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Ready-to-use and advanced methodologies to prioritise the regionalisation effort in LCA

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Abstract – The spatial dimension is an important aspect in life cycle assessment (LCA). Indeed life cycle processes, and therefore also elementary flows, are most likely to be geographically scattered due to global supply chains. The environmental impacts related to an elementary flow can be different across the globe depending on the spatial variability of ecosystem sensitivity. Integrating spatial dimension seems to be a promising way to increase LCA results' reliability by reducing spatial uncertainties. LCA regionalisation refers to the integration of the spatial variability that really exists to improve result representativeness and reduce spatial uncertainties. As regionalisation requires additional effort for LCA practitioners, it is necessary to ensure the interest of such an effort and to prioritise it. This work proposes two methodologies to prioritise the regionalisation effort in LCA depending on the decision context and the type of study. They allow the selection of impacts, processes and regionalisation aspects that LCA practitioners need to focus on. The first one is a ready-to-use methodology and the second one involves more advanced tools based on spatial uncertainty analysis. The proposed methodologies are stepwise. The ready-to-use methodology involves tools that are already used by LCA practitioners and is based on impact contribution analysis. Regarding the advanced methodology, most relevant impact categories and processes to be further investigated for regionalisation are selected according to their impact contribution and their uncertainty level by using Monte Carlo simulation and regression analysis. The regionalisation effort is estimated depending on the confidence level required for the case study. The relevance and limits of each methodologies are investigated. Results underline the importance to take into account both impact and uncertainty contributions to select processes that need to be regionalised. The proposed methodologies highlight the need to focus on the goal and scope at the early stages of a study in order to clearly identify the intended audience and its requirements regarding study quality. A dialogue with the decision maker during the study would be beneficial. Those approaches can be relevant for other types of uncertainty but should be adapted.

Key words: Life cycle assessment / uncertainty / Monte Carlo / sensitivity analysis / regionalization / spatialization / prioritization

1 Introduction

The spatial dimension is inherent to life cycle assessment (LCA). Its importance has been underlined from its beginning especially for the development of life cycle impact assessment (LCIA) methods [1]. Indeed impact categories have different spatial scale. Some are global such as climate change or ozone depletion meaning that the impact of related elementary flows do not depend on their location. In other words, elementary flows (emissions or withdrawals to the environment) contributing to

global impact categories will affect any part of the world in a same way. Conversely, some impact categories have local scale such as eutrophication or acidification [2] for which the effect of related elementary flows will not be the same depending on the region where they occur. Regarding local scale impact, the fate of a pollutant and then its exposure to sensitive receptors is influenced by local conditions around its source location. Therefore the environmental impacts related to an elementary flow can be different across the globe depending on the spatial variability of ecosystem sensitivity.

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Spatial location should also be considered in life cycle inventory (LCI) phase. Most of value chains are scattered across the globe due to market globalisation. Thus some life cycle steps can occur in different countries or continents. The resulting technological variability between regions should be taken into account by LCA practitioner. This variability is due to differences in types of technology, yields, supply chains, etc. For instance, the electricity supply mix differs from one country to another depending on several factors such as electricity production technology (coal or gas based, renewable energy, etc.), yield (recent plants are more efficient than old ones, yields for wind power depend on local wind conditions, etc.), plant operations, electrical imports [3]. Some processes such as agricultural ones face a high geographical variability even within a country, e.g. for N_2O emission amount at field [4].

This article deals with the concept of regionalisation to integrate the spatial dimension in the LCI and LCIA phases. Two main challenges arise from the operationalisation of regionalisation by LCA practitioner: which spatial aspects should be included in priority in an LCA study and which detail level is relevant. Firstly, regionalisation concepts are defined. Their main benefits and limits are underlined. Secondly, two methodologies are described to prioritise the regionalisation effort in LCA depending on the decision context. The first one is a ready-to-use methodology and the second one involves more advanced tools based on spatial uncertainty analysis. The relevance and limits of each methodologies are investigated. Finally, the operationalisation of both methodologies by LCA practitioner is discussed.

2 Regionalisation concepts

The term “regionalisation” was firstly introduced in the LCA field in the 90’s [5]. Since then, it has been used a lot for different purposes without any clear definition. Here we propose a nomenclature for the regionalisation concepts with their corresponding definitions.

The term region refers here to a geographic zone delimited by boundaries within some parameters are homogeneous. For instance, a region can be political (country), economical (market), based on a homogeneous climate or watershed. The region size depends on the nature of parameters selected and on the required precision level. Regionalisation can be defined as the fact to divide an area into smaller regions. In LCA field, it refers to the fact of describing in a more representative way processes and phenomena that have a spatial variability for a given area. Regionalisation could occur in the LCI and LCIA phases:

- Inventory regionalisation refers to the regionalisation during the LCI phase. It enables to obtain a more representative inventory of the required geographical coverage [6–8]. All LCA practitioners currently apply this concept even if sometimes they are not aware of it. They use two complementary practices to regionalise the inventory. The first one is called process

recontextualisation [9]. It deals with increasing the representativeness of the product system description by choosing more relevant processes (generally within processes available in LCA database) or by modifying the process architecture. For instance, the electricity supply in a process that we want to regionalise could be replaced by the electricity supply process that is more specific to one region. The second one refers to the numerical data adaptation within each process. Site specific data or more aggregated data can be used to enhance the geographical representativeness of the inventory.

- Impact regionalisation refers to the regionalisation during the LCIA phase. This term deals with the calculation of different regionalised characterisation factors (CF) which are valid in a given area for a same elementary flow. The native CF resolution depicts the spatial variability of most influent parameters and mechanisms and depends on the considered impact category. Few regionalised LCIA methodologies exist. An example is LIME 2 that provides regionalised CF at different scales for Japan [10, 11]. Nevertheless its geographical coverage is limited only to Japan. Therefore its use is based on the assumption that all life cycle elementary flows occur in Japan, which can be misleading for studies with broader life cycles. IMPACT World+ is a regionalised LCIA method that tries to overcome this issue with a global geographical coverage [12]. This methodology proposes native CF regionalised at different scales depending on the impact category. The type of spatial differentiation is different from one impact to another, depending of main drivers for geographical variability which are determined by LCIA method developers. Some impact categories use archetypes such as the respiratory inorganics impact on human health for which one of the main geographical variability drivers is the population density [13]. Other impact categories have their native resolution based on delimited geographical areas like watersheds for water use or biomes for land use or higher resolution grid for acidification and eutrophication. Spatially aggregated CF are also provided at country and continent level as well as generic CF in order to ease their use for LCA practitioners. Corresponding uncertainty related to spatial aggregation is given for each CF.
- The use of regionalised CF requires the addition of a geographical information to elementary flows. This is what we call inventory spatialisation. The type of geographical information to add depends on the impact category, the selected LCIA method and the required regionalisation scale. It could be continent or country or archetype or specific geographical area. One way to spatialise the inventory is to regionalise it and to apply the geographical validity area of a process to each of its elementary flows [14]. Therefore, the detail level would be the same as for inventory regionalisation. However geographical information provided by inventory regionalisation (generally administrative regions such

Fig. 1. Evolution of LCA result uncertainty depending on the accuracy and reliability level of LCA results.

as countries) does not always fit with LCIA method requirements. An additional work could be needed to match spatialised elementary flows with regionalised CF. The spatialisation of elementary flows could also be done by specifying the geographical distribution of an elementary within a process. For instance, tail pipe emissions can be spatialized in order to evaluate the impacts of a vehicle fleet in France. Geographical Information System tools can be used for the inventory spatialisation [15].

Introducing the regionalisation in LCA benefits to the robustness of LCA results. Inventory and impact regionalisation increase the representativeness of the LCA model. Therefore, LCA results are more accurate, i.e. better depict the reality. Additionally, regionalisation reduces the uncertainty due the additional spatial variability that is induced by the use of too much generic data to represent something more specific (e.g. CF representative of Europe to represent impacts in Germany). So LCA results are more reliable, i.e. less scattered. Consequently, regionalisation is a way to lower the uncertainties of LCA results by reducing spatial uncertainties (see Fig. 1).

Nevertheless, some challenges remain for the regionalisation operationalisation by LCA practitioners. Indeed, regionalisation may induce an additional workload for LCA practitioners, especially regarding data collection and building of LCA model [16]. Therefore the regionalisation effort should be prioritised. Furthermore the development of tools to handle regionalised LCA should

continue for LCA database as ecoinvent v3 [17], impact methodology as IMPACT World+ and appropriate calculation methods [18]. The integration of regionalised tools into mainstream LCA software is the cornerstone of more systematic regionalisation practices by LCA practitioners.

3 Methods to prioritise the regionalisation effort

At present, no method dedicated to the prioritisation of the regionalisation effort is available. However, recommendations to prioritise data collection to enhance data quality (that includes the geographical representativeness) have been formulated [17,18]. Heijungs et al. recommends to prioritise the data collection on data which are major contributors to impact results and that are more likely uncertain.

Current practices to analyse LCA results are deterministic approaches based on impact contribution analysis. Based on this, we can derive a ready-to-use method to prioritise the regionalisation effort that can be easily applied by LCA practitioners. Firstly, midpoint impact categories that contribute the most to endpoint ones are selected for further investigation. Then practitioners perform inventory regionalisation focusing on processes that are larger contributors to selected impact categories. Elementary flows to be spatialised are selected by elementary

flows contribution analysis for selected impact categories. The inventory spatialisation effort is focused only on most contributing processes for selected elementary flows. This ready-to-use method is easy to apply by using mainstream LCA software such as Simapro. Besides, it makes sense to focus on biggest impact contributors if we refer to recommendations. However, it does not integrate the uncertainty notion as recommended. Thus this method assumes that the largest impact contributors are also the largest result uncertainty contributors. Hence there is a risk to focus on inputs that do not have a high sensitivity on LCA results. The regionalisation effort on non-sensitive inputs is worthless since regionalisation aims at reducing uncertainty. Thus, the practitioner effort should focus on inputs which have the biggest potential for uncertainty reduction. Moreover, this method does not allow the effort prioritisation between inventory regionalisation and inventory spatialisation.

To address the shortcomings of the ready-to-use method, we propose an advanced method using a probabilistic approach based on variance contribution analysis. Unlike perturbation contribution, variance contribution is a good measure that integrates both impact contribution and sensitivity analysis by taking into account the overall range of values of input parameters [19, 20]. Variance contribution analysis is based on uncertainty propagation using Monte Carlo analysis. This sampling-based method has been chosen because the results allow for a sensitivity contribution analysis based on probability theory to identify most contributing inputs. In particular, the nature of the results (family of distributions) using possibility theory (for instance, Fuzzy interval arithmetic) does not allow such analysis [21, 22]. The Spearman rank correlation (ρ) between each uncertain input and results distribution is calculated. The contribution to variance (CTV) for a given uncertain input j is defined as follows:

$$CTV_j = \frac{\rho_j^2}{\sum_{i=1}^m (\rho_i)^2}$$

The CTV measures the influence of uncertain inputs on result uncertainty. Uncertain inputs in an LCA model could be numerical values for economic or elementary flows or parameters, process choices, CF, etc. The advanced method is stepwise. Firstly, midpoint impact categories to be further investigated are selected on their CTV regarding endpoint impact categories. Secondly, input sources that have a high CTV for selected impact categories are chosen to be regionalised. If highest CTV are due to CF, then inventory spatialisation should be done in priority in order to use less uncertain CF (i.e. less aggregated CF). If other types of inputs have highest CTV, the inventory regionalisation should be prioritise for those inputs. Contrary to the ready-to-use method, this advanced method focuses on the true objective of regionalisation: the reduction of LCA uncertainty. The concepts of Monte Carlo and CTV is quite easy to understand and could be easily used and explained by LCA practitioners. Nevertheless, this method faces some challenges to be fully efficient. Indeed, it relies on uncertainty propaga-

tion and the estimation of input uncertainty is crucial to make a relevant prioritisation. Some approaches like the Pedigree Matrix [23] could help to convert qualitative estimation of the additional uncertainty for numerical values into quantitative measure. However, scenario uncertainty as process choices as well as model uncertainty are still difficult to capture to be integrated into a Monte Carlo analysis. Another challenge of the advanced method is the computational time due to the use of Monte Carlo analysis. To face this issue, Mutel et al. has proposed to use the elementary effect method to preselect most influencing uncertain inputs before performing the Monte Carlo analysis [19, 24]. Finally, this method should be implemented into LCA software to be used as a routine.

Figure 2 summarises the type of contribution to impact and uncertainty that could be prioritised by both methods.

An illustration of both methods has been performed by applying them to a simple case study based on Ecoinvent v3. Figure 3 represents the ranking of foreground processes of “Viscose fibre {GLO} |viscose production| Alloc Def, U” for Ecosystem quality endpoint impact calculated with IMPACT World+ (1% cut-off) using the ready-to-use method (on the top) and the advanced method (on the bottom). For this case study, one could have selected “Heat, district or industrial, other than natural gas {RoW} |market for| Alloc Def, U” process for further investigation using the ready-to-use method whereas the advanced method indicates that this process poorly contributes to the variance of the overall result. The difference in process ranking between the two methods highlights the importance to take into account the variance contribution. Furthermore, more than 95% of the overall variance is explained by the variance of one process (Sulfate pulp (GLO)). Thus, the LCA practitioner could save time by only focusing on this process. Note that this case study has been performed by taking into account all uncertainties assessed in Ecoinvent v3 using Simapro software. CF uncertainties are not taken into account. For regionalisation purpose, it would be worthwhile to focus specifically on spatial uncertainties.

4 Discussion and perspectives

Both methods that have been proposed to prioritise the regionalisation have their strengths and weaknesses. The main strength of the ready-to-use method is its simplicity and straightforward applicability with existing tools. On the contrary, the advanced method can be more complicated to apply and to implement into current LCA software. Indeed it relies on uncertainty analysis which is not a usual practice of LCA practitioners. Hence an additional effort should be done to add uncertainty information on inputs parameters which induce an additional data collection. Fortunately some LCA databases used to model foreground inventory, such as one of the most used one ecoinvent [25], provide uncertainty information on input parameters. The main effort for LCA practitioner is then to add uncertainty information on

Fig. 2. Type of uncertain inputs identified by the ready-to-use and the advanced methods depending on their contribution to impact and to uncertainty results. “Not a problem” means that those inputs do not present a high potential for uncertainty reduction and so are not a problem that need to be addressed with regionalisation. “Potentially a problem” are inputs that present a high potential for uncertainty reduction.

Fig. 3. Foreground process contribution for “Viscose fibre GLO [viscose production] Alloc Def, U” for Ecosystem quality endpoint impact calculated with IMPACT World+ v1.0 (1% cut-off). Mean values and 95% confidence intervals are represented. Process are ranked by their mean values on the graph on the left and by their CTV values for the graph on the right. The contribution to the overall variance is represented on the right axis of the right graph.

his foreground inventory (the one that he built himself). Most of LCA software allow for Monte Carlo analysis. The CTV concept is quite easy to understand for LCA practitioners with little mathematical background, and could be applied easily. Nevertheless the CTV analysis should be integrated into LCA software in order to be fully operational. The main challenge would be to store all the information of each Monte Carlo draw that requires a lot of memory storage. Therefore a trade-off should be found between the increase of the study complexity by applying the advanced method and the reduction of uncertainty. First such a method should be used only if needed, i.e. if the starting uncertainty does not allow to draw conclusions in the study. Second, a less complex method derived from the ready-to-use and the advanced method can be used as described in the next section.

The main strength of the advanced method is that it allows to focus on real problems when our goal is to reduce the LCA uncertainty by applying regionalisation. Conversely, the ready-to-use method could mislead the practitioner. It can lead him to focus his effort on inputs that have a low contribution to result uncertainty and that indeed do not need to be regionalised. One way to promote the benefits of both methods and to limit their weaknesses is to keep the best of both worlds. Firstly, the ready-to-use method could be applied to identify key impacts and processes that need to be further investigated. Then the advanced method can be used to identify key inputs that induce highest uncertainty on results considering only uncertain inputs of selected impacts and processes. This combined approach allows at least to focus practitioner effort on inputs which have a high contribution to impact and to uncertainty. Unfortunately some problematic inputs that induce a high uncertainty on results but low impact contribution will be set aside. Only the advanced method can reveal those inputs.

One issue that is not addressed by both methods is the required level of regionalisation: How many inputs should be selected to be regionalised? To what level of detail the regionalisation should be done? All these questions refer to the issues of quantifying the regionalisation effort and setting a target for the required level of regionalisation. As a reminder, the aim of regionalisation is to reduce spatial uncertainty. Uncertainty defines the confidence level one can have on study results [26]. As LCA is a decision support tool, the expected confidence should be set by the decision maker. Therefore, LCA practitioners should try to adapt the LCA uncertainty level to the level set by decision makers. The difference between both levels defines the level to which LCA practitioners should focus their effort to reduce uncertainties. Indeed, this uncertainty reduction effort will depend on the study goal, the product system assessed, time and financial means for the study, knowledge of the LCA practitioner, data availability, etc. [27]. In addition, some uncertainties are nearly impossible or really hard to reduce [23]. Thus, the expected confidence level should be realistic. Further developments are needed to help for setting the expected confidence level and quantifying the required effort to reach

it. Meanwhile, the expected confidence level can at least be estimated qualitatively. A dialogue should be established between LCA practitioners and decision makers at the early stages on an LCA study to clearly identify the intended audience and its requirements regarding study quality. The practitioner should remain transparent regarding the study limitations especially for regionalisation issues. It implies that the practitioner would be himself aware of regionalisation stakes. Communication of results especially on uncertainty plays here a major role.

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