework, the use of different tools to perform LCA will become the heart of the debate and the research. Different issues will emerge, such as the need for and type of interoperability between LCA and other tools, such as GIS or quantitative models. This interoperability can be integrative or federative and depends on the expected complexity of system modeling. According to Vincent Colomb (ADEME), freeware will definitely be chosen to provide simple, inexpensive and intuitive tools that will be the keys to success in spatializing LCA.

Is spatialized LCA useful for assessing territorial projects?

The territory concept is increasingly cited and used by LCA practitioners to put their results in a territorial perspective or to attempt to assess a territory as an object. According to Jean-Baptiste Bahers, the risk is to underestimate the complexity of the territory concept and to ruin the importance of contextualizing LCA to increase the relevance of LCA results. As mentioned, a robust framework is needed. In addition, connections with industrial ecology tools, such as material flow analysis, must be made. Stakeholders' representations are too complex to be examined only through the spatial prism.

Vincent Colomb (ADEME) suggested that if contextualization/spatialization is performed in detail in LCAs, these LCAs may reconcile production systems with their territory and allow for a multiscale approach (product, industrial sector and territory). In this way, LCA may be an effective tool to integrate a project into its territory.

Conclusion of the workshop

Research agenda for spatialization in LCA

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This workshop highlighted the need for spatialization in Life Cycle Assessment (LCA) to improve robustness of LCA results and presented a variety of existing tools and methods. During this workshop, several questions emerged to improve the relevance and feasibility of the integration of spatial information, and some answers were identified.

The issue of the most appropriate resolution

The most appropriate spatial scale at which to consider spatial information depends on the nature of the impact and its associated emissions. The nature of the impact first determines a geographical area (watershed, urban area, region, etc.) for the extent of the impact's effect. Second, this area's relevance has to be put into perspective with the nature and, especially, fate of emissions. The area of emission fate cannot be the area of impact effect. In this case, both areas are superimposed to obtain the native resolution.

Considering the native resolution is recommended; however, it is sometimes necessary to aggregate spatially. Spatial aggregation can be applied at different scales, such as the region, country, continent or world. Spatial aggregation at continent or country scales has a high level of uncertainty that could nullify the utility of spatialization.

The issue of the change in scale

Spatializing the Life Cycle Inventory (LCI) is time consuming. Thus, LCA practitioners use many strategies to choose the life cycle stages to be spatialized and thus to prioritize their efforts to obtain spatialized LCI. Two strategies arise:

- Using uncertainty analysis to identify the most uncertain life cycle stages to be spatialized
- Using the spatialization continuum framework to identify the nature of spatialized LCA results, which influences the level of spatial differentiation at different LCA steps

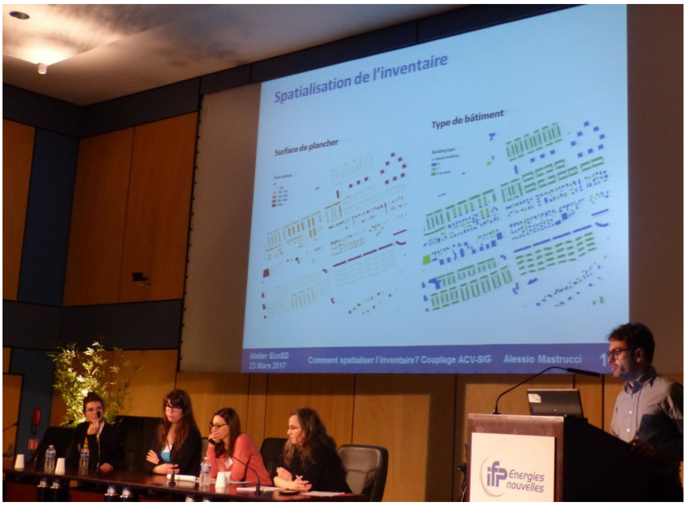
For each case study, LCA practitioners, with the help of decision makers, have to determine the most relevant strategies to identify the life cycle stages to be spatialized and to limit uncertainties due to spatialization.

Despite these answers, the change in scale remains the most complex issue facing implementation of spatial differentiation in LCA and concerns both the LCI and Life Cycle Impact Assessment (LCIA). For the LCI, the issue is to connect spatialized and non-spatialized life cycle stages. For LCIA, the issue is to connect the area of emission fate and the area of impact effect. The change in scale should be resolved to perform robust spatialized LCA.

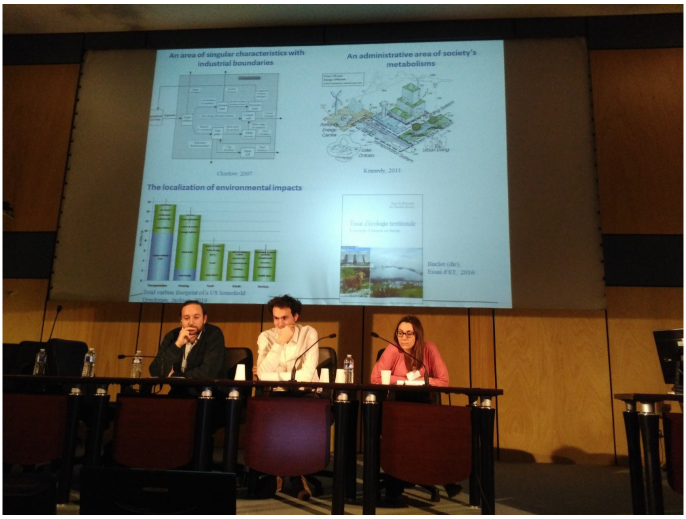
Towards the concept of territory

Spatialization of LCA refers to the concept of territory and always to that of industrial ecology. Integrating spatial information in LCA makes it possible to use LCA to assess industrial ecology scenarios. However, spatial differentiation is necessary but not sufficient to assess such scenarios in a relevant manner. The risk is to underestimate the complexity of the territory concept, especially its organizational dimension. As mentioned, a robust framework is needed. Industrial ecology case studies are too complex to be examined only through the spatial prism. The research challenge is to integrate in LCA not only the spatial dimension but also organizational and identity dimensions through stakeholders' representations.


Journée thématique EcoSD 2017 - La spatialisation en ACV
à IFPEN le 23 mars 2017


Spatialisation de l'inventaire
Surface de plancher
Type de bâtiment
Atelier EcoSD
23 Mars 2017
Comment spatialiser l'inventaire? Couplage ACV-SIG
Alessio Mastrucci
Énergies nouvelles


L'avis des utilisateurs
Pour un constructeur « Ensemblier », l'usage du logiciel NOVAEQUER et de ses développements en cours sur la spatialisation des émissions de polluants est « naturel ».
L'objet analysé, un territoire, est par nature spatialisé.
Il importe d'en rendre les résultats encore plus lisibles c'est l'objectif de la "signature" qui transcrit l'efficience du tissu urbain.


An area of singular characteristics with industrial boundaries
Chertow, 2007
An administrative area of society's metabolisms
Lake Ontario
Transportation System
Urban Living
Kennedy, 2011
The localization of environmental impacts
Total carbon footprint of a US household
Essai d'écologie territoriale
Buclet (dir),
Essai d'ET, 2016