



HAL
open science

Normalisation in life-cycle assessment: consequences of new European factors on decision-making

Virgile Aymard, Valerie Botta-Genoulaz

► To cite this version:

Virgile Aymard, Valerie Botta-Genoulaz. Normalisation in life-cycle assessment: consequences of new European factors on decision-making. *Supply Chain Forum: An International Journal*, 2017, Sustainability trends: metrics and approaches, 18 (2), pp.76-83. 10.1080/16258312.2017.1333385 . hal-01787845

HAL Id: hal-01787845

<https://hal.science/hal-01787845v1>

Submitted on 22 Jun 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Normalization in Life-Cycle Assessment: consequences of new European factors on decision-making

Virgile AYMARD, Valérie BOTTA-GENOULAZ¹

Univ Lyon, INSA-Lyon, UCBL, UL2, DISP EA4570, F-69621 Villeurbanne cedex, France

¹ Corresponding author: valerie.botta@insa-lyon.fr

Normalization in Life-Cycle Assessment: consequences of new European factors on decision-making

Abstract. Environmental performance assessment of products is necessary to improve sustainability in supply chains. Life-Cycle Assessment (LCA) and its optional normalization step may be used for this purpose. Based on an illustration, this paper studies the most recent International reference Life-Cycle Data system (ILCD) normalization factors and compares them with the most commonly used normalization factors given by CML and ReCiPe H methods. Normalization with ILCD shows differences in the results, compared to normalization with older methods, which may have consequences on business decisions. Indeed some impacts categories are undervalued with old methods because their factors are not up to date. We conclude on the importance of using the latest methods to assess environmental impacts, and on the need to link these approaches or metrics with supply-chain performance evaluation models.

Keywords: Life-Cycle Impact Assessment (LCIA), Normalization, ILCD, Decision-making, Multi-criteria, Supply chain performance.

Introduction

Performance evaluation of supply-chains has been studied extensively, yet remains a promising field of research, as the concept of sustainable development has now become a key element in this area (Botta-Genoulaz et al. 2010; Estampe et al., 2013). Jaegler and Sarkis (2014) highlight the difficulty of universal rules when it comes to the complexities of sustainability in the supply chain. There is a need for new methods in the field of metrics, for measuring sustainable supply chains, and for new tools to integrate them into assessment models. Life-Cycle Assessment (LCA) is a powerful method in environmental performance measurement because it considers the entire life-cycle of a product or a service, and it measures their impacts by means of multi-indicators. The ISO standard 14040 (ISO 2006a) specifies that a LCA is carried out in four distinct phases as illustrated in Figure 1.

< Insert Figure 1 around here >

According to the same ISO standard, LCA is based on principles like transparency, and it gives priority to a scientific approach – which explains why it is such a widely used tool. Yet LCA is usually not used to assess the sustainability of supply-chain management practices (Chardine-Baumann & Botta-Genoulaz 2014), as it is generally believed to be a complicated method whose results are difficult to understand.

This paper studies normalization as a way to examine the importance and the magnitude of the third step of a LCA, the Life-Cycle Impact Assessment (LCIA) results. The International reference Life-Cycle Data system (ILCD) Handbook produced

by the Institute for Environment and Sustainability at the European Commission's Joint Research Centre (2010), defines LCIA as followed: "In a Life Cycle Assessment, the emissions and resources consumed that are linked to a specific product are compiled and documented in a Life Cycle Inventory (LCI). An impact assessment is then performed, considering human health, the natural environment, and issues related to natural resource use. Impacts considered in a Life Cycle Impact Assessment include climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related) respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. The emissions and resources are assigned to each of these impact categories. They are then converted into indicators using impact assessment models. Emissions and resources consumed, as well as different product options, can then be cross-compared in terms of the indicators." Normalization is then interesting to communicate on these results, and it can be used as a decision support tool for businesses. Several methods are available to calculate LCIA and each method has its own normalization factors. It is not always easy to know which method a LCA-analyst may use to reduce risks and uncertainties.

We focus on the ILCD Handbook, which proposes the most recent method to perform LCIA and LCIA normalization. Based on an illustration, we show the consequences on strategic decisions if old normalization methods are used.

The remainder of this paper is organized as follows: The second Section introduces LCA methods and the normalization concept. The third Section highlights the difficulties and limits with the normalization of environmental LCA results. In the fourth Section we propose an approach to reduce uncertainties, based on the ILCD Handbook. Finally, in the last Section, we conclude on the importance of using the

latest available methods to assess the environmental impacts of a system, and on the need to link these approaches with supply-chain performance evaluation models.

Normalization for the interpretation of environmental LCA results

LCA, a powerful but complex decision support methodological tool for companies

Many methodologies and tools are available to perform an environmental analysis of a product or a service system. Two main groups can be distinguished:

- Mono-criteria analyses that focus on one type of environmental impact (e.g. the Bilan Carbone® tool developed by ADEME² that looks only at greenhouse gas emissions);
- Multi-criteria analyses that use different environmental impacts (e.g. LCA).

As a multi-criteria quantitative and transparent methodology based on a scientific approach, LCA is a powerful decision support methodological tool for the environmental management of industries and of supply chains. According to the ISO standard 14040 (2006a) introduces previously, there are four phases in an LCA study: 1) the goal and scope definition phase, 2) the inventory analysis phase, 3) the impact assessment phase, and 4) the interpretation phase. Phases three and four allow us to identify the hot spots where the product or service system under study can be improved throughout its life-cycle. These hot spots are identified using impact categories, which represent environmental issues of concern (e.g. climate change, acidification, human

² ADEME, French Agency for Environment and Energy Management, <http://www.ademe.fr/> (available online 21/03/2016)

toxicity, etc.). Many impact category indicators quantify these impact categories. LCA results may vary and may include errors due to system boundary definition, to data uncertainty and to data hypotheses because of data gaps (Huijbregts 1998).

Different LCIA methods have been developed to characterize the elementary flows crossing the boundary of the studied system into impact categories (third phase of an LCA study). The most widely accepted and most used characterization methods for LCIA convert the inventoried flows into impact category indicators at the midpoint level: they measure the potential impacts of the studied system, unlike the endpoint methods which measure the potential damage to human health and the ecosystems. In this study we compare three midpoint characterization methods found amongst those available for Europe. They are the three following:

- CML (Guinée et al. 2002), one of the most complete and most commonly used methods;
- ReCiPe H (Goedkoop et al. 2008), an enriched (from CML) and harmonized method;
- ILCD (European Commission 2010), the latest up-to-date method.

The LCIA method chosen to characterize the input and output elementary flows may add uncertainties to the LCA results (Reap et al. 2008). However, the choice of a method for calculating the environmental impact of a “product-system” does not always stand to reason. In addition, LCIA results are not always easy to understand for a non-LCA expert. In general, a LCA end-user who is a non-expert would prefer to have only one indicator, e.g. the single “ABC...G” European Union energy efficiency label for electrical products (Europa 2011). Yet a LCA is not designed to use a single indicator, which is a simplistic approach. A LCA analyst may have difficulties ranking the impact

categories used in a same method in order to select only those with the greatest impact on the environment. The question is thus how to rank impact categories that do not measure the same thing (e.g. how to compare the impact of global warming and the impact of acidification)? This is why the International Organization for Standardization standard 14044 (ISO 2006b) provides an optional process to compare several impact category indicators. This option, called “normalization”, is presented in the next section.

Interest of normalization for the interpretation of environmental LCA results

As defined in the ISO standard 14044 (ISO 2006b), normalization is a process to calculate the magnitude of the results of impact category indicators, in relation to some reference information. It is an optional process that can be carried out to complement a LCIA. The characterized results of each impact category are divided by a selected reference value, which puts all the results on the same scale (see equation 1).

$$N_i = S_i / R_i, \quad (1)$$

where, i is the impact category, N_i is the normalized results, S_i is the characterized impact of the impact category i of the system under study, and R_i is the characterized impact of the impact category i of the reference system.

The reference system can be:

- The total inputs and outputs for a given geographical area over a given reference year (e.g. the impact of the European Union for 2010);
- The total inputs and outputs for a given geographical area over a given reference year on a per capita basis (e.g. the impact of a European in 2010).

Examples of normalization references:

- CML: EU25+3, 2000 which represent the impact in 2000 of the 25 European Union countries of 2006 + Iceland, Norway and Switzerland (CML2000 2015);
- ReCiPe H: Europe ReCiPe H, 2000 which represent the impact of Europe in 2000) (Sleeswijk et al. 2008).

Normalization can be helpful in interpreting LCIA results, and in providing and communicating information on the relative significance of the impact category indicator results (Kim et al. 2013; Dahlbo et al. 2013; Van Hoof et al. 2013). The normalization results will be more understandable for non-LCA experts because they are closer to their personal preoccupations. The environmental impact of a product is easier to understand when one can compare it to the environmental impact of a single person over a full year.

Difficulties and limitations with the normalization of environmental LCA results

Normalization is an interesting tool, but depending on the chosen characterization method and reference system, LCIA results may vary widely. As a result, the right decisions may not be taken when using it. Equation 1 shows that the Normalization is calculated by dividing the impact of a system under study by the impact of the reference system. Uncertainties may exist on both the numerator and the denominator due to incompleteness. They can stem from the category indicator results of the product under study, or from the reference system (Heijungs et al. 2007); therefore, the results of the normalization can be too low or too high. Some bias may result from the following:

- Uncertainties from the LCIA model (see second Section), and from the number of considered substances / materials in the model;

- The reference geographical area of the reference system that can be consistent or not with the area of the studied system;
- The reference year of the reference system that can be consistent or not with the study;
- The number of considered substances in the reference system.

We have shown in the second Section that it is complex to compare LCIA characterization methods because they do not always have the same impact categories and they can use different impact category indicators. The only common impact category among all methods is “climate change”, for which the Intergovernmental Panel on Climate Change developed a globally recognized model (IPCC 2007). The model calculates the radiative forcing of all greenhouse gas, measured using the Global Warming Potentials (GWP) expressed as a factor of carbon dioxide (CO₂). In the present section we compare two LCIA methods (CML and ReCiPe H) that measure the GWP of substances for the 100-year time horizon (which is the basis adopted for the Kyoto Protocol).

The LCA tool used for this study is openLCA³ and includes CML and ReCiPe H. Both methods calculate climate change based on the GWP factors extracted from the fourth assessment report of the IPCC (2007). We should have the same LCIA results regardless of the method. However, LCIA calculation gives different results using CML or ReCiPe H. These differences are explained by:

- A different number of greenhouse gas elementary flows included in the model: CML (359 elementary flows), ReCiPe H (461 elementary flows);

³ openLCA, GreenDelta, <http://www.openlca.org/>

- A different strategy for the characterization of wood products' impact: the CML method uses a negative impact factor (positive impact for global warming) for agricultural and forestry products (carbon dioxide consumption during the growth period is greater than carbon dioxide release during the product life-cycle). By contrast, ReCiPe H does not have any negative impact factors.

Therefore, the Normalization factors for the CML method and the ReCiPe H method are different (see Table 1).

< Insert Table 1 around here >

This confirms that the LCIA results will differ, depending on the LCIA methods used for a LCA study (Dreyer et al 2003; Bueno et al. 2016). Consequently, the normalization calculation will also give different results (see Equation 1). These differences will even be amplified if each LCIA method uses different normalization references and normalization factors.

The limits and uncertainties of the normalization process can create different interpretations of LCA results, which can have serious consequences for the environmental strategy of a company. The classification of indicators inside the LCA may give end-users the impression that some environmental impacts are more important than others. There is a risk of ignoring some environmental impacts and therefore of planning environmental strategies that lean towards some strategic choices rather than others. This can go against the interests of the LCA: to use a multi-criteria tool to avoid impact transfer from one impact category to another.

An approach based on new ILCD normalization factors to reduce uncertainties

The ILCD Handbook

The ILCD Handbook is a guide produced by the Institute for Environment and Sustainability at the European Commission's Joint Research Centre on Best Practices in LCA (2010). It provides LCA experts with recommendations to make quality LCAs and to use the best LCIA methods in the European context. It is a combination of different methods, both for midpoint and endpoint assessments (European Commission 2011). This handbook actually provides the most up-to-date and the most complete method for LCIA in Europe, yet until 2014 there were no normalization factors proposed for it. This is no longer the case since in 2014 the Joint Research Centre from the European Commission published a document with recommended normalization factors for the EU-27, related to the domestic inventory in 2010 (European Commission 2014; Sala et al 2015). See Table 2.

< Insert Table 2 around here >

In Table 2, units are defined as follows: kg CO₂ eq. (kg equivalent in CO₂), kg CFC-11 eq. (kg equivalent of trichlorofluoromethane), CTUh (comparative toxic units for humans), mol H⁺ eq. (equivalent molar concentration of the hydrogen ion), kg PM2.5 eq. (kg equivalent of particulate matter with diameter under 2.5 μm), CTUe (comparative toxic units for ecosystems), kBq U235 eq. to air (equivalent uranium radiation measured in kilo Becquerel), kg NMVOC eq. (kg equivalent of non-methane volatile organic compounds), mol N eq. (equivalent molar concentration of the nitrogen atom), kg P eq. (kg phosphorus equivalent), kg N eq. (kg equivalent nitrogen), kg C

deficit (soil organic carbon deficit in kg), m³ water eq. (equivalent volume of water), kg Sb eq. (kg equivalent of antimony).

The domestic inventory (third column) represents the total emissions of the EU-27 countries in 2010. Per person normalization factors (fourth column) have been calculated using Eurostat data on the EU-27 population in 2010 (domestic inventory divided by 499 million inhabitants). The robustness inspires confidence in the quality of the data and methods used to calculate the normalization factors; it is based on the level of maturity of the scientific approach to measure the environmental impacts, as we have more perspective on the assessment of global warming than on the assessment of human toxicity of all chemical substances.

Illustration

In the scientific literature, many European LCA studies have been done using normalization factors from LCIA methods like ReCiPe H (Van Hoof et al. 2013; Dahlbo et al. 2013), but this is not the case for the ILCD normalization factors. The normalization factors for ILCD, given in Table 2, have been calculated recently (European Commission 2014; Sala et al 2015) with data related to the domestic inventory in 2010 consistent with the ILCD method. These new normalization factors have not yet been incorporated into LCA tools.

We conducted our LCA study on an urban furniture product made with reinforced glass fibre composite materials, using openLCA. The company producing the urban furniture needed to develop an eco-design tool to perform LCA analysis in order to communicate with its customers on the product's environmental impacts. Because of the high number of existing environmental impact categories, the company did not know which one to use. In order to select the most critical one, we first updated our LCA database with the ILCD normalization factors, and then applied them on the LCIA

results of the product. This analysis gave us the opportunity to compare the ILCD normalization results with the results previously obtained with the ReCiPe H normalization factors. We set all the LCA parameters and models for both analyses. With these fixed parameters, variations in the LCIA results can only be explained by the differences between ReCiPe H and ILCD characterization methods and normalization methods. The normalization results are presented in Table 3 (the impact categories description has been harmonized between ReCiPe H and ILCD to help the comparison).

< Insert Table 3 around here >

There are differences between the normalized impacts calculated by the two methods. Table 4 presents the variations between ReCiPe H results and ILCD results.

< Insert Table 4 around here >

Some differences were already expected due to discrepancies in the normalization reference year (2000 for ReCiPe H and 2010 for ILCD). Looking at the details by impact category, differences for the ionizing radiation are given by a different total impact of domestic inventory (the LCIA results are the same with ILCD or ReCiPe H). The Joint Research Centre Technical Report (European Commission, 2014) gives explanations on the fact that the ReCiPe H reference system led to a large overestimation of radioactive emissions. The same reason explains the ranking difference for freshwater eutrophication: different choices in the modelling of the domestic inventory (whereas the LCIA result is the same).

However, the previous explanations with the reference year or the domestic inventory are not valid for other important variations. Using the ILCD method instead of the ReCiPe H method substantially increases the normalized results for the impact categories affecting the “human health” endpoint impact category: human toxicity, particulate matter, and photochemical ozone formation. These differences confirm the high level of uncertainty for the characterization and the normalization of some impact categories. As regards the “Human toxicity” impact category, studies have shown that there is a lack in the characterization factors with the ReCiPe H method (Pizzol et al. 2011; Laurent et al. 2011). The UNEP (United Nations Environment Program) and SETAC (Society for Environmental Toxicology and Chemistry) recommendation is to use the USEtox™ model and factors (Rosenbaum et al. 2008), which is included in the ILCD method. This leads to the conclusion that the ReCiPe H characterization method for the “Human toxicity” impact category is now obsolete.

Using an impact category normalization factor instead of another one may totally change the conclusions of a life-cycle interpretation and the decisions taken based on a LCA report. If one does not take certain indicators into account, and focuses only on specific ones, some strategic decision may change, such as the choice of materials, the choice of energy mix, the choice of transport mode, etc. This can have consequences on the eco-design strategies within a company, and even on a global supply chain.

Conclusions and future research

LCA is a powerful method for environmental performance measurement. LCA can be typically used by companies and trade organisations to understand impacts for a product category, and to guide sustainable innovation by identifying the steps in a product life cycle that could be changed to use fewer resources or reduce the risk of negative impact

on the environment. As reported by Weisbrod et al (2016), it is not enough due to the complexity of supply chains and their impacts as it: (a) estimates a limited number of potential environmental impacts, and (b) is a generalised assessment. Normalization is an interesting optional step for LCIA interpretation. Even if it is optional for the ISO standard 14044, it is a very interesting tool for studying the relative importance and magnitude of the results of impact category indicators, and it can be used to present LCIA results for internal use in a company or a supply chain network. Normalization must nevertheless be used with awareness of its risks and limits. The analyst must really understand the chosen LCIA method and its associated normalization factors. He or she must be able to evaluate its uncertainties and gaps, must use the most appropriate normalization references for the system under study, and must clearly inform LCA end-users about the limits of the results and their interpretations. For these reasons, it is important to use the latest available methods to assess the environmental impacts of a system. As explained previously with the illustration, we recommend using the ILCD Handbook for LCA in Europe, which proposes a combination of methods for a LCIA. The ILCD method and its normalization factors are the most up-to-date, even if the quality needs to be improved for some impact category indicators. Research has still to be done to fill in the gaps and improve the models (European Commission, 2014). Normalization factors for specific areas or countries are also required for more precise LCIA (Slapnik et al. 2015; Lautier et al. 2010).

Supply-chain performance evaluation models rarely use LCA methods and indicators. From an experimental point of view, case studies are expected with the ILCD method and its normalization factors in order to have more examples of LCA applied to supply chains. Links should be created between these two fields of research – environmental assessment and supply chain evaluation - in order to improve the

assessment of a supply chain from a sustainability point of view. Consequently, LCA approaches could be considered as good practices for the improvement of the design or management of supply chains.

List of acronyms

EU: European Union

GWP: Global Warming Potentials

ILCD: International reference Life-Cycle Data system

IPCC: Intergovernmental Panel on Climate Change

LCA: Life-Cycle Assessment

LCI: Life-Cycle Inventory

LCIA: Life-Cycle Impact Assessment

Acknowledgments:

Funding provided by the Region Rhône-Alpes, France, supported this work.

References

- Botta-Genoulaz, V., Campagne, J.-P., Llerena, D., & Pellegrin C. 2010. *Supply Chain Performance: Collaboration, Alignment and Coordination*, ISTE Ltd (London, UK) and John Wiley & Sons, Inc. (Hoboken, NY, USA), 370 p.
- Bueno, C., Hauschild, M. Z., Rossignolo, J. A., Ometto, A. R., & Mendes, N. C. 2016. "Sensitivity analysis of the use of Life-Cycle Impact Assessment methods: a case study on building materials." *Journal of Cleaner Production*, 112: 2208-2220.
- Chardine-Baumann, E., & Botta-Genoulaz, V. 2014. "A framework for sustainable performance assessment of supply-chain management practices." *Computers & Industrial Engineering*, 76: 138-147.
- CML2000 (2015) Normalization factors for the year 2000, <https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors> (available online 05/09/2016)

- Dahlbo, H., Koskela, S., Pihkola, H., Nors, M., Federley, M., & Seppälä, J. 2013. "Comparison of different normalised LCIA results and their feasibility in communication." *The International Journal of Life Cycle Assessment*, 18(4): 850-860.
- Dreyer, L. C., Niemann, A. L., & Hauschild, M. Z. 2003. "Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99." *The International Journal of Life Cycle Assessment*, 8(4): 191-200.
- Estampe, D., Lamouri, S., Paris, J.-L., Brahim-Djelloul, S. 2013. "A framework for analysing supply chain performance evaluation models." *International Journal of Production Economics*, 142(2): 247-258
- Europa 2010, *Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products*. Europa (web portal). Retrieved 24 April 2011, <http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32010L0030>, (available online 21/03/2016)
- European Commission - Joint Research Center - Institute for Environment and Sustainability (2014) *Normalisation method and data for Environmental Footprints.*, Report from Benini L., Mancini L., Sala S., Manfredi S., Schau E. M., Pant R. Publications Office of the European Union, Luxemburg, ISBN: 978-92-79-40847-2, 113p.
- European Commission - Joint Research Centre - Institute for Environment and Sustainability (2011): *International Reference Life Cycle Data System (ILCD) Handbook- Recommendations for Life Cycle Impact Assessment in the European context*. First edition November 2011. EUR 24571 EN. Luxemburg. Publications Office of the European Union. 159 p.
- European Commission - Joint Research Centre - Institute for Environment and Sustainability (2010): *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance*. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union. 417 p.
- Goedkoop M.J., Heijungs R, Huijbregts M., De Schryver A.; Struijs J., Van Zelm R, 2009. *ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation*; Published by Dutch National Institute for

- Public Health and the Environment (RIVM), Netherland, <http://www.lcia-recipe.net> (available online 21/03/2016), 132 p.
- Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M.A.J. 2002. *Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background.* Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 692 pp.
- Heijungs, R., Guinée, J., Kleijn, R., & Rovers, V. 2007. "Bias in normalization: causes, consequences, detection and remedies." *The International Journal of Life Cycle Assessment*, 12(4): 211-216.
- Huijbregts, M. A. 1998. "Application of uncertainty and variability in LCA." *The International Journal of Life Cycle Assessment*, 3(5): 273-280.
- IPCC 2007. *Climate Change 2007: Synthesis Report: Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. A report of the Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 104 pp.
- ISO 2006a. *Environmental management - Life cycle assessment - Principles and framework.* International Standard Organisation, ISO14040, Geneva, 20 p.
- ISO 2006b. *Environmental management - Life cycle assessment - Requirements and guidelines.* International Standard Organisation, ISO14044, Geneva, 46 p.
- Jaegler, A., and Sarkis, J., 2014. "The Theory and Practice of Sustainable Supply Chains", *Supply Chain Forum: An International Journal*, 15(1): 2-5.
- Kim, J., Yang, Y., Bae, J., & Suh, S. 2013. "The importance of normalization references in interpreting life cycle assessment results." *Journal of Industrial Ecology*, 17(3): 385-395.
- Laurent, A., Lautier, A., Rosenbaum, R. K., Olsen, S. I., & Hauschild, M. Z. 2011. "Normalization references for Europe and North America for application with USEtox™ characterization factors." *The International Journal of Life Cycle Assessment*, 16(8): 728-738.
- Lautier, A., Rosenbaum, R. K., Margni, M., Bare, J., Roy, P. O., & Deschênes, L. 2010. "Development of normalization factors for Canada and the United States and

- comparison with European factors.” *Science of the Total Environment*, 409(1): 33-42.
- Pizzol, M., Christensen, P., Schmidt, J., & Thomsen, M.(2011. “Impacts of “metals” on human health: a comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA).” *Journal of Cleaner Production*, 19(6): 646-656.
- Reap, J., Roman, F., Duncan, S., & Bras, B. 2008. “A survey of unresolved problems in life cycle assessment.” *The International Journal of Life Cycle Assessment*, 13(5): 374-388.
- Rosenbaum, R. K., Bachmann, T. M., Gold, L. S., Huijbregts, M. A., Jolliet, O., Juraske, R., & McKone, T. E. 2008. “USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment.” *The International Journal of Life Cycle Assessment*, 13(7): 532-546.
- Sala, S., Benini, L., Mancini, L. & Pant, R. 2015. “Integrated assessment of environmental impact of Europe in 2010: data sources and extrapolation strategies for calculating normalisation factors.” *International Journal of Life Cycle Assessment* 20(11): 1568-1585.
- Slapnik, M., Istenič, D., Pintar, M., & Udovč, A. 2015. “Extending life cycle assessment normalization factors and use of machine learning—A Slovenian case study.” *Ecological Indicators*, 50: 161-172.
- Sleeswijk, A. W., van Oers, L. F., Guinée, J. B., Struijs, J., & Huijbregts, M. A. 2008. “Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000.” *Science of the Total Environment*, 390(1): 227-240.
- Van Hoof, G., Vieira, M., Gausman, M., & Weisbrod, A. 2013. “Indicator selection in life cycle assessment to enable decision making: issues and solutions.” *The International Journal of Life Cycle Assessment*, 18(8): 1568-1580.
- Weisbrod, A., Bjork, A., McLaughlin, D., Federle, T., McDonough, K., Malcolm, J. & Cina, R. 2016. “Framework for evaluating sustainably sourced renewable materials.” *Supply Chain Forum: An International Journal*, 17(4): 259–272.

Biographical notes:

Virgile Aymard obtained a Master's Degree in Industrial Engineering at the National Institute of Applied Sciences of Lyon (INSA-Lyon) in 2003. He worked for 10 years in various industries as a Supply Chain engineer, in France and Italy. In 2012, he obtained a Specialist Master's degree in Eco-design and Environmental Management at Arts et Métiers ParisTech, which gave him the skills to assess environmental impacts of products or services throughout their life cycle. He joined the DISP Laboratory in 2014 for 2 years to perform Life-Cycle Assessments (LCA) within a research project composed of industrial companies and laboratories. He currently works as a R&D project leader within a cluster for the textile industry, where he manages collaborative projects with industrial companies and laboratories of the Auvergne-Rhône-Alpes region.

Valérie Botta-Genoulaz is a full Professor at the National Institute of Applied Sciences of Lyon (INSA-Lyon) at the University of Lyon, and Head of the DISP Laboratory (Decision and Information systems for Production Systems). After 6 years of experience in industry, she obtained a PhD in Production Management (Lyon, France), in 1996, and was certified as an application consultant in "Production Planning" for SAP ERP, in 2000. Her research interests include operation planning, supply chain management, the alignment of information systems (information sharing, ERP systems), and their impacts on enterprise performance, with a particular emphasis on sustainable development. She is involved in many research networks, collaborative projects, international conference programme committees, and international journal editorial boards, as well as providing expertise and co-chairing the steering committee of the International Conference on Information Systems, Logistics and Supply Chains.

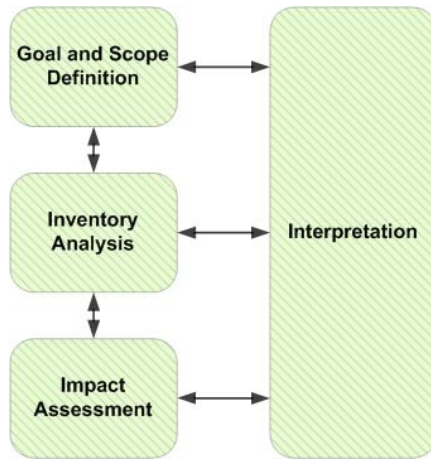


Figure 1: The four phases of LCA (ISO 2006a)

Table 1. CML and ReCiPe H characterization factors and normalization references

<i>"Climate Change" impact category</i> <i>Unit : kg CO2 eq./kg</i>	CML	ReCiPe H
<i>Number of characterization factors</i>	359	461
<i>Normalization references</i>	EU25+3, 2000	Europe ReCiPe H, 2000
<i>Normalization factors</i>	5,21E+12	8,15E+12

Table 2. ILCD recommended normalization factors for the EU-27 (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2014)

Impact category	Unit	Domestic	Normalization Factor per Person (domestic)	Overall Robustness
Climate change	kg CO ₂ eq.	4,60E+12	9,22E+03	Very High
Ozone depletion	kg CFC-11 eq.	1,08E+07	2,16E-02	Medium
Human toxicity - cancer effect	CTUh	1,84E+04	3,69E-05	Low
Human toxicity - non-cancer effect	CTUh	2,66E+05	5,33E-04	Low
Acidification	mol H ⁺ eq.	2,36E+10	4,73E+01	High
Particulate matter/Respiratory Inorganics	kg PM _{2.5} eq.	1,90E+09	3,80E+00	Very High
Ecotoxicity for aquatic fresh water	CTUe	4,36E+12	8,74E+03	Low
Ionising radiations – human health effects	kBq U235 eq. (to air)	5,64E+11	1,13E+03	Medium
Photochemical ozone formation	kg NMVOC eq.	1,58E+10	3,17E+01	Medium
Eutrophication - terrestrial	mol N eq.	8,76E+10	1,76E+02	Medium
Eutrophication - freshwater	kg P eq.	7,41E+08	1,48E+00	Medium to Low
Eutrophication - marine	kg N eq.	8,44E+09	1,69E+01	Medium to Low
Land use	kg C deficit	3,74E+13	7,48E+04	Medium
Resource depletion - water	m ³ water eq.	4,06E+10	8,14E+01	Medium to Low
Resource depletion - mineral, fossil & renewable	kg Sb eq.	5,03E+07	1,01E-01	Medium

Table 3. ReCiPe H and ILCD normalization results for the case study

Impact category	Amount normalization Europe 2000 (ReCiPe Midpoint H)	Amount normalization EU27 2010 (ILCD)
Human toxicity	5,69E-11	2,40E-10
Ionizing radiation	6,01E-12	4,84E-11
Freshwater ecotoxicity	2,88E-10	4,14E-11
Marine eutrophication	4,47E-11	3,54E-11
Particulate matter	1,14E-11	2,58E-11
Photochemical ozone formation	8,89E-12	2,53E-11
Climate Change	1,43E-11	2,39E-11
Acidification	1,36E-11	1,89E-11
Freshwater eutrophication	4,31E-11	1,71E-11
Ozone depletion	6,04E-13	8,91E-13

Table 4. Ranking comparison of ILCD and ReCiPe H normalization results

Impact category ILCD	ILCD ranking	ReCiPe H ranking	Indicator variation ILCD vs. ReCiPe
Human toxicity	1	2	322%
Ionizing radiation	2	9	705%
Freshwater ecotoxicity	3	1	-86%
Marine eutrophication	4	3	-21%
Particulate matter	5	7	127%
Photochemical ozone formation	6	8	185%
Climate Change	7	5	67%
Acidification	8	6	39%
Freshwater eutrophication	9	4	-60%
Ozone depletion	10	10	47%