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Critical review and practical recommendations to integrate the spatial
dimension into life cycle assessment

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Abstract

Addressing the spatial dimension in life cycle assessment (LCA) appears to be a promising avenue to reduce the uncertainty of LCA results. However, to our knowledge, there is no comprehensive literature review on how to integrate geographic aspects at every LCA stage. This study aims to create a common language and build a framework guiding the LCA community to integrate the spatial dimension in LCA towards three specific objectives: (a) to review the literature to synthesize and classify current recommendations and approaches to integrate the spatial dimension in LCA, (b) to analyze each identified approach based on their level of relevance, development and operationalization and (c) to formulate recommendations on how to integrate the spatial dimension in LCA.

From the literature review, 33 recommendations and 37 approaches were identified. The approaches were classified according to the main issue they aim to address when integrating the spatial dimension in LCA: goal and scope, inventory regionalization, inventory spatialization, regionalized impact calculation, impact regionalization, interpretation and application in LCA software. Then, each approach was critically and qualitatively assessed against the three following criteria: relevance of the approach, level of development and level of operationalization. Short- and long-term recommendations on how to address spatial dimension in LCA for each identified issue and for the different stakeholders in the LCA community were derived from the critical analysis. A decision-support diagram was set up to help for the implementation of the short-term state-of-the-art recommendations and guide LCA practitioners to prioritize inventory regionalization and spatialization efforts.

Highlights

- Nomenclature and definitions related to the spatial dimension in LCA are proposed.
- Main approaches to integrating the spatial dimension in LCA are reviewed.
- Recommendations to address spatial dimension in LCA are provided.
- A decision-support diagram is proposed to guide LCA practitioners.

Keywords

Life cycle assessment, review, spatial dimension, regionalization, spatialization, geography

Wordcount

11 462 words

1. Introduction

Life cycle assessment (LCA) methodology was first developed without considering any spatial aspects because spatial differentiation was historically related to site-specific risk assessment while LCA was designed for global pollution prevention (Potting and Hauschild, 2006). But misleading conclusions that may be drawn from a site-generic LCA and the importance of taking spatial differentiation into account in life cycle impact assessment (LCIA) was demonstrated (Ross and Evans, 2002). First, activities along the product life cycle and related elementary flows (EF) that constitute the life cycle inventory (LCI) may be geographically scattered owing to the globalization of supply chains. Also, an EF (emission or extraction) in a given area may have a different impact depending on its location. The environmental consequences of the EF may be local, regional, continental or global depending on the type and characteristics of the EF and receiving environment (Potting and Hauschild, 2006).

Addressing the geographic aspects in LCA appears to be a promising avenue to increase the representativeness and reliability of the results (Mutel and Hellweg, 2009). Ultimately, it could improve the discrimination power for comparative LCA (Udo de Haes et al., 1999). Regionalization provides a representative description of processes and phenomena that are spatially variable. Variability involves current variations in the real world and is distinguished from uncertainty, which refers to a lack of knowledge on reality (Huijbregts, 1998). Providing more representative descriptions of spatially variable processes and phenomena should reduce the uncertainty associated with the shortage of information on their spatial location. In addition, more and more regionalized LCI databases (Colomb et al., 2015; Durlinger et al., 2014; Lansche et al., 2013; Vionnet et al., 2012; Weidema B P et al., 2012) and regionalized LCIA methods are being developed (Bulle et al., 2017; Verones et al., 2016), offering opportunities for LCA practitioners to improve the quality of their studies. However, enhancing geographic representativeness may require an increased workload for the LCA practitioner, specifically in terms of data collection and modeling (Baitz et al., 2012). One of the challenges of integrating regionalization is therefore to find a level of geographic representativeness that is adapted to the study objectives (Patouillard et al., 2016).

It is possible to consider geographic aspects at every phase in LCA methodology (Aissani, 2008; International Organization for Standardization (ISO), 2006a, 2006b):

- The goal and scope (G&S) when defining the object of the study and its spatial requirements
- When regionalizing the inventory, the LCI ensures the better geographic representativeness of the studied systems (inventory regionalization). In addition, attributing a spatial location to the EFs (inventory spatialization) makes it possible to use regionalized characterization factors (CF).
- The LCIA when assessing the spatial variability of impact scores as a function of the characteristics of the receiving environment (impact regionalization)

- The interpretation when identifying the potential transfer of impacts from one geographic location to another

To our knowledge, there is no comprehensive literature review, i.e. peer reviewed article with an exhaustive overview of existing literature, on how to integrate geographic aspects at every stage of LCA or provide guidance on how to regionalize inventory data or handle different resolution scales between the inventory and impact assessment. Furthermore, there is no framework or consistent terminology in relation to spatial aspects in LCA. In this context, the SCORELCA association, which includes leading stakeholders in life cycle thinking (EDF, ENGIE, Renault, Total, Veolia) and the French environmental protection agency (ADEME), and the authors initiated a research study to investigate the interest and relevance of considering and implementing geographic aspects in LCA. This study intends to assist the LCA community to consistently integrate the spatial dimension and create a common language. It further aims to guide LCA practitioners gathering relevant spatial information to increase the robustness of the results through a streamlined process.

Therefore, the main aim of this study is to build a framework to structure and provide recommendations on the use of the different existing approaches to integrating the spatial dimension in LCA. The three objectives of this study are to (a) synthesize and classify current recommendations and approaches to integrate the spatial dimension in LCA, (b) analyze each identified approach based on their level of relevance, development and operationalization and (c) formulate recommendations on how to integrate the spatial dimension in LCA. To achieve those goals, this article is structured in three sections: (a) literature review of existing approaches to integrating the spatial dimension in LCA, (b) critical analysis of the selected approaches, and (c) practical recommendations for the implementation of the approaches by LCA practitioners. The article builds on the report of the SCORELCA study by Patouillard et al. (2015). This work benefitted from the active participation of SCORELCA member experts on the steering committee.

2. Methods

2.1. Literature review

2.1.1. Terminology related to the spatial dimension in LCA

In the literature, numerous terms related to the spatial dimension in LCA are inconsistently used and often not clearly defined. Therefore, we propose the following terminology and definitions based on the literature review.

- Economic flow: An exchange with the technosphere, i.e. an intermediate exchange of goods or services
- Elementary flow (EF): An exchange with the ecosphere (to/from the environment)

- Process: A unit process that describes an activity (ecoinvent). It lists the exchanges with the technosphere (economic flow) and ecosphere (EF) involved to carry out the activity.
- Geographic vs. spatial: Both adjectives are used as synonyms in this article.
- Region: Geographic area delimited by boundaries with homogeneous parameters. For instance, a region may be political (country), economic (market), topologic (e.g. watershed) or based on a homogeneous set of natural conditions (e.g. climate zone).
- Spatial coverage: Area of the geographic validity of an inventory dataset or impact assessment method. For example, the ReCiPe impact assessment methodology is representative of Europe (Goedkoop et al., 2013) and TRACI is geographically representative of the United States (Bare et al., 2003).
- Regionalization: Term used to describe the representativeness of the processes and phenomena of a given region.
- Spatialization: Act of assigning a location to something, e.g. a flow.
- Inventory regionalization: Improvement of the geographic representativeness of inventory data (type and quantity of economic flows and EFs) to be more representative of specific geographic areas in the product life cycle.
- Inventory spatialization: Attribution of a geographic location to an EF, which is inherited from the process it stems from. This geographic location is necessary when using regionalized CFs. Different types of geographic information may be used (specific geographical coordinates, administrative region, archetypes, etc.) and eventually match the native spatial resolution of the impact method.
- Impact regionalization: Used to calculate 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 by considering the spatial variability of the LCIA model parameters and most influential mechanisms. The native resolution may be defined using geographic differentiation or archetypes.
- Archetype: Used to regionalize LCIA methods by accounting for the most influential parameters and impact mechanisms without the need for a specific geographic location but only its characteristics, which are the archetypes.
- Regional impact calculation: Impact calculation that makes it possible to match spatialized EFs and regionalized CFs.
- Receiving environment: The place where environmental interventions occur. The receiving environment of emissions (the origin of emissions) may be distinguished from the receiving environment of depositions (where the impacts of the emissions occur).

2.1.2. Recommendations on geographic representativeness requirements in LCA

Recommendations on geographic representativeness requirements in LCA were from publications and reports by international bodies, focus groups and organizations willing to bring consensus and provide guidance to the LCA community. They are used as a starting point to further elaborate our recommendations on how to address geographic aspects in LCA. For each reference reviewed, recommendations related to the integration of the geographic dimension in LCA were extracted and reformulated as a simple statement (see details in Supplementary Information).

2.1.3. Approaches addressing spatial dimension in LCA

The literature selection is based on queries in the following databases and search engines: Google, Google Scholar, Science Direct and Web of Science. The query was formulated with the following key words: (life cycle analysis OR life cycle assessment OR LCA) AND (region* OR spatial* OR geograph*). Only bibliographic references describing approaches that specifically deal with the geographic dimension in LCA were selected. They were categorized into five groups: (1) LCA case study, (2) methodological development, (3) LCIA method, (4) LCA database (DB) and (5) LCA software.

2.2. Critical analysis of the selected approaches

Every approach identified in the literature review was classified according to the main question it aims to address in term of regionalization in LCA. These questions were then used to frame the critical analysis. The theoretical and practical strengths and limitations of each approach were analyzed against three criteria: (1) relevance of the approach: Is the approach relevant in respect to the approach question?; (2) level of development: Is the approach sufficiently mature and robust to respond to the question?; (3) level of operationalization: Is the approach easily applicable with existing tools? A qualitative evaluation of the three criteria was performed using a 5-level rating system + (satisfactory) and - (poor) that indicates the adequacy between the approach's characteristics and its question. The significance of each level rating for each criterion is explicitly available in the Supplementary Information. If the approach fully addresses the question for the criteria, the note will be maximal. The rating allows comparing for a criterion different approaches dealing with the same question. We recognize that this qualitative assessment implies a certain degree of subjectivity associated to the judgement of the researchers performing the analysis. To minimize subjectivity, we transparently exposed our reasoning and judgment on how we assessed each approach against each criterion against within the core text of the section 3.2.

2.3. Practical recommendations

Practical recommendations on how to address spatial dimension in LCA were derived from the critical analysis of the approaches. The recommendations are intended for the different stakeholders in the LCA community: LCA practitioners, LCI database developers, LCIA method developers, LCA software

1 developers and LCA researchers. Short-term recommendations refer to what can be already done with
2 state-of-the-art approaches and current tools. Long-term recommendations are meant to suggest
3 improvements for future developments. A decision-support diagram was set out to guide LCA
4 practitioners in the implementation of the short-term recommendations.
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6 These recommendations aim to respond to questions related to practical challenges and
7 methodological issues that arise when seeking to integrate geographic aspects in LCA: How can
8 inventory data be regionalized? What should the level of detail be? How can EFs be spatialized? What
9 should the level of detail be? How can LCIA methods be regionalized? How should regionalization and
10 spatialization efforts be prioritized? How should different resolution scales between the inventory and
11 impact assessment be handled? How should the results be interpreted? What tools are available to
12 handle spatial dimension in LCA?
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19 **3. Results and discussion**
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21 **3.1. Literature review**
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23 In total, 75 references were consulted as part of the literature review, leading to 33 recommendations
24 on geographic representativeness requirements in LCA and 37 approaches addressing the spatial
25 dimension in LCA. The 15 references used to identify the recommendations have been written between
26 2006 and 2014, and are standards or directives or reports that claim to provide recommendations in
27 LCA. The 60 references used to identify the approaches have been written between 1996 and 2017 but
28 50% of them date from 2012 to 2015. It includes Ph.D. thesis, reports, conference proceedings, but
29 most of them are scientific articles, dealing with LCA case study, LCA database, LCA software, LCIA
30 method, and methodological development. The complete list of reviewed literature, as well as the
31 description of identified recommendations, are available in Supplementary Information.
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40 **3.2. Critical analysis of the selected approaches**
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42 Selected approaches are synthesized and analyzed in Table 1 and Table 2 based on their main question.
43 The detailed correspondence between each selected approach and their bibliographic references can
44 be found in Supplementary Information. The following sections provide more details on the critical
45 analysis.
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Table 1 – Critical analysis of identified approaches from the literature for questions related to G&S and inventory regionalization

| Questions | Approach definition | Relevance | Level of development | Level of operationalization |
|--|--|-----------|----------------------|-----------------------------|
| G&S | | | | |
| Does the scope of the study refer to a territory? | Territorial LCA approach | +++ | ++ | + |
| How are the spatial requirements of the LCA study defined? | Description of the spatial coverage in the goal of the study or functional unit Definition of spatially differentiated scenarios if relevant Description of spatial needs for LCI data quality and LCIA method | +++ | ++ | ++ |
| Is the implementation of an inventory regionalization or spatialization process necessary? | No identified approach | | | |
| How should inventory regionalization and spatialization efforts be prioritized? | No identified approach | | | |
| Inventory regionalization | | | | |
| | Approaches for inventory regionalization | | | |
| How should the inventory be regionalized? | Adaptation of numerical data to better fit the spatial coverage | ++ | +++ | ++ |
| | Process recontextualization | ++ | +++ | ++ |
| | Approaches to evaluate data quality | | | |
| How should the geographic representativeness of the data be analyzed? | Pedigree matrix to assess the quality of the geographic representativeness of LCI data | ++ | +++ | +++ |
| | Quantification of the spatial variability of data at different spatial scales using representative datasets | +++ | -- | -- |
| | Approaches to guide inventory regionalization efforts | | | |
| How should efforts be prioritized? | Expert judgement to identify parameters with geographical variability | +(++) | +++ | ++ |
| | Impact contribution analysis | +(++) | +++ | ++(+) |
| | Effort on land use inventory | +(++) | + | (+) |
| | Uncertainty contribution analysis | +++ | - | - |
| | Approaches to identify the required level of regionalization | | | |
| What should the level of detail be? | Regionalization at the country level for energy infrastructures | + | ++ | ++ |
| | Regionalization level depending on the geographical variability of each market and its influence on spatial uncertainty results | +++ | + | ++ |
| | SAME approach: definition of regions where impacts are homogeneous to define the inventory resolution | -- | - | - |

Table 2 – Critical analysis of identified approaches from the literature for questions related to inventory spatialization, regionalized impact calculation, impact regionalization, interpretation

| Questions | Approach definition | Relevance | Level of development | Level of operationalization |
|--|--|-----------|----------------------|-----------------------------|
| Inventory spatialization | | | | |
| How can spatialization be carried out? | 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 | +++ | ++ | +(++) |
| What type of spatial information should be used? | Archetype description | ++ | +++ | ++ |
| | Textual information on the geographical zone of the EF (continent, country, administrative region, etc.) | +(++) | ++ | ++ |
| | Use of geographical information system (GIS) to spatialize the EF | +++ | + | + |
| How should efforts be prioritized? | Impact contribution analysis | +(++) | +++ | ++(+) |
| | Uncertainty contribution analysis | +++ | - | - |
| What should the level of detail be? | SAME approach: definition of regions where impacts are homogeneous in order to define the inventory resolution | (++) | - (+) | -(++) |
| Regionalized impact calculation | | | | |
| How can regionalized impacts be calculated? | Modification of the matrix calculation when the spatial resolution of inventory and LCIA method are the same | + | | + |
| | Modification of the matrix calculation when the spatial resolution of inventory and LCIA method are different | +(++) | +(++) | +(++) |
| Impact regionalization | | | | |
| How can impact assessment methodology be regionalized? | Archetype based LCIA model | ++ | +++ | +++ |
| | Spatially differentiated approach – multi-regional model | +++ | +++ | +++ |
| | Spatially differentiated approach – region-specific nested model | ++ | +++ | +++ |
| Which impact assessment methodology should be used? | IMPACT World+ and LC-IMPACT – spatial coverage: Global | +++ | + | + |
| | LIME 2 – spatial coverage: Japan | ++ | + | - |
| How can uncertainty related to spatial variability be assessed? | Quantification of uncertainty due to the spatial variability for aggregated CF | +++ | + | + |
| How can a regionalized impact assessment method be implemented? | Differentiation in the EF names | +(++) | ++ | -(++) |
| | Geographic information handle with a GIS | +++ | ++ | + |
| Interpretation | | | | |
| How should the impacts be visualized? | Results integrated over space (none regionalized results) | ++ | +++ | +++ |
| | Maps showing impacts depending on the EF geographical origin | +++ | ++ | ++ |
| | Maps showing resulting impact location | +++ | - | -- |
| How should sensitivity analyses be carried out in regionalized LCA? | Perturbation analysis | - | ++ | + |
| | Two-step approach: elementary effects method and contribution to variance | +++ | + | -- |

3.2.1. *Integration of the spatial dimension in G&S phase*

In most LCA studies, the spatial coverage is described in the G&S when specifying the study objectives and/or functional unit. Alternative scenarios that aim to compare results obtained for other regions may also be defined. Spatial requirements regarding LCI data quality (geographical representativeness) or LCIA methods (need for a regionalized LCIA method?) are seldom mentioned or justified. Yet, such requirements can drastically increase the time spent by LCA practitioners on a study. No approach was found to determine the necessity of implementing an inventory regionalization or spatialization process or prioritize the effort between both.

If the scope of the study is a territory, as is often the case in land planning, a territorial LCA approach should be adopted (Loiseau et al., 2013, 2012). Laurent (2015) proposes a spatialized systemic approach for territorial LCA to use spatial information to better define the G&S (Laurent, 2015). This approach makes it possible to define the main function within the studied territory, the potential scenarios fulfilling this main function and the preferential zones for locating the envisioned scenarios. In order to also account for the spatial variability of the potential impacts on a territory, Nitschelm et al. (2015) propose an LCA framework for spatialized territorial LCA.

3.2.2. *Inventory regionalization*

Inventory regionalization deals with the improved geographic representativeness of inventory data (type and quantity of economic flows and EFs). Taking into account the spatial variability of inventory data is important seeing as a given technology can have different characteristics (such as yields, operation conditions, synergy with other technology, etc.) depending on their location (Ciroth and Hagelüken, 2002a).

Approaches for inventory regionalization

There are two current and complementary practices for inventory regionalization.

- Process recontextualization: the adaptation of a unit process to be more representative of an expected geographical coverage (Lesage and Samson, 2013). For instance, the electricity production mix used in a process could be adapted to represent a specific region.
- Adaptation of numerical data within a process to better reflect its representativeness of a given geographical coverage (Lesage and Samson, 2013). For instance, the amount of electricity input in a process could be adapted to better reflect actual consumption for a specific region. Data could be specific to a site, represent the average for a region or a country or be a generic value.

Both practices are relevant to improve the geographic representativeness of a product system but require an additional effort for data collection. This effort depends on the nature of the data that is required (which economic sector? local or average data?), their required quality and their availability.

Bellekom et al. (2006) report that the effort may be reduced by more than half if the regionalization approach is set up as soon as the study gets underway. They also mention that the main obstacle for inventory regionalization is the access to data and their confidentiality. Milà i Canals et al. (2011) underline that the greater the effort to improve data, the lower the uncertainty of the collected data. Prioritizing the data collection process is also a way to optimize the regionalization effort (Patouillard et al., 2016).

Several data sources may be used and combined to improve the geographic representativeness of a product system. Specific on-site data collection may provide very relevant and accurate data but may also be very difficult to set (Bellekom et al., 2006). Regionalized information may also be taken from other data sources, including statistical data (European Commission, n.d.; International Energy Agency (IEA), n.d.; United Nations, n.d.; United States Department of Agriculture, n.d.); input/output (IO) tables (Hertel and Hertel, 1997; Lindner et al., 2013; Yang, 2015); data from legislation (European Parliament, 2009; United States Environmental Protection Agency (EPA), 2010); LCI databases (Colomb et al., 2015; Durlinger et al., 2014; Lansche et al., 2013; Steinberger et al., 2009; Vionnet et al., 2012; Weidema B P et al., 2012); agro related databases (Keeffe et al., 2013; Urban et al., 2012); geo-spatialized data as physicochemical maps (Gasol et al., 2011; Keeffe et al., 2013); data from models as the LandSHIFT model (Humpenöder et al., 2013, 2011) or outputs from energy/economic/environmental models (Dandres et al., 2012; Marvuglia et al., 2013). Data extrapolation from existing LCA studies to represent other geographical regions should be carried out carefully to ensure the representativeness of the extrapolation. The Modular EXtrapolation of Agricultural LCA (MEXALCA) method based on statistical estimators was proposed to extrapolate the LCA results of crops from one country to another (Roches et al., 2010). It considerably reduces the effort for inventory regionalization but is not suitable to estimate LCA results for regionalized impact indicators. Milà i Canals et al. (2011) propose a hierarchy to create missing data depending on their contribution to LCA result uncertainty and the effort required to create them. Therefore, the use of proxies and data extrapolation to adapt data from other regions, which is a common practice in LCA, should be conducted while evaluating the associated uncertainty.

Approaches to evaluate data quality

The quality of the geographic representativeness of data must be evaluated to estimate the overall uncertainty. The Pedigree matrix (Weidema and Wesnæs, 1996) used in ecoinvent is available in most of LCA software. The European Life Cycle Database (ELCD) has developed a rather similar pedigree approach for data uncertainty (Recchioni et al., 2012). This semi-quantitative approach makes it possible to assess the quality of numerical data within the context of its use based on expert judgment and convert them into standard variation. ecoinvent proposes five qualitative levels for data quality assessment, one of which is geographical representativeness. The pedigree approach is relevant and

operational for data quality assessment but must still be improved by developing more sector-dependant uncertainty factors (Muller, 2015). An alternative to this judgment-based approach would be to quantify the spatial variability of data at different spatial scales using representative datasets. Nevertheless, data for this approach are not available and further developments are required.

Approaches to guide inventory regionalization efforts

One of the main challenges in inventory regionalization is identifying the priority data to be regionalized. The following approaches were identified to do it.

- Expert judgment: Ciroth and Hagelüken (2002b) use expert judgment to identify parameters with geographic variability and create a regionalized and parameterized inventory. Although this approach is widely used in LCA, it requires access to one or more experts depending on the complexity of the product systems and may lead the LCA practitioner to focus his/her effort on regionalizing data with little or no influence on the LCA results.
- Impact contribution by process: Bellekom et al. (2006) set a threshold based on impact contribution from selected processes to be regionalized. In this study, the threshold is arbitrarily set depending on the product system. Similarly, a threshold may be set at the inventory level (International Organization for Standardization (ISO), 2006b). This approach based on impact contribution is a current practice and may be operationalized with any LCA software without any additional workload. However, a process that significantly contributes to the impact score must not necessarily be regionalized if its spatial variability is low. Therefore, this approach would be fully relevant only if it may be combined with a spatial uncertainty contribution analysis (Patouillard et al., 2016). Alternatively, expert judgment may be used here to point out the most potentially uncertain processes among those selected from the impact contribution analysis.
- Uncertainty contribution analysis: As stated by Heijungs (1996) and Milà i Canals et al. (2011), the efforts to improve data quality should focus on the most uncertain data and the data that most influence the results. Global sensitivity analysis approaches such as contribution to variance or the Sobol index can help identify the data that most contribute to spatial uncertainty (Mutel et al., 2013; Wei et al., 2015). Although these approaches would be the most relevant, they may be time-consuming, since there is no methodology or tool to operationalize it in LCA. These approaches may help prioritize the regionalization effort (Patouillard et al., 2016).

More and more LCA studies (e.g. agricultural or forestry production system) use geographical information system (GIS) to model and regionalize their land use inventory and other EFs closely dependent on soil and climate conditions (Geyer et al., 2010a, 2010b, Humpenöder et al., 2013, 2011;

Keeffe et al., 2013; Urban et al., 2012). Land use regionalization is relevant if the land use midpoint impact category significantly contributes to the ecosystem quality endpoint impact scores. Data availability and data treatment, especially using GIS, can limit the implementation of the approach.

Approaches to identify the required level of regionalization

Another challenge in inventory regionalization is figuring out the level of detail that is required. This level depends on the modeled sector and geographic coverage. Steinberger et al. (2009) put forward the big difference between industrialized countries and emerging ones with regard to energy infrastructures. They recommend regionalizing processes that consume energy at the country level, according to the national grid mix. This approach may be easily operationalized with country-differentiated electricity data in LCI databases. Nevertheless, data availability remains an issue for energy markets other than electricity. The regionalization level should be adapted depending on the geographic variability of each market and its influence on spatial uncertainty results.

The Spatial Area of iMPact Equivalency (SAME) approach aims to reduce the effort to enhance the quality of an LCA study by determining the required level of inventory regionalization and spatialization, taking into account the spatial variability of the evaluated impact categories (Nansai et al., 2005). This approach is based on the identification of regions where impact scores are homogeneous in order to define the required inventory resolution. One of the main limits of this approach is that it forces the inventory regionalization level to match the impact regionalization level, even though they are not necessarily the same. Indeed, the former is linked to technosphere variability while the latter is associated with ecosphere variability. Thus, the inventory regionalization level should not be driven by the spatial variability of the impact category.

Inventory regionalization in ecoinvent v3

ecoinvent v3 is an LCI database with global spatial coverage regionalized by country or continent (Weidema B P et al., 2012). A range of economic sectors is represented. For a single technology, countries that are the main producers on the global market are represented as far as possible. Nevertheless, there are still more datasets representing Europe (RER) and Switzerland (CH) than emerging countries since the database was historically developed for Switzerland. A geographic descriptor (point, line or area encoded in KML) is attached to each process to provide information on the geographic zone of validity for the process. Most of the descriptors are predefined (continent, country, state) but new descriptors may be added. There is no possible overlap between descriptors within the same activity to avoid double counting. Indeed, input data within a dataset can come from other geographic zones and be interpolated or extrapolated for a considered area. Therefore, ecoinvent v3 uses the pedigree matrix approach (Muller et al., 2014) to assess the quality of the numerical data (flow quantity) for each economic flow and EF with regard to their geographical representativeness.

3.2.3. Inventory spatialization

Inventory spatialization attributes geographic information to an EF for characterization with a regionalized CF. The inventory may be spatialized at the process level (EFs inherit from process locations) or at the EF level (each EF may be spatialized independently from the process location). LCA software are used to handle the geographic information inheritance between process and EF. Inventory spatialization helps to identify the contribution of geographic zones to impact scores that may be displayed on maps (Mutel et al., 2012).

Different types of spatial information

Different types of geographical information can be added to spatialize an EF depending on the LCA software used and the LCIA method used.

- Textual information on the geographical zone of the EF (continent, country, administrative region, etc.) may be added to the EF name or written in the process or EF description. This is how water EFs were spatialized in ecoinvent v3 (Pfister et al., 2016). Although the approach is widely used, its relevance is limited to the spatial resolution used by the selected LCIA methods.
- Archetype description associated with the EF is a current practice for some impact categories such as toxicity with archetypes based on population density (Humbert, 2009). The information on archetypes may be added to the EF name or use the compartment and sub-compartment names of the EF. Archetypes are defined by LCIA methods and differ from one impact category to another. Several archetypes may be required for an EF that contributes to more than one impact category, limiting the application of the approach in terms of data collection and implementation.
- Geographic coordinates may be used to localize the EF. The EF location may be described by a GIS using geometric features as a point, line or surface. This spatialization is relevant because the LCA practitioner only needs to specify the geographic location for an EF once and it may then be used for all impact categories. Maps linking archetypes and geographic coordinates may be required. GIS use is expanding in LCA and is increasingly integrated into LCA software, such as Brightway and openLCA (Ciroth et al., 2014; Mutel, 2014).

Approaches for inventory spatialization

There are different approaches to spatialize the inventory.

- Use the geographic information from the inventory regionalization: The zone of the geographic validity of the process may be used to spatialize the associated EF (Mutel and Hellweg, 2009). The level of detail would be the same as the one resulting from the inventory regionalization. This approach is implemented for EF spatialization in ecoinvent v3 and openLCA (Rodríguez and Greve, 2016; Weidema B P et al., 2012). It was also applied by Bellekom et al. (2006) in an LCA

study where EFs were disaggregated at the country level, except for EFs from very low contributing processes. According to the authors, this systematic disaggregation requires 10% to 30% of additional time that is often spent for processes that do not significantly contribute to the impact. These conclusions underline the importance of prioritizing the inventory regionalization and spatialization effort. The main strength of the approach is that it does not require additional data collection if the inventory is already regionalized. However, the resulting level of EF spatialization may not be sufficient to use regionalized CFs at native resolution and additional data collection may be required.

- Spatialize the EF without further inventory regionalization: An EF may be spatialized by finely describing its geographic distribution within the spatial coverage of its related process, using for example sales statistics (Patouillard et al., 2017). The approach is relevant for technologies whose characteristics are relatively invariant with respect to geographic location (no need for inventory regionalization) or when the maximum level of inventory regionalization has been reached but whose impact is very sensitive to geographic location. Patouillard et al. (2017) use production regions and their market shares within countries to spatialize the water and land EFs related to the production processes of agricultural products in each main exporter country. The LCA practitioner may carry out additional data collection depending on the level of detail that is required. A GIS may be used to spatialize the inventory in order to deal with geolocated data (Geyer et al., 2010b; Nitschelm et al., 2015) and perform regionalized impact calculation (see section above).

Approaches to guide inventory spatialization efforts

As for inventory regionalization, one of the challenges of inventory spatialization is identifying which EFs to spatialize and the level of detail required. EF spatialization requirements depend on the goal and scope of the study. Patouillard et al. propose an approach based on impact contribution analysis per EF to guide the spatialization effort in order to select the priority EFs to be spatialized and suggest basing future prioritization on uncertainty contribution analysis (Patouillard et al., 2017, 2016). The SAME approach could help determine the required level for inventory spatialization, defined as the resolution level where the spatial variability of impacts is null (i.e., it will correspond to the native resolution of the LCIA method) (Nansai et al., 2005).

Inventory spatialization in LCI databases

Beloin-Saint-Pierre (2012) propose a methodology to determine the best approach to spatialize flows in an LCI database. They conclude that every EF should be described by a compartment, a sub-compartment, and a region. In addition, they recommend that the region resolution for EF spatialization be defined in order to be able to use native regionalized CFs. However, the region definition varies from one LCIA method to the next and should be harmonized (For which regions

should a LCIA method provide a regionalized CF?). Alternatively, the CF corresponding to a specific region could be directly calculated by the LCA software on the native resolution map, as proposed by openLCA. In ecoinvent v3, each EF inherits the location given by the geographic descriptor of the associated process (Weidema B P et al., 2012).

3.2.4. Integration of regionalization in impact calculation

To calculate an impact score, ISO 14044 requires that the EFs first be aggregated over the entire life cycle before multiplying them by their respective CFs (Heijungs and Suh, 2002; International Organization for Standardization (ISO), 2006a, 2006b), implying that the impact characterization is independent of the EF location and useless for interpretation. Furthermore, information on the geographic origin of the EFs responsible for the impact is lost. Regionalized impact calculation calls for a change in the conventional computational structure of LCA.

To tackle this issue, impact scores must be calculated at each location with the respective regionalized CFs before any aggregation (Mutel and Hellweg, 2009). To do so, one may include the spatial information within the nomenclature of each EF. Nevertheless, it may drastically increase the number of EFs and the matrix size and computing burden. Furthermore, it implies that the spatial resolution of inventory and LCIA methods are the same, which is rarely the case, especially if some prioritization has been carried out, making the inventory heterogeneous in terms of resolution. Therefore, Mutel et al. (2012) propose a modified matrix calculation based on the weighted surface of the overlap between inventory regions and CF regions using GIS tools that are available in LCA software such as openLCA and Brightway. Nevertheless, the calculation is based on surface weighting, i.e. assuming that an activity leading to EFs has an equal probability to happen anywhere in the overlapping regions as long as there is a piece of land to support it. It is an arbitrary choice that is not necessarily representative of EF location. For example, the IMPACT World+ regionalized impact assessment methodology recommends that CFs be aggregated based on the emission probability of each EF (Bulle et al., 2017).

3.2.5. Impact regionalization

Integration of regionalization in LCIA methods

Regionalization in LCIA methods makes it possible to consider the spatial variability of the receiving environment by developing regionalized (or spatially differentiated) CFs (i.e. CFs that are valid for a defined region). Three levels of regionalization in LCIA models are defined: site-generic LCIA model when the receiving environment is considered generic; site-dependent when there is some spatial differentiation in the receiving environment and site-specific when the spatial differentiation of the receiving environment is very detailed (Potting and Hauschild, 2005). The level of regionalization of a LCIA method is independent of the spatial span of the impact category, which may be local, regional or global. The spatial span of the impact category is the typical distance between the receiving

environment of the emission and the receiving environment of the deposition (where the impact takes place), which is defined by the fate of the EF. For instance, freshwater acidification has a regional spatial span but is regionalized with a site-specific approach (Roy et al., 2013).

There are two approaches to define regionalized CFs: the archetype approach and the spatial differentiation approach. The parameters on which the archetype is based are not directly related to their geographic position and are used generically. For example, an archetype based on population density makes it possible to differentiate the impact of fine particle emissions on human health between urban and rural areas (Fantke et al., 2015; Humbert, 2009). Archetypes may be used by LCA practitioners without knowing the exact location the emission occurred. The archetype approach is relevant when the spatial variability is driven by very few parameters that may be easily guessed by LCA practitioners. If not, spatial differentiated LCIA model would be more relevant.

There are two types of architecture for spatially differentiated LCIA models: multi-regional models and region-specific nested models. Both are considered site-dependent or site-specific. Multi-regional models calculate regionalized CFs at a spatial scale, such as watersheds, sub-watersheds or countries for water use impacts methods (Boulay et al., 2011, 2015; Kounina et al., 2012) or ecoregions for land use impacts on biodiversity (Chaudhary et al., 2015; de Baan et al., 2013) or arbitrary regions such as a longitude-latitude grid (Roy et al., 2013). The native resolution corresponds to the resulting spatial scale for which CFs are calculated. The input data of LCIA models may have their own spatial resolution that does not necessarily match the final native one (UNEP/SETAC Life Cycle Initiative, 2016; Verones et al., 2016). Then, native CFs may be spatially aggregated into larger regions (e.g. the country level) to assess corresponding spatialized EF (Bourgault, 2013; Bulle et al., 2017). Region-specific nested models are based on a regionalized parameterization of a generic nested model (Kounina et al., 2014). Such models calculate one regionalized CF for every EF, which is valid for the spatial coverage of the model. For instance, this approach was used to create continental versions of the USEtox model (Kounina et al., 2014). The main advantage of a multi-regional model is that it can take into account interactions between cells whereas region-specific several nested models consider the rest of the world as a black box. However, the latter is lighter in terms of modeling.

The native resolution or archetypes are determined by the LCIA method developer depending on expertise, the influence of LCIA model parameters on the CF values, primary data availability and computing capacity. Each impact category has its own characteristics and, therefore, specific native resolution or archetype. Ultimately, the choice of the native resolution influences the LCA results (Boulay et al., 2015). Most of the time, LCIA method developers cannot describe all input data at a relevant spatial level because of data availability within the spatial coverage of the method. Therefore, all the input data of a regionalized LCIA model are not regionalized at the same resolution. Sometimes, the resolution level of a spatially differentiated LCIA model could lead to a very large number of CFs

that are not necessarily very different. To avoid handling a great deal of unnecessary data, Mutel et al. (2012) propose a statistical approach to determine the relevant native resolution for regionalized CF. This approach is based on the minimization of the spatial autocorrelation between each cell. If the autocorrelation is high, the cells may be merged.

Several regionalized LCIA methods have been developed but few LCIA methodologies are regionalized in a consistent way and provide CFs at a high resolution. The IMPACT World+ LCIA methodology was developed to address the need for regionalization in impact assessment (Bulle et al., 2017). It has global coverage and provides CFs at native resolutions, as well as aggregated CFs at country level, continent level and global level for spatially differentiated impact categories with their uncertainty related to spatial variability. IMPACT World+ is very relevant to consistently assess globally spread product systems. However, its integration into LCA software is a work in progress. LC-IMPACT is another regionalized LCIA methodology (Verones et al., 2016) that also has a global coverage and provides aggregated CFs at the country and global levels. However, this methodology does not provide the uncertainty related to the spatial variability of aggregated CFs, making it impossible to perform an uncertainty contribution analysis to prioritize the inventory spatialization effort for instance. LIME 2 is a regionalized LCIA methodology developed for Japan (Itsubo and Inaba, 2012). CFs are regionalized at a fine native resolution and then aggregated CFs are calculated for Japan. Unlike IMPACT World + and LC-IMPACT, the coverage of LIME 2 is national and Japanese CFs are applied to EFs emitted outside Japan, limiting its relevance for activities occurring abroad.

Evaluation of the uncertainty of regionalized CF

Two sources of uncertainty may be distinguished for regionalized CFs: the basic uncertainty inherited from the LCIA model uncertainty at the native resolution and the uncertainty due to the spatial variability for aggregated CFs. The more a CF is aggregated, the higher its uncertainty due to the spatial variability (Bourgault, 2013). Thus, the LCA practitioner who seeks to minimize results uncertainty should prefer CFs at high spatial resolution (ideally at native resolution) instead of aggregated CFs. However, this implies better spatialization of the EFs. The IMPACT World+ methodology provides the uncertainty due to the spatial variability for every aggregated CF (Bulle et al., 2017) .

Integration of regionalized LCIA methods in LCA software

There are two main ways to integrate regionalized LCIA methods into LCA software: either by differentiating the EF names or using GIS. In the first approach, many EF names are created in software substances database to represent region and/or archetype that exist in each regionalized impact category for that EF. This implementation can drastically increase the number of required EFs. In addition, additional effort by the LCA practitioner or the LCI database developer is required to manually

spatialize the EF. However, this approach makes it possible to use regionalized LCIA methods without the need for regionalized impact calculation. Regionalized LCIA methods were integrated this way in SimaPro and GaBi software and in the ecoinvent LCI database (Pfister et al., 2016). The other way to implement regionalized LCIA method is to use GIS functionalities available in openLCA or Brightway LCA software. Maps containing regionalized CF values may be uploaded, creating spatialized parameters that may be used to parameterize LCIA methods (Rodríguez et al., 2014; Rodríguez and Greve, 2016). The mapping between EFs and regionalized CFs is automatically done with the regionalized impact calculation using GIS.

3.2.6. Integration of the spatial dimension during the interpretation phase

Approaches to visualize regionalized impact results

Regionalized CFs have a spatial validity related to the location where environmental interventions occur and represent impacts integrated over space (and time). Consequently, it is impossible to differentiate the geographic zones impacted by the EF, which may be outside the spatial validity area of the regionalized CF. This approach is relevant when the goal is to reduce the impact, regardless of the affected target. Thus, different populations across the globe are considered fairly. openLCA provides maps showing impacts depending on the geographical origin of EF but not the regions affected by the impacts (Rodríguez and Greve, 2016). Liu et al. propose an approach to visualize resulting impact location that is tracked by map overlaps of EF fate, exposure, and effect (Liu et al., 2014). This approach improves the interpretation phase but is data intensive and difficult to handle with existing tools, jeopardizing its operationalization. In addition, GIS skills are required for implementation.

Approaches to conduct sensitivity analyses in regionalized LCA

Sensitivity analyses in LCA are often performed with the perturbation analysis, where each parameter varies one at the time (Bjorklund, 2002; Heijungs, 1996), or using model parameter variances to compute sensitivity factors (Heijungs, 2010). However, these approaches seem to be inappropriate for regionalized LCA because of the large numbers of parameters and the modified matrix structure. To perform sensitivity analyses adapted to regionalized LCA, a two-step approach is proposed (Mutel et al., 2013). The first step is to identify the most likely sensitive parameters using a screening method (the elementary effects method). The second step is to test the contribution to variance in order to estimate the relative importance of selected parameters using Monte Carlo simulation. The preselection of most sensitive parameters significantly reduces computation time afterward. This approach is only available in Brightway. More developments are needed to make it operational in other software and more widespread.

3.2.7. Application in LCA software

The most popular LCA software, e.g. SimaPro and Gabi, make it possible to add textual geographical information into the process description but the information is not used dynamically in the calculation. EFs are identified by name, compartment, and sub-compartment. Therefore, these types of software can support regionalized LCIA methods that provide EFs adequately defined, i.e. which are actually named with the required geographic information (emission by country, for example). As mentioned in 3.2.5, the number of EFs can increase drastically when integrating a regionalized LCIA method with these types of software. In addition, integrating CFs at native resolution is almost impossible. If a new region is created by the user, a new EF should be added and the calculation of the corresponding regionalized CF value cannot be performed by the software. Therefore, those types of software without GIS are not appropriate to perform regionalized LCA.

openLCA and Brightway are LCA software that integrate GIS functionalities. Brightway is mainly for research purposes. openLCA is more user-friendly and has been adopted by many LCA practitioners in recent years. From our point of view, it is currently the most appropriate tool for LCA practitioners to deal with spatial dimension in LCA. The integration of spatial dimension in openLCA is summarized in Supplementary Information. Process location is described by a form and a set of geographic coordinates using a Keyhole Markup Language (KML) editor. As in ecoinvent v3, each EF inherits from the location given by the geographic descriptor of the associated activity. This software can support the use of regionalized LCIA method using maps. The regionalized calculation is achieved depending on the intersection between regions defined in the inventory and CF at native resolution weighted by the area intersection. Therefore, aggregated CFs may be calculated by the software for any region defined. Impact results may be analyzed and visualized as a function of the geographic origin of EFs. LCIA methods may be parameterized (Rodríguez et al., 2014): each CF may be parameterized with spatialized parameters depending on the site and EF properties. Regionalized variables are contained in a shapefile. It reduced the amount of data and computing power required. Nevertheless, only simple regionalized LCIA methods relying on basic equations can be fully recalculated by the software using the spatial parameterization feature. In other words, entirely re-encoding a complex regionalized LCIA method, like the acidification impact indicators that need results from the GEOSchem model (Roy et al., 2013), seems quite impossible.

3.3. Practical recommendations

3.3.1. List of practical recommendations

Short- and long-term recommendations for each identified question are described in Table 3 for questions related to G&S and inventory regionalization, Table 4 for questions related to inventory spatialization, Table 5 for questions related to regionalized impact calculation, impact regionalization and interpretation. More complete tables are in the Supplementary Information.

Table 3 – Recommendations for the short- and long-term integration of spatial dimension into LCA for questions related to G&S and inventory regionalization

| Questions | Short-term recommendations | Long-term recommendations |
|---|--|---|
| G&S | | |
| Does the scope of the study refer to a territory? | <u>For practitioners:</u> Use a territorial LCA approach | |
| How can the spatial requirements of the LCA study be defined? | <u>For practitioners:</u> Always specify the spatial coverage in the functional unit. Specify and justify the spatial requirements for LCI data quality and for LCIA methodology selection. | |
| Is the implementation of an inventory regionalization or spatialization process necessary? | <u>For practitioners:</u> Define the acceptable level of uncertainty, at least qualitatively, by discussing with the study commissioner. Assess the spatial uncertainty of preliminary LCA results, at least qualitatively, based on expert knowledge. Compare the level of uncertainty to the acceptable level of uncertainty to determine whether there is a need for inventory regionalization or spatialization. Special focus on studies supporting decisions that are sensitive for public policies, studies disclosed to the public, addressing international supply chain and consequential LCAs. | <u>For research:</u> Develop systematic and operational guidelines to assess the interest of regionalization in a specific case study. |
| How can the inventory regionalization and spatialization efforts be prioritized? | <u>For practitioners:</u> Carry out inventory regionalization and spatialization in parallel whenever relevant. Inventory regionalization minimizes the efforts required during inventory spatialization since spatial information may have already been collected. | <u>For research:</u> Develop systematic and operational guidelines to prioritize inventory regionalization and spatialization efforts. |
| Inventory regionalization | | |
| How can the inventory be regionalized? | <u>For practitioners:</u> Use both process recontextualization and the adaptation of numerical data. Carry out recontextualization as a priority if the geographical coverage of the selected processes is not representative of the modeled region. Anticipate regionalization from the onset to save time. | <u>For DB developers:</u> Set out regionalized datasets that are representative of all regions of the world, including emerging countries when they are important to the global market. |
| How can the geographic representativeness of the data be evaluated? | <u>For practitioners:</u> Assess the geographic representativeness of data with the pedigree matrix as it remains the most operational method from now. The spatial uncertainty associated with the most impactful economic flows and EFs of the processes can, therefore, be evaluated to prioritize inventory regionalization over lesser quality data. | <u>For DB developers:</u> Continue the efforts to associate a pedigree matrix to each economic flow. <u>For research:</u> Provide uncertainty conversion factor sets for the pedigree matrix for each type of process. |
| How should efforts be prioritized? | <u>For practitioners:</u> Use the most detailed data regardless of the processes whenever accessible. Perform a contribution analysis to the damage score to identify processes that should be regionalized in priority. Select for regionalization only the most impacting processes with the highest potential spatial variability using the pedigree matrix or expert knowledge. Special focus on processes for energy production and consumption, transport, agriculture-related, land use and waste management processes, since they may be affected by geographic variability from one region to the next. Align the inventory regionalization effort (i.e. the number of processes to be regionalized) with the goal of the LCA study and data availability. Electric grid mix regionalization is relatively straightforward to apply and often yields significant benefits. Prioritize the regionalization of foreground data, following ILCD recommendations. | <u>For practitioners:</u> Select the processes to be regionalized based on their contribution to the spatial uncertainty. <u>For LCA software developers:</u> Set out software that can compute LCA calculations in a probabilistic manner to be able to carry out contribution analyses that account for data uncertainty. <u>For research:</u> Develop a method to give priority to more systematic inventory regionalization efforts based on the study objectives, decision-making context, studied sector and available means. |
| What should the level of detail be? | <u>For practitioners:</u> Analyze each process individually as the effort depends on the type of processes and determine the level of detail required based on expert knowledge, available data and available resources. Regionalize data based on economic market limits, following ILCD recommendations. | <u>For research:</u> Develop guidelines that provide a relevant level of regionalization for each process type. |

Table 4 – Recommendations for the short- and long-term integration of spatial dimension into LCA for questions related to inventory spatialization

| Questions | Short-term recommendations | Long-term recommendations |
|--|---|---|
| Inventory spatialization | | |
| How can spatialization be carried out? | <p><u>For the practitioner:</u> Use CFs that have already been aggregated by LCIA methodology developers and for which the practitioner has the information (continent, country), it will be the least time-consuming recommendation for spatialization. Use the geographic coverage of the processes resulting from the inventory regionalization as a spatial information to spatialize to related EFs for finer spatialization. Spatialize EFs case by case using proxies to describe their spatial distribution if a higher level of spatial detail is needed. Use GIS software if necessary. Take the practitioner's level of expertise in spatialization into consideration to adapt the spatialization strategy, especially regarding its GIS experience.</p> <p><u>For LCIA methodology developers:</u> Set out aggregated CFs by clearly specifying the aggregation proxies and provide the uncertainty related to the spatial variability of the CFs.</p> <p><u>For LCA software developers:</u> Facilitate flow spatialization by, for example, making it possible to automatically apply the geographic scope of a process to related EF.</p> | |
| What type of spatial information should be used? | <p><u>For the practitioner:</u> Use SimaPro or GaBi only for studies that require little flow spatialization or spatialization at a relatively low aggregated level. Use openLCA or Brightway for studies that require the spatialization of many flows or spatialization at higher resolution.</p> <p><u>For LCIA methodology developers:</u> Describe the geographic variability of the CFs for a given impact category for native resolutions. Consider the level of geographic information that is accessible to practitioners (which is often the country level) to develop regionalized CFs or the aggregate CF at a useful level. For example, aggregation of CF at country level is more practical for a practitioner because inventory data are more likely available for this spatial resolution.</p> | <u>For LCA software developers:</u> Set out software that can simply and consistently support different types of spatial information. |
| How should efforts be prioritized? | <u>For practitioners:</u> Select the regionalized impact categories for which the EF must be spatialized based on an impact contribution analysis of midpoint impacts to damage. For IMPACT World+, the regionalized impact categories are land use impacts on biodiversity, water use impacts, terrestrial acidification, aquatic acidification (freshwater), aquatic eutrophication, marine eutrophication, carcinogenic effects (short and long term), non-carcinogenic effects (short and long term) and respiratory effects (inorganic). Select the EFs associated with the most contributing processes to the impact score to be spatialized. The inventory spatialization effort (i.e. the number of EFs to be spatialized) must reflect the study quality requirements set out by the commissioner of the study and data availability. | <p><u>For practitioners:</u> Select the EF that must be spatialized by systematically considering their contribution to the spatial uncertainty.</p> <p><u>For LCA software developers:</u> Set out software that can compute LCA calculations in a probabilistic manner to carry out contribution analyses that account for data-related uncertainty.</p> <p><u>For research:</u> Develop a systematic guidance to assign the priority based on the study objectives, decision-making context, studied sector and available means.</p> |
| What should the level of detail be? | <u>For the practitioner:</u> Impossible to recommend a specific level of detail as it depends on the considered impact category and is driven by the objectives of the LCA and a trade-off between time spent and gains in terms of relevance. It should be part of an iterative approach. | <u>For research:</u> Propose a systematic methodology able to identify the level of detail that is the most suited to the study objectives, decision-making context, studied sector and available means. |
| How should sensitivity analyses be carried out in regionalized LCA? | <u>For practitioners:</u> Determine impact categories and processes on which sensitivity analyses should be carried out by the means of expert knowledge. | <u>For research and LCA software developers:</u> Set out a simplified tool to easily carry out global sensitivity analyses for regionalized LCA. |

Table 5 – Recommendations for the short- and long-term integration of spatial dimension into LCA for questions related to regionalized impact calculation, impact regionalization and interpretation

| Questions | Short-term recommendations | Long-term recommendations |
|--|--|---|
| Regionalized impact calculation | | |
| How can regionalized impacts be calculated? | <p><u>For practitioners:</u> Use SimaPro and GaBi to calculate regionalized LCA using spatialized EFs if available.</p> <p><u>For LCIA method developers:</u> Predefine spatialized EF in SimaPro and GaBi.</p> <p><u>For DB developers:</u> Integrate spatialized EFs in datasets.</p> | <p><u>For practitioners:</u> Perform regionalized LCA calculations by accounting for the uncertainty of aggregated CFs accounting for the spatial variability of an approximate or unknown location of EF.</p> <p><u>For software developers:</u> Integrate user-friendly functionalities in LCA software to manage localization uncertainty and discrepancies in spatial resolution between the inventory and automatically spatialize process-related EF during regionalization.</p> |
| Impact regionalization | | |
| How can impact assessment methodology be regionalized? | <p><u>For LCIA method developers:</u> Regionalize by using archetypes when the variability is driven by very few parameters that can be readily identifiable by LCA practitioners. Regionalize by using a spatially differentiated LCIA model otherwise. Provide maps of native CFs and aggregated CFs if using multi-regional model. Provide the uncertainty related to spatial variability for aggregated CFs.</p> | |
| Which impact assessment methodology should be used? | <p><u>For practitioners:</u> Select the LCIA methodology with a geographic scope that is aligned with the goal of the study. Choose regionalized LCIA methodologies whenever possible. Apply continent- and country-level aggregated CFs whenever possible. Use regionalized CFs at the native scale only if specifically required.</p> <p><u>For LCIA method developers:</u> Set out CFs that are aggregated at relevant levels considering the information that an LCA practitioner could gather. Provide detailed documentation on the impact assessment methodologies, specifically indicating the aggregation proxies that are used. Highlight the area of validity of the CFs that are developed to limit irrelevant uses.</p> | <p><u>For practitioners:</u> Integrate the uncertainty associated with the CFs when calculating results uncertainty.</p> <p><u>For LCIA method developers:</u> Systematically set out CFs and their related uncertainty. Make it possible to parameterize the CFs to best adapt them to the context of the study when required by the practitioner.</p> <p><u>For LCA software developers:</u> Set out software to calculate uncertainty that integrates CF uncertainty and parameterization.</p> |
| How can uncertainty related to spatial variability be assessed? | <p><u>For LCIA method developers:</u> Document the spatial variability of the aggregated CFs for all new regionalized LCIA methods.</p> <p><u>For practitioners:</u> Use information on spatial variability, at least qualitatively, to be able to provide an expert judgment on the relevance of further spatialization.</p> | <p><u>For LCIA method developers:</u> Systematically quantify the spatial variability of CFs for all new regionalized LCIA method.</p> <p><u>For LCA software developers:</u> Set out software to calculate uncertainty that integrates CF uncertainty.</p> |
| How can a regionalized impact assessment method be implemented? | <p><u>For LCA software developers:</u> Implementation using GIS is recommended if LCIA method developers provide maps of their regionalized CFs.</p> | |
| Interpretation | | |
| How should the impacts be visualized? | <p><u>For practitioners:</u> Interpret impact results aggregated at the global level if the study does not require specific information on impact localization so as not to increase the practitioner's workload. Alternatively, use a software such as openLCA, which makes it possible to visualize impact origins on a map.</p> | <p><u>For LCIA method and LCA software developers:</u> Set out software to visualize the original and final locations of the impacts on a map.</p> |
| How should sensitivity analyses be carried out in regionalized LCA? | <p><u>For practitioners:</u> Use the expert knowledge to determine impact categories and processes on which sensitivity analyses should be carried out.</p> | <p><u>For research and LCA software developers:</u> Set out a simplified tool to easily carry out global sensitivity analyses for regionalized LCA.</p> |

3.3.2. *Decision-support diagram to guide LCA practitioners in the implementation of short-term recommendations*

A decision-support diagram was set out to guide LCA practitioners in the implementation of inventory regionalization and spatialization and prioritize their efforts based on the current state-of-the-art (Figure 1). The diagram defines a logical series of steps that may be carried out using common tools such as LCA software (e.g. Simapro), inventory databases (e.g. ecoinvent v3) and impact assessment methods (e.g. IMPACT World+). The process is iterative. Some steps in the diagram depend on the G&S of the study and available resources and data to, for example, determine the number of processes to be regionalized by the LCA practitioner. The approach described here considers a LCIA midpoint-endpoint framework but is also applicable to a midpoint-oriented methodology. The proposed framework has been tested and tuned through case studies which are not presented here but are available in Patouillard et al. (2015). A more detailed version of the diagram is available in Supporting Information. It consists of three phases.

- **Phase 1 – Preliminary phase:** This phase aims to identify the needs in terms of reducing spatial uncertainty. As a reminder, we consider here that the main objective of inventory regionalization and spatialization is to reduce spatial uncertainty in order to increase the relevance of the results. Tools to quantitatively assess the uncertainty related to spatial variability are not yet available in the mainstream use. However, the LCA practitioner should conduct a qualitative analysis estimating the geographic variability per impact category within a system (e.g. based on expert knowledge or available information on spatial variability, as provided by IMPACT world+). The first step in the diagram is about establishing the level of acceptable uncertainty for the decision-maker regarding the G&S of the study. It results from a dialogue between the LCA practitioner and study commissioner. If the estimated spatial uncertainty of the results is higher than the targeted acceptable level of uncertainty, the LCA practitioner should enter the second phase.
- **Phase 2 – Inventory regionalization:** Inventory regionalization is carried out before inventory spatialization. Indeed, several of the geographic data collected in this phase may be used afterward to spatialize the inventory. Inventory regionalization phase is based on the identification of the most contributing processes likely to be associated with a high geographic variability (2.a.). Impact contribution analyses should be carried out at the damage level for each indicator but may also be carried out at the midpoint level. The selected processes are regionalized based on the geographic representativeness of both the spatial coverage of the process and the amount required with respect to this spatial coverage. The amount we are referring to here is the magnitude of the economic flow for the processes selected in 2.a. If the geographical coverage of the selected processes is not representative of the modeled region, those processes should be recontextualized (2.b.), either by using more representative processes already available in LCI

databases (2.b.i.) or by adapting the process with more representative and contextual data (2.b.ii.). When using a more representative process already available in the LCI database (2.b.i), the LCA practitioner should nevertheless check its comprehensiveness, i.e. if the list of economic and elementary flows in the dataset is fairly complete to well represent the activity. The effort for recontextualizing process data (2.b.ii.) should be focused on the most impacting and less representative economic and elementary flows within the process. Then, the magnitude of the associated economic flow should also be adapted to the regional context (2.c.).

- **Phase 3 – Inventory spatialization:** First, a contribution analysis should be carried out to identify the most contributing midpoint impact categories to their respective damage categories (3.a.). Those identified categories are selected for inventory spatialization only if they are sensitive to spatial variability and if corresponding regionalized CFs are available (3.a.i.). Alternatively, no spatialization is needed in this context, as it will not contribute to lower the spatial uncertainty of the results. For instance, if climate change is dominating the damage scores, inventory regionalization could be key to lower the spatial uncertainty, but inventory spatialization is worthless. The spatialization of the inventory is given priority for sets of {elementary flow|process} that most contributed to a given impact score (3.b.). Finally, additional data collection and integration of spatialization can be conducted (3.c.).

Once inventory regionalization and spatialization are carried out, the diagram must be iterated to verify whether the resulting level of uncertainty is acceptable based on the targeted level of acceptable uncertainty. The LCA practitioner should stop iterating when he is not able to lower further the spatial uncertainty of results because of a lack of relevant available data or lack of resources to conduct a more representative study.

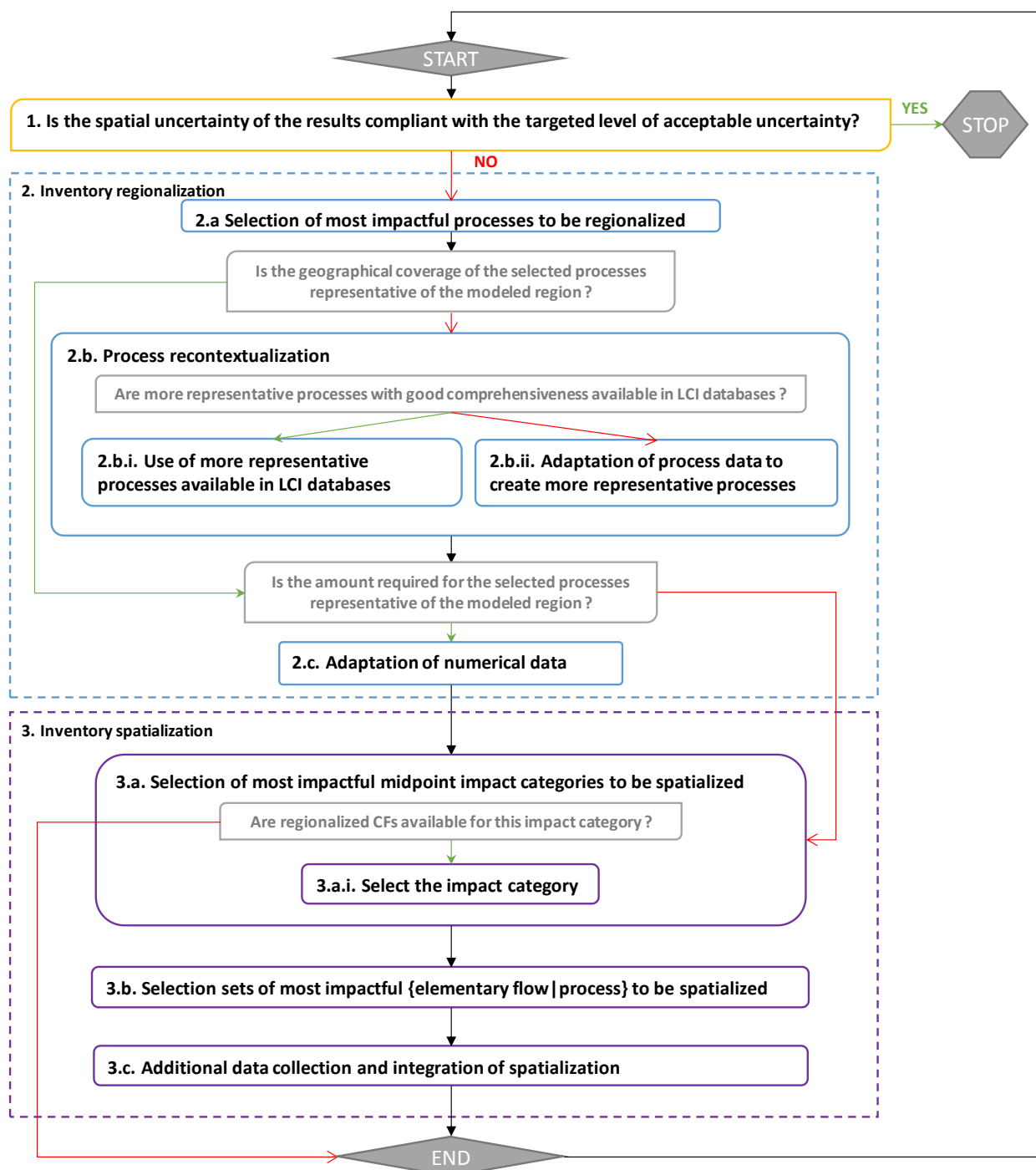


Figure 1 – Logic diagram for the operational implementation of inventory regionalization and spatialization in LCA by practitioners. Red arrows correspond to “no” answers and green arrows to “yes” answers. A more detailed figure is available in Supporting Information. (Abbreviations: LCI: life cycle inventory, CF: characterization factor)

3.3.3. Discussion of the practical recommendations

In the decision-support diagram, we considered that the main objective of inventory regionalization and spatialization is to reduce spatial uncertainty to enhance the results quality in term of relevance and representativeness. Nevertheless, inventory spatialization still can be relevant for other purposes, for instance, to enhance the interpretation of results by displaying impact origins on a map as for urban planning (Mastrucci et al., 2017). Inventory regionalization and spatialization can also increase the discriminating power of an LCA.

Setting the level of acceptable uncertainty is a challenge. Indeed, the efforts for reducing the uncertainty of impact scores depend on the goal of the study, the assessed product system, the available time and financial resources for the study, knowledge of the LCA practitioner, data availability, etc. (Herrmann et al., 2014). In addition, some uncertainties can hardly be reduced (Weidema and Wesnæs, 1996). For instance, in a comparative LCA where the spatial dimension is deemed of potential influence on some impact categories for both systems under comparison, the spatial uncertainty might not have much impact on the differential score if there is a strong correlation of elementary flows. Thus, the level of acceptable uncertainty should be defined with respect to the context of the study. Besides, the practical and quantitative way to define this level should be further investigated. For now, checking if the results are compliant with the level of acceptable uncertainty mainly consist of checking if the recipient agrees (or disagrees) with the limitations of the LCA study and may require (or not) a more extensive study. It is therefore important for the practitioner to be explicit and transparent with regards to the limitations of the study in terms of regionalization and spatialization.

In the preliminary phase, the spatial uncertainty of results should be assessed as accurately as possible, ideally by performing an uncertainty analysis integrating the spatial variability from the inventory and from the CFs. To do LCA software should be able to handle uncertainty data from the inventory and from the impact assessment. Unfortunately, the spatial variability of the CFs still cannot be added in SimaPro. A standard deviation which can represent the spatial variability can be added to CFs on GaBi. For now, only openLCA and Brightway LCA software can perform Monte Carlo analysis integrating both uncertainty data. In addition, regionalized LCIA method developers should also provide a quantitative assessment of the spatial variability associated with the CFs to enable a comprehensive uncertainty analysis by LCA practitioners (Verones et al., 2017).

Inventory regionalization and spatialization are sequential in the proposed diagram. Indeed, there is no way to prioritize the efforts between both by using contribution analysis to the impact score as proposed here. Contribution analysis to the uncertainty instead the impact score would be required: if the main source of uncertainty comes from inventory data then inventory regionalization would be required; if the main source of uncertainty comes from spatial variability of CFs, then inventory

spatialization would be required. Similarly, the hotspot identification to prioritize regionalization efforts should be based on uncertainty contribution analysis rather than impact contribution analysis, to focus the regionalization effort on the main contributors to the overall spatial variability in order to reduce it. Indeed, using impact contribution analysis to identify the hotspots that need to be regionalized or spatialized assumes that the largest impact contributors are also the largest uncertainty contributors, which is not necessarily the case. Therefore, large uncertainty contributors could be missed by using impact contribution analysis (Patouillard et al., 2016). On the long-term, efforts are needed from LCA researchers and LCA software developers to provide methodology and tools enabling uncertainty contribution analysis for LCA practitioner as a routine.

4. Conclusion

Building on an extensive critical review from the literature, this study identified the state of the art on how to integrate the spatial dimension in LCA, highlighted practical and conceptual obstacles and created a common language. Recommendations were formulated for LCA practitioners, LCI database developers, LCIA method developers, LCA software developers and LCA researchers to enhance the integration of the spatial dimension in LCA on the short and the long term.

A decision-support diagram was further developed to guide LCA practitioners through an iterative process in the implementation of short-term recommendations aiming to reduce the spatial uncertainty of the LCA with a minimum of effort and only when needed. On the long-term, LCA researchers and LCA software developers are invited to go beyond the surrogate of a contribution analysis on the impact score to prioritize inventory regionalization and spatialization. To do so, more relevant methods and tools need to be developed, especially about enabling the analysis of contribution based on the uncertainty.

Those long-term recommendations focus on developments that still require additional experience to be gained through regionalization efforts, which are still in its infancy and are so far addressed by a limited number of stakeholders. In the future, enhanced knowledge of the drivers that influence regionalization in each technology or sectors and in each impact category will further help in organizing and prioritizing long-term developments. We recognize this study is a little step towards the long pathway LCA community still need to walk through consistently integrating the spatial dimension in LCA.

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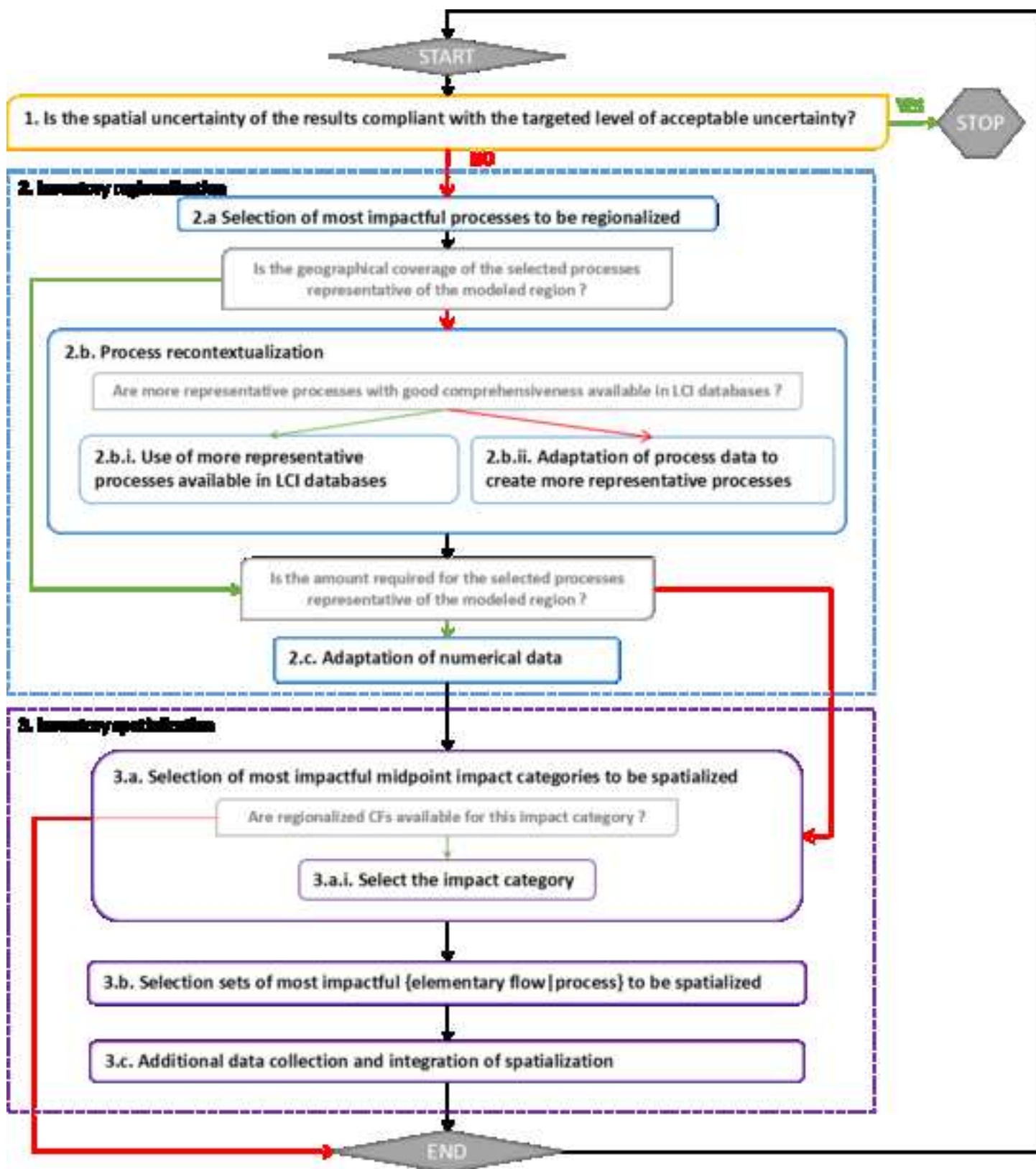
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Figure
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Highlights

- Nomenclature and definitions related to the spatial dimension in LCA are proposed.
- Main approaches to integrating the spatial dimension in LCA are reviewed.
- Recommendations to address spatial dimension in LCA are provided.
- A decision-support diagram is proposed to guide LCA practitioners.

Supplemental Information

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