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Rédacteurs	Vérificateurs	Approbateurs
Georg SEITFUDEM Pablo TIRADO SECO Ivan VIVEROS SANTOS	Cécile BULLE Laure PATOUILARD Julien PEDNEAULT	François SAUNIER

International Reference Center for Life Cycle
Assessment and Sustainable Transition (CIRAIG)
www.ciraig.org



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- En Bibliographie, ce document sera cité sous la référence :
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- Les informations et les conclusions présentées dans le présent document ont été établies au vu des données scientifiques et techniques et d'un cadre réglementaire et normatif en vigueur à la date de l'édition des documents.

1. Background and objective of the study

Since the early days of Life Cycle Assessment (LCA), the integration of the spatial dimension has been a subject of study and development. About ten years ago, ScoreLCA published work on the integration of the geographical dimension in LCA. This study is a continuation of those studies, with the aim of assessing the spatialization of impacts in LCA through a review of existing methods, a case study and practical recommendations aimed at users and developers of LCA tools.

The specific objectives of the project included :

- A state-of-the-art report on the integration of geographical aspects in LCA;
- A case study to illustrate the operational challenges;
- Recommendations for practitioners and developers;
- Disseminate the results of this work to different audiences.

This document is a summary of the complete study available online on the ScoreLCA website:

SCORE LCA, Spatialisation des impacts en ACV, 2024, 179 pages, n°2023-05.

2. Concepts linked to spatialization of impacts

In the scientific literature, various terms related to the integration of the geographical dimension in LCA are often used interchangeably, without an explicit clarification of the vocabulary. This document adopts and enhances the definitions established in the 2015 ScoreLCA study, carried out jointly by CIRAIG and IFP Énergies Nouvelles (Patouillard et al., 2015), which were taken up in the subsequent article by Patouillard et al. (2018).

2.1 Basic terminology

Spatial unit: This is the geometric definition of a spatial entity, such as the coordinates of a raster cell or polygon, along with all associated spatial and non-spatial metadata (Mutel et al., 2019). A spatial unit therefore corresponds to a region.

Spatial resolution: This is the set of spatial units used in an inventory database or impact assessment method (LCIA). This definition differs slightly from the traditional definition of spatial resolution, which generally refers to the smallest distinguishable spatial units. Indeed, in LCIA methods, spatial units such as watersheds, can vary considerably in size (Mutel et al., 2019).

Spatial scale is defined as the level of analysis or detail at which data is observed or presented. It determines the size and scope of the spatial units (regions) used in LCA. A larger spatial scale might include extensive geographical regions with larger spatial units, while a finer spatial scale would focus on smaller areas with more detailed spatial units. Spatial scale thus has a direct influence on the granularity and scope of spatial considerations in LCA.

Regionalization: term used to describe the representativeness of processes and phenomena in a given region (Patouillard et al., 2018).

Spatialization: the action of assigning a location to something, for example, an elementary flow or an impact score (Patouillard et al., 2018).

Inventory regionalization: This involves improving the geographical representativeness of inventory data, by refining the type and quantity of economic and elemental flows to match the specific geographical areas where activities take place (Patouillard et al., 2018). The result is a regionalized inventory model, and this operation is performed either by LCI database designers or by LCA practitioners.

Impact regionalization: This involves calculating regionalized CFs specific to a geographical area for the same elementary flow, taking into account the spatial variability of the most influential environmental parameters and mechanisms. This task is performed by the developers of LCIA methods (Patouillard et al., 2018). LCIA method developers can provide these CFs themselves in software-compatible formats or pass on a native version to LCA software developers, so that they can integrate them into their tools.

Spatialization of the inventory: This process involves assigning a geographical location to the elementary flows based on their place of origin. Different geographic scales can be used, such as geographic coordinates, administrative regions or archetypes (Patouillard et al., 2018). The result of this operation is a spatialized inventory, which can be presented in different ways: either as a list of elementary flows with associated spatial information, or on a map per elementary flow showing the emission or abstraction locations of that flow. This task can be performed by the LCA practitioner when assigning a location to the elementary flow corresponding to the region of the process being modeled. Some LCA software packages facilitate this spatialization by integrating geographic information system

(GIS) algorithms that can associate a location to elementary flows according to their origin. This approach avoids duplication of elementary flows and simplifies manual spatialization, which nevertheless remains a task for the LCA practitioner or LCI database developers.

Impact spatialization : Spatializing impacts involves distributing impact scores geographically, according to their origin or destination. This operation is carried out using specialized LCA software, which means that analyses incorporating the spatialization of impacts are limited by the functionalities of this software.

Regionalized LCA: LCA that calculates spatialized impact scores by combining a spatialized inventory with regionalized CF.

2.2 Regionalized LCA calculation

2.2.1 Impact spatialization steps

With the exception of global impact categories, a spatialization of impacts requires two fundamental conditions: a spatialized inventory and the availability of regionalized CF (Figure1).

The spatialized inventory results from the spatialization process, which may be carried out by the LCI database developer or by the LCA practitioner. An additional step, usually carried out either within the software or by the LCA method developers, is to calculate aggregated regionalized CFs at the inventory scale from the regionalized CFs at their native scale. Once the inventory and the CFs have been harmonized at the same scale, they are linked by matrix calculations integrated into the LCA software. It is important to note that the spatialized impact score will be consistent with the inventory scale.

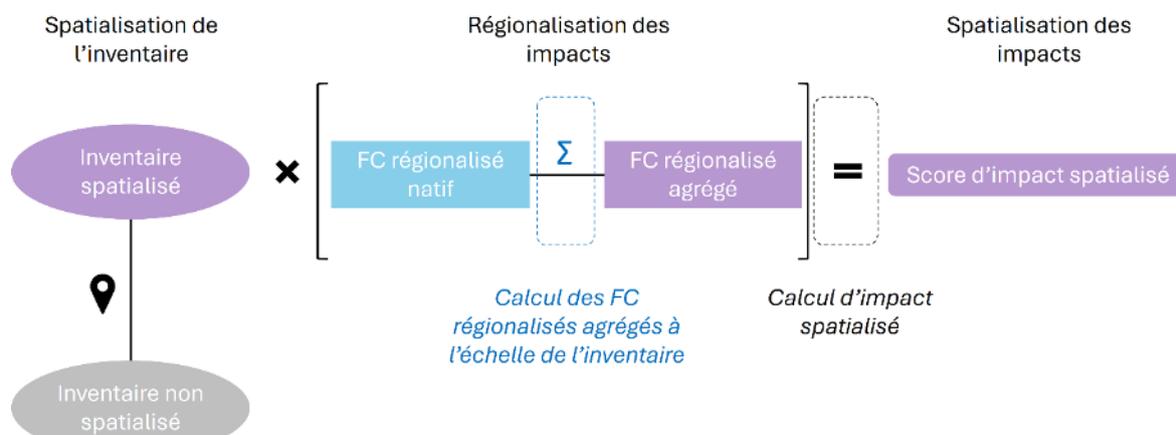


Figure1 . Stages in the spatialization of impacts, with colors indicating different scales.

3. State of the art of impact spatialization in LCA

3.1 Identification of methodological issues and current limitations

Taking the geographical dimension into account is an essential element of LCA for several reasons: the location of the system when defining objectives and context, the modeling of supply chains that take place in different regions of the world, the calculation of emission impacts that will depend on the place of emission, but also on dispersion from this place of emission and the sensitivity of the receiving environment (Patouillard et al., 2015). The level of precision of this geographical information will determine the reliability and accuracy of the calculated results. The previous ScoreLCA report on the subject (Patouillard et al. (2015) gave a general overview of the state of play in taking account of the geographical dimension in LCA, and identified various issues related to this dimension:

- Integration into inventories (regionalization and spatialization) and databases;
- Taking impact methods into account in development;
- Interpretation of results;
- Integrating geographic information into LCA software.

In the same vein, Mutel et al. (2019) identify the main challenges of taking into account the geographical dimension in LCA, including:

- Harmonization with inventory data: Align the spatial resolutions of regionalized impacts with life cycle inventory data, which are often aggregated to a more general level;
- Development of LCIA methods: Constant development is needed to improve the accuracy of regionalized assessment methods and their applicability to diverse geographical environments;
- Spatial aggregation methods: Develop approaches for aggregating or detailing spatial data in order to maintain or improve the relevance of regionalized LCIA results;
- Operationalization: Ensure that regionalization works in everyday LCA practice, including effective integration into LCA software and facilitation of its use by practitioners;
- Uncertainty assessment: Understand and manage uncertainty related to input parameters and model structure used in regionalized impact assessments.

3.2 Life cycle inventory

The creation of regionalized inventories can require considerable effort, depending on data availability and the level of regionalization envisaged. However, the availability of LCI data with associated geographic information is a crucial issue for calculating regionalized impact results and reducing the uncertainty inherent in the inventory.

Geographic information is associated with the process, which affects two aspects:

- The nature of inputs and outputs to and from the technosphere (e.g. the electrical *grid-mix* used, the yield of a crop or the type of transport existing). This is what we define, adopting the nomenclature of Patouillard et al. 2015, as the **regionalization** of the inventory.
- The location of the elementary flows that will form part of the inventory and will be used to calculate impact results. This is what we define, adopting the nomenclature of Patouillard et al. 2015, as the **spatialization** of inventory **flows**.

3.2.1 Databases

As outlined in the study by Patouillard et al. (2015), the databases integrate the geographical dimension at the level of inventory regionalization, regions covered, and operationalization of elemental flow spatialization. Based on these questions, Table 1 summarizes the spatial treatment of various ICV databases.

Table 1. The spatial dimension in various ICV databases.

Database	Regions covered	Regionalization of the inventory	Spatialization of flows
ecoinvent	Several	Yes	According to software (water and land use)
Managed content (GaBi) LCA	Several	Yes	Water and land use only, via LCA for Experts (GaBi)
USLCI	US mainly	Yes	No
Agribalyse	France (+ecoinvent)	Yes	According to software (water and land use)
Agrifootprint	Several	Yes	No

3.3 LCIA methods

After the spatialized inventory, the second element required to calculate regionalized impacts is a regionalized impact method, i.e., with CFs that each model the cause-effect chain of an environmental intervention (withdrawal of a primary resource or emission) from a precise point of origin.

3.3.1 A review of the latest LCIA methods

Since the last ScoreLCA-sponsored report on the integration of the geographical dimension in LCA (Patouillard et al., 2015), there have been significant advances in LCIA methods, particularly in incorporating developments relating to regionalized impact categories. In this section, we highlight the main LCIA methods currently in use: IMPACT World+ (Bulle et al., 2019), ReCiPe 2016 (Huijbregts et al., 2017), EF3.0 (EPLCA, 2024) and LC-IMPACT (Verones et al., 2020). Although the LCIA method resulting from the work of the *Life Cycle Initiative's GLAM (Global Guidance for Life Cycle Impact Assessment Indicators and Methods)* project has not yet been published¹, we also devote a subsection to it in order to present the recommendations of the working group aimed at developing a consensus method, reconciling scientific rigor and applicability (Frischknecht & Jolliet, 2017, 2019).

Figure 2 summarizes the inclusion of the geographical dimension in the main LCA methods and its integration in the main LCA software.

¹ An interim version has been available since October 2024, but the analysis is based on information available prior to the publication of this version.

	IW+	ReCiPe	EF 3.1	LC-IMPACT
Nombre de catégories	v. Midpoint: 17 v. Endpoint: 27 (2 endpoint)	22 (3 endpoint)	17	20 (3 endpoint)
Catégories avec FC différenciés spatialement	11	5	2	9

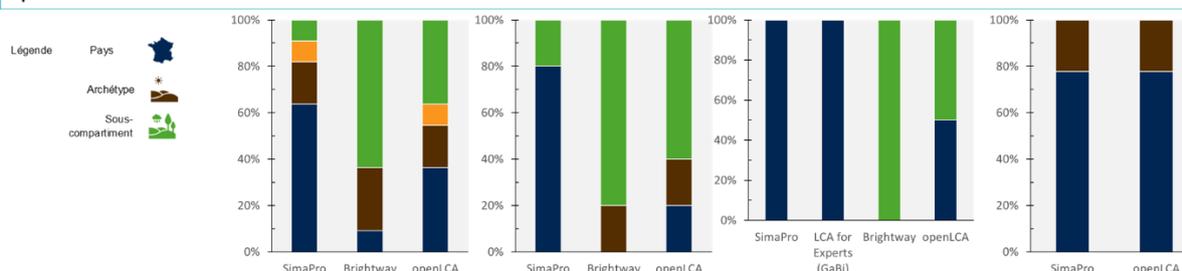


Figure 2 . The spatial dimension in various LCIA methods.

3.4 Operationalization

3.4.1 Issues on the operationalization of regionalized LCA in software

The main issue for regionalized LCA is the combination of the two previous elements, i.e., the combination of spatialized inventory and regionalized CF. Two main methods are used, depending on the approach available for the spatialization of elementary flows:

- **Spatialization based on elementary flow names:** This method follows the standard LCA matrix calculation, where each elementary flow is multiplied by its CF for a given impact category. The special feature of this approach is the integration of location directly into the flow name, enabling each flow to be associated with its CF according to its region of origin.
- **Geospatial:** This approach avoids the duplication of elementary flows required in the flow-name method. Thanks to GIS algorithms integrated into certain LCA software packages, it becomes possible to efficiently manage differences in spatial resolution between the inventory and regionalized CFs. This simplifies the calculation of spatialized impacts by adapting calculation scales to the regions defined by practitioners.

The various LCA software packages have integrated one or both approaches. Table 2 presents the summary for the different software packages.

Table 2 : Regionalization approach implemented by LCA software

Regionalization approach	SimaPro	LCA for experts (GaBi)	Brightway	openLCA
Based on the names of elementary flows	✓	✓	✓	✓
Geospatial	✗	✗	✓	✓

3.5 Interpretation

3.5.1 Issues related to the interpretation phase

One of the aims of the LCA interpretation phase is to identify, by means of contribution analysis and analyses of data quality, sensitivity and uncertainty, the data that should be improved as a priority in order to increase the reliability and precision of the results and the robustness of the conclusions.

In current LCA practice, practitioners often use aggregated CFs, obtained by averaging or weighting native regionalized CFs, better suited to the resolution of their inventory data. However, these aggregations can mask significant disparities between regions within the same country (Patouillard et al., 2015) . Different prioritization approaches have been described:

- **Expert judgement:** processes to be regionalized are identified with reference to literature or expert recommendations (Patouillard et al., 2015) .
- **Contribution to impact:** Processes are regionalized if they contribute significantly to the overall LCI or to the final LCIA results (Patouillard et al., 2015) . Patouillard et al.(2016) propose a method based on the contribution to impact and the level of process uncertainty using Monte Carlo simulation (possible just with software that allows inclusion of CF uncertainty).
- **Global sensitivity analysis:** Global sensitivity analyses determine which impact indicators require more geographical detail, whether an effort should be made to regionalize or spatialize the inventory and identify which key elements (processes or flows) require further detail. The possibility of including uncertainty linked to the spatial variability of CF is necessary for the application of this method.

3.6 Review of regulatory and standards requirements

In the standards and reference documents consulted, the geographical dimension is dealt with in a relatively summary manner. Only general recommendations are provided concerning the spatial aspects of LCA, particularly about defining the scope of the study and the use of regionalized data. Key issues identified for future research include the development of specific data formats for regionalized impact categories, the aggregation of CF, and the creation of appropriate software. Finally, the PEF guide deals with regionalization in a limited way, focusing mainly on the use of regional electricity mixes and a few other specific categories.

4. Case study

4.1 General description of the case study

To illustrate the issues and limitations identified, a case study was developed. It was used to illustrate the effects of different combinations of levels of consideration of the spatial aspects of the LCIA phase with those of the inventory phase. The main objective is to assess the impact of improved inventory regionalization on LCA results, by comparing them with impact methods with and without regionalization.

The subject of this case study is the use of a shampoo in France. The study is conducted using the ecoinvent 3.9.1 database, as well as SimaPro, openLCA and Brightway software, to illustrate how each tool addresses current issues. Various regionalized LCIA methods are tested, including EF 3.1, IMPACT World+ 2.0.1 and LC-IMPACT.

Figure 3 illustrates this analysis through a matrix showing the various possible combinations of inventory regionalization levels and LCIA methods. It should be noted that certain combinations are not presented in the study for two reasons: redundancy in the approach between software and the presence of a higher regionalization level by default.

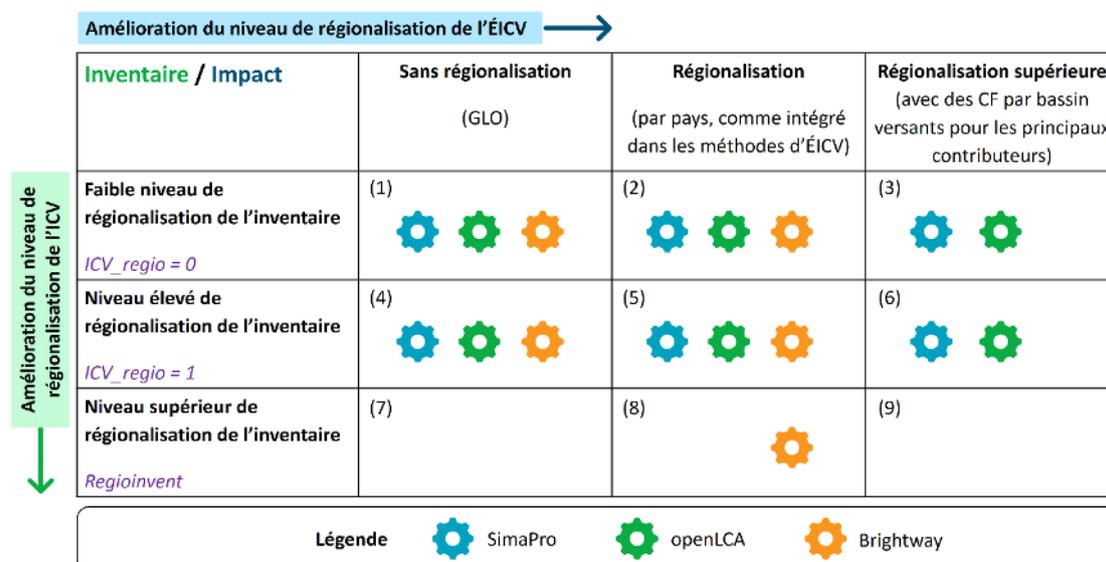


Figure 3 . Matrix of possible analyses for the case study. Columns illustrate increasing levels of regionalization applied to the LCIA phase (left to right), while rows reflect levels of improvement in inventory regionalization (top to bottom). Gear icons indicate the possibility of performing an analysis with each software. Numbers in brackets identify elements of the matrix .

For the different levels of regionalization of the LCIA phase, three levels were considered:

- **LCIA without regionalization:** Use of a LCIA method with generic (global) CFs, i.e., without spatial differentiation . This case corresponds to the implementation of LCIA methods in Brightway, where the CFs have no spatial differentiation (see section3.3). In cases where regionalization is present by default, notably in SimaPro, this level of regionalization has not been included in the case study.
- **LCIA with regionalized CF:** Use of versions of LCIA methods with regionalized CF, particularly for water and land.
- **LCIA with native regionalized CF :** Use of native CF. As a preliminary analysis has shown the influence of the spatialization of impacts related to water consumption, only this indicator is considered for this advanced level of spatialization of impacts. The native regionalized CFs of the AWARE method as originally published by Boulay et al., (2017) at their native watershed resolution were used to assess the impact of a finer resolution scale.

4.1.1 System modeling with SimaPro

In SimaPro software, the ecoinvent integration already includes spatialized flows for certain categories, notably those affected by water flows.

Improving the geographical representativeness of the results requires numerous manipulations at different levels:

- Adapting processes to increase representativeness;
- Creation of new elementary flows;
- Modification of foreground streams to include new streams;
- Copy and modify background strings for editing;
- Copy and modify LCIA methods;
- If you want to use regionalized CF aggregated to a scale other than that offered by default by the method developers or already available in the software, the calculation must be performed outside the software.

Some of these modifications may require a great deal of manipulation and time, but the gain in representativeness of the results can be significant. A parsimonious approach is needed to determine the elements to be refined, since SimaPro's configuration does not allow you to simply make modifications that affect the whole system.

4.1.2 System modeling with openLCA

The openLCA software offers two approaches for considering geographical aspects when modeling an LCA. The integration of ecoinvent in the software is available in two versions, one which already includes spatialized flows in their name for certain categories, and a second where flows are not spatialized in the name which allows the calculation of LCA regionalized with the geospatial approach.

Refining the results with the geospatial approach requires a number of manipulations at different levels:

- Adaptation of inventory processes to increase representativeness;
- Regionalized CF calculation *using GeoJSON* maps. Currently, only the LC-IMPACT method is available for this kind of calculation;
- Modification of the location of the most contributing processes;
- Creation of new geographies. These geographies may or may not correspond to the native scale, and the software allows the calculation of aggregated CFs for different geographies. However, aggregation does not use the same weighting basis as that recommended by DCIA method developers;
- Calculation of regionalized CF for new geographies;

Some of these modifications may require a great deal of manipulation and time, but a priori, the potential of this approach is greater than that of the approach presented for SimaPro. This approach enables regionalized calculations to be carried out for all the flows and processes in the system, according to the impact categories that have regionalized CFs. The parsimonious approach to determining the elements to be refined becomes unnecessary in this case. However, the lack of implemented methods and the flaws in the calculation of aggregated CF (no freedom on the weighting approach) mean that this approach is not yet usable by all practitioners.

The possibility of providing information on the uncertainty of the CF of LCIA methods can also be of interest for carrying out uncertainty contribution analyses and determining the elements to be refined in the systems to improve the representativeness of the results.

4.1.3 System modeling with Brightway

Brightway software offers two main methods for integrating spatial aspects into an LCA. The first is based on the bw2-regional library, which enables geospatial analysis based on practitioner-defined regions. This approach facilitates the spatialization of inventories and the aggregation of native regionalized CFs, adapted to the scale of the inventory. The second method consists in spatializing the

inventory based on the names of elementary flows, an approach similar to those implemented in SimaPro and openLCA.

At the time of this study, computer errors prevented the use of the bw2-regional library. Consequently, only the approach based on the spatialization of elementary flows was tested.

- This method requires certain additional operations on the part of the LCA practitioner. In particular, the Regioinvent database must be generated using the eponymous Python library, an automated operation that requires the availability of the ecoinvent 3.9.1 database. Although this generation takes around two hours, the database remains available for other projects integrating spatial dimensions into LCA.
- When Regioinvent is generated, elemental flows related to water, land, eutrophication and acidification are automatically spatialized. This automation reduces the time the practitioner would have to spend spatializing the elemental flows of the most contributing processes. However, the practitioner still has to spatialize foreground processes manually, as is the case with software such as SimaPro or openLCA.
- At present, only the regionalized CFs of the IMPACT World+ method are available for calculation based on this inventory spatialization approach. These CFs are implemented in parallel with Regioinvent generation, without the need for additional operations.
 - It is essential to use a regionalized LCIA method when elemental flows are spatialized, to ensure accurate results.
- Unlike SimaPro or openLCA, the integration of aggregated regionalized FCs at a scale suitable for inventory is not straightforward in Brightway. This task requires lines of code to first create an elementary flow, then generate its regionalized FC, which implies performing this aggregation operation outside Brightway.
- Despite this constraint on the creation of spatialized elementary flows and their corresponding regionalized CFs, the use of complementary tools such as Regioinvent saves time by automating the spatialization of elementary background flows. As a result, the refinement approach used in modeling with SimaPro becomes superfluous. However, the main limitation of this method lies in the lack of availability of other LCIA methods compatible with this spatialization approach.

Finally, Brightway offers the possibility of including CF uncertainty in LCIA methods, which can be relevant during contribution analysis, identifying elements to be refined to reinforce the robustness of results.

5. Conclusions and recommendations

5.1.1 Regionalized CF calculation

Spatial differentiation is the main method for calculating regionalized CF in impact regionalization. This approach takes into account the spatial variability of impacts depending on where the elementary flows are emitted.

Native regionalized CFs, defined at a finer resolution, are aggregated to a larger scale (e.g. national or continental) by means of weighting. This aggregation facilitates implementation in software and compatibility with inventory databases. Weighting is based on a number of factors, including the probability of occurrence or the quantity of elemental flux in each native region.

Summary of recommendations

Regionalized CF calculation

Recommendations for LCIA method developers

Develop methods at the finest possible native scale for the indicator ;

Define archetypes in cases where a large number of CFs show little variability according to certain characteristics;

Ensure consistency between indicators for the aggregation methods used;

Explain the approach adopted for handling missing data (zero CF).

Recommendations for software developers :

Enable the calculation of aggregated CF with different aggregation bases.

5.1.2 Regionalized LCA calculation

Spatializing impacts, whether in terms of origin or destination, requires two fundamental conditions:

- a **spatialized**
- **regionalized CF**.

The regionalized calculation is mainly based on **two methods**. The first **method, based on the names of elementary flows**, involves integrating the location directly into the flow name, enabling each flow to be multiplied by its CF according to its region of origin, following the standard LCA matrix calculation. On the other hand, the **geospatial method**, using GIS, makes it easier to manage differences in spatial resolution between the inventory and regionalized CFs.

Summary of recommendations

Regionalized LCA calculation

General recommendations

Use a common nomenclature for elementary flows compatible with that used by database developers;

Recommendations for database developers :

Developing regionalized and spatialized data;

Document the spatial resolution of the data developed;

Provide information including the third dimension for relevant assessments, such as the impacts of emissions according to altitude (e.g. the troposphere);

Facilitate the creation of archetype data ;

Use a common nomenclature for elementary flows compatible with that used by DTIS method developers.

Recommendations for LCIA method developers :

Provide aggregation factors with documentation of the methods and assumptions used and some generic aggregate CFs (global, continents, etc.).

Recommendations for practitioners :

Use the most appropriate tools for the defined geographical scale

5.1.3 Operationalization of regionalized LCA

LCA software uses both regionalized LCA calculation methods. **The most common** approach is based on the spatialization of the inventory **using the name of the elementary flows**.

At the same time, operationalization using the **geospatial method** enables more integrated management of inventories and regionalized CF. Software capable of using this approach, notably openLCA and Brightway, can also generate aggregated regionalized CF adapted to each region from native CF maps, simplifying the calculation and management of spatialized impacts.

Summary of recommendations Operationalizing spatialized impact

Recommendations for software developers :

Integrate the geospatial approach to calculate spatialized LCIs for all elementary flows

Facilitate the use of LCIA data and methods at their native scale;

Document the algorithms used to calculate regionalized LCA;

Support harmonized data exchange formats such as *GeoTIFF*, *GeoJSON* or the *Open Knowledge Foundation's Data Package*.

Recommendations for practitioners :

Define the geographic scale required for the study objectives:

The use of tools such as *Regioninvent* optimizes the process of spatializing elementary process flows in the background, resulting in significant time savings.

5.1.4 Spatial impact interpretation

Interpreting spatialized impact results involves several steps:

- Analysis of results at default scale ;
- Contribution analysis, using either uncertainty results, if available, or impact scores to identify areas for improvement;
- A parsimonious, iterative approach to improving the representativeness of results.



Summary of recommendations Spatial impact interpretation

Recommendations for LCIA method developers :

Calculate uncertainty values for regionalized CFs

Recommendations for software developers :

Integrate CF uncertainty into uncertainty analyses.

Enable calculation of Global Sensitivity Analyses

Recommendations for practitioners :

Define the geographic scale required for the study objectives;

Improve the representativeness and robustness of the results through an iterative approach, focusing on the main contributors to the overall impact or uncertainty of the results) ;



Prioritize the geospatial method when available and functional. This geospatial approach makes it possible to calculate spatialized inventories for any type of flow, without duplicating elementary flows.

