



*Article*

## Life Cycle Impact Assessment: Research Needs and Challenges from Science to Policy Making

Serenella Sala <sup>1,\*</sup>, Rana Pant <sup>1</sup>, Miguel Brandao <sup>1</sup> and David Pennington<sup>1</sup>

<sup>1</sup> European Commission - Joint Research Center - Institute of Environment and Sustainability. Via E. Fermi, 2749 I-21027 Ispra (VA), Italy

E-Mails: [serenella.sala@jrc.ec.europa.eu](mailto:serenella.sala@jrc.ec.europa.eu); [rana.pant@jrc.ec.europa.eu](mailto:rana.pant@jrc.ec.europa.eu) ;  
[miguel.brandao@jrc.ec.europa.eu](mailto:miguel.brandao@jrc.ec.europa.eu); [david.pennington@jrc.ec.europa.eu](mailto:david.pennington@jrc.ec.europa.eu)

\* Author to whom correspondence should be addressed; Tel.: +39-0332-786417; Fax: +39-0332-786645 ([serenella.sala@jrc.ec.europa.eu](mailto:serenella.sala@jrc.ec.europa.eu))

*Received: / Accepted: / Published:*

---

**Abstract:** Environmental implications of the whole supply-chain of products, both goods and services, their use, and waste management, i.e. their entire life cycle from "cradle to grave" have to be considered to achieve more sustainable production and consumption patterns. Progress toward environmental sustainability requires enhancing the methodologies for environmental integrated assessment and promoting their use in different domains. In the context of Life Cycle Assessment of products, in the last years, several methodologies have been developed for Life Cycle Impact Assessment (LCIA) and some efforts have been made towards their harmonisation. In this context, the Joint research centre (JRC) of the European Commission led a "science to decision support" process which resulted in the International Reference Life Cycle Data System (ILCD) Handbook. The Handbook provides guidelines to methods and assessments to assess emissions into air, water and soil, as well as the natural resources consumed in terms of their contributions to different impacts on human health, natural environment, and availability of resources. Those guidelines come from a comprehensive process of selection of methods based on a set of scientific and stakeholder acceptance criteria and involving experts, advisory groups and the public. In this "from science to decision support" process a number of research needs, critical issues and challenges for LCIA emerged and are presented here as a basis for development, both in terms of comprehensiveness of the impact coverage and of the further mainstreaming of sustainability concept.

**Keywords:** life cycle impact assessment, science for policy support, integrated environmental assessment

---

## 1. Introduction

Environmental implications of the whole supply-chain of products, both goods and services, their use, and waste management, i.e. their entire life cycle from "cradle to grave" have to be considered to achieve more sustainable production and consumption patterns. For several authors, Life Cycle Assessment (LCA) represents the state of the art in science and application relating to the environmental dimension of sustainability.[e.g.1], despite some limitations [2], and it essentially aims at making better informed decisions related to products and services in both business and policy. LCA is distinguished from other environmental assessment tools by two main features [3]:

- Life cycle perspective: all phases ("from the cradle to the grave") of the life cycle of a product (good or service)—from the extraction and processing of the resources, over production and further processing, distribution and transport, use and consumption to recycling and disposal—have to be assessed with regard to all relevant material and energy flows.
- Cross-media environmental approach: all relevant environmental impacts are taken into account, i.e., both on the input side (use of resources) and on the output side (emissions to air, water and soil, including waste).

In the Communication on Integrated Product Policy (IPP) [4], the European Commission committed to produce a handbook on best practice in Life Cycle Assessment (LCA). The Sustainable Consumption and Production (SCP) Action Plan [5] confirmed that "(...) consistent and reliable data and methods are required to assess the overall environmental performance of products (...)".

In this context, JRC led a "science to policy" process which resulted in the ILCD International Reference Life Cycle Data System (ILCD) Handbook. The ILCD Handbook is a series of detailed technical documents, providing guidance for good practice in Life Cycle Assessment in business and government, serving as "parent" document for developing sector- and product-specific guidance documents, criteria and simplified tools. For Life Cycle Impact Assessment (LCIA), the Handbook provides guidelines to methods and assessments to analyze the emissions into air, water and soil, as well as the natural resources consumed in terms of their contributions to different impacts on human health, natural environment, and availability of resources. Several methodologies have been developed for LCIA and some efforts have been made towards harmonization. In order to support the selection of the methods, criteria for good characterization modeling practice were developed in advance to be used in the evaluation and comparison of the selected methods. The criteria include scientific, applicability and stakeholder acceptance issues. Methods and models for LCIA were reviewed, covering different impact categories such as climate change, ozone depletion, photochemical ozone formation, respiratory inorganics, ionizing radiation, acidification, eutrophication, human toxicity, ecotoxicity, land use and resource depletion.

The guidelines for LCIA come from a comprehensive process of selection of methods based on a set of scientific and stakeholder acceptance criteria and involving extensive hearings of domain experts, advisory groups and the public, during a public consultation. In this "from science to policy support" process a number of research needs, critical issues and challenges for Life Cycle Impact Assessment emerged. Robustness of models and reliability of characterization factors must be the basis for further development in Life Cycle Impact Assessment (LCIA).

## 2. The European Platform on Life Cycle Assessment and the ILCD Handbook

Life Cycle Assessment is successfully used in the private sector, e.g. for: continuous environmental improvement of products; internal strategic decision support; evaluating risks and opportunities along the supply chain; communication on strategic aspects with stakeholders at company and association level; communication with customers on products, e.g. via Environmental Product Declarations (EPD), carbon labels and footprints.

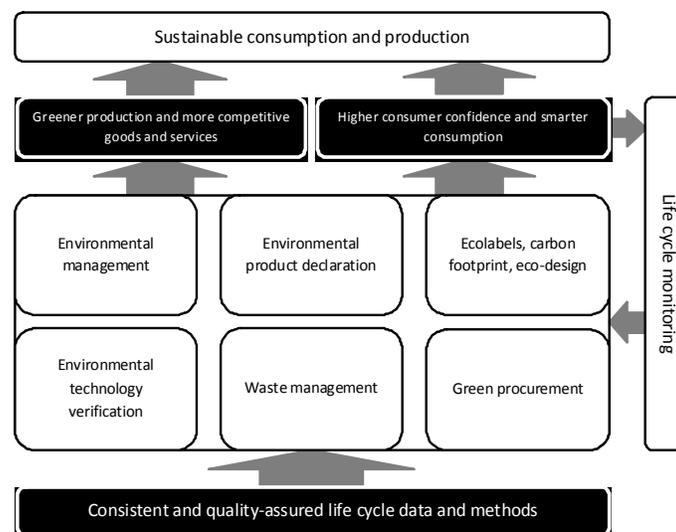
Nevertheless, there is a need for increasing the interaction among stakeholders involved in the development, application and use of the LCA results (such as scientific community, business associations, policy makers).

Since 2005 the JRC-IES is working on the European Platform on Life Cycle Assessment [6] aiming at:

- improving the quality and reliability of life cycle data and assessments;
- increasing the availability of life cycle data;
- facilitating knowledge exchange; and
- promoting networking among various stakeholder

The purpose of the Platform is to improve credibility, acceptance and practice of Life Cycle Assessment (LCA) in business and public authorities. It has been set up to ensure greater coherence across LCA instruments and robust decision support to a range of environmental policies and business instruments (see Figure1).

**Figure 1.** Life-cycle-based instruments supporting sustainable production and consumption



The activities and deliverables of the European Platform on LCA build on five guiding principles: achieving the best attainable consensus; capitalising on existing practice and knowledge; ensuring the scientific robustness; supporting practicality and affordability; providing long-term support.

The main deliverables of the Platform are: the International Reference Life Cycle Data System (ILCD), the European Reference Life Cycle Database (ELCD), the LCA Resources Directory and LCT Forum mailing list.

Those deliverables are performed involving various stakeholders in order to reflect current best practices and improve their overall acceptance. The main stakeholders consulted are: the European Union's 27 Member States and Commission services; representatives of non-EU national LCA database projects, as well as with the United Nations Environment Programme (UNEP); an Advisory Group of European-level business associations; an Advisory Group of LCA software and database developers; and an Advisory Group of Life Cycle Impact Assessment method developers.

### **3. ILCD Handbook and data network**

The ILCD has been built upon the ISO standards for LCA (ISO 14040 series [7]) but provides further detailed technical guidance on all steps required in a LCA. The ILCD has been developed in coordination by the European Commission's Joint Research Centre (JRC), Institute for Environment and Sustainability (IES) together with Directorate-General Environment and through a series of invited and public consultations with global outreach. This has aimed at best-attainable consensus, reflecting best available practice in industry and government. It has to be noted, that the objective was not to create new methods during this process. The ILCD consists primarily of a Handbook and a Data Network

#### *3.1. ILCD Handbook*

The ILCD Handbook is a series of technical guidance documents that provides the basis for developing consistent and quality-assured life cycle data and assessments.

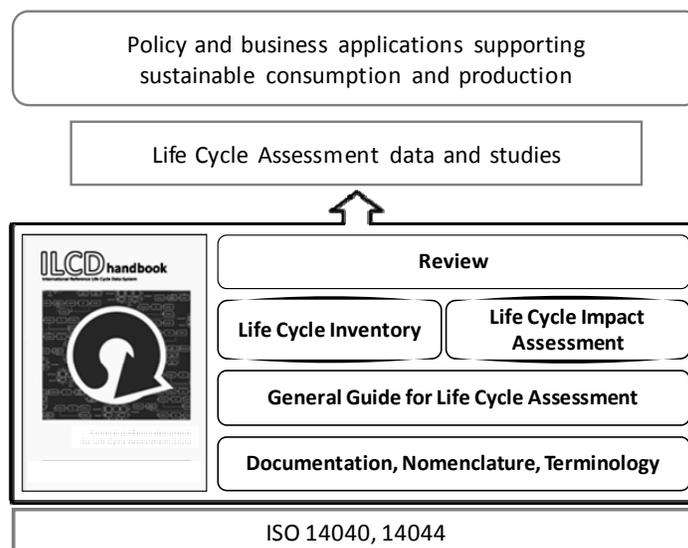
The ILCD Handbook is based on the existing international standards on LCA, ISO 14040/44, that provide the indispensable framework for LCA. This framework, however, leaves the individual practitioner with a range of choices that can change the results and conclusions of an assessment. Further guidance is therefore needed to support consistency and quality assurance. The ILCD Handbook has been set up to provide governments and businesses with a basis for assuring quality and consistency of life cycle data. The structure of the ILCD Handbook is presented in Figure 2.

#### *3.1. ILCD Data Network*

Based on requirements of the ILCD Handbook, the upcoming ILCD Data Network will provide consistent and quality-assured data on resource consumption and emissions (Life Cycle Inventory - LCI). It is open to all providers globally, such as businesses, national LCA projects, researchers, consultants. The data owners maintain their own data and give access via their own servers, based on their own license conditions. These data are to be ISO-conform and be properly documented and independently reviewed as well as use the common ILCD elementary flows. As one foreseen contribution those data sets contained in the European Reference Life Cycle Database (ELCD) that

fulfil at least the entry level requirements of the ILCD are intended to be made available via the ILCD Data Network, covering core LCI data relevant to the European market. Stakeholders worldwide can provide their data to this decentralised network, on their own terms and conditions, e.g. for free or against a fee.

**Figure 2.** Overview of the structure of the ILCD Handbook



#### **4. ILCD Handbook on Life Cycle Impact Assessment: from scientific literature to identifying best practice**

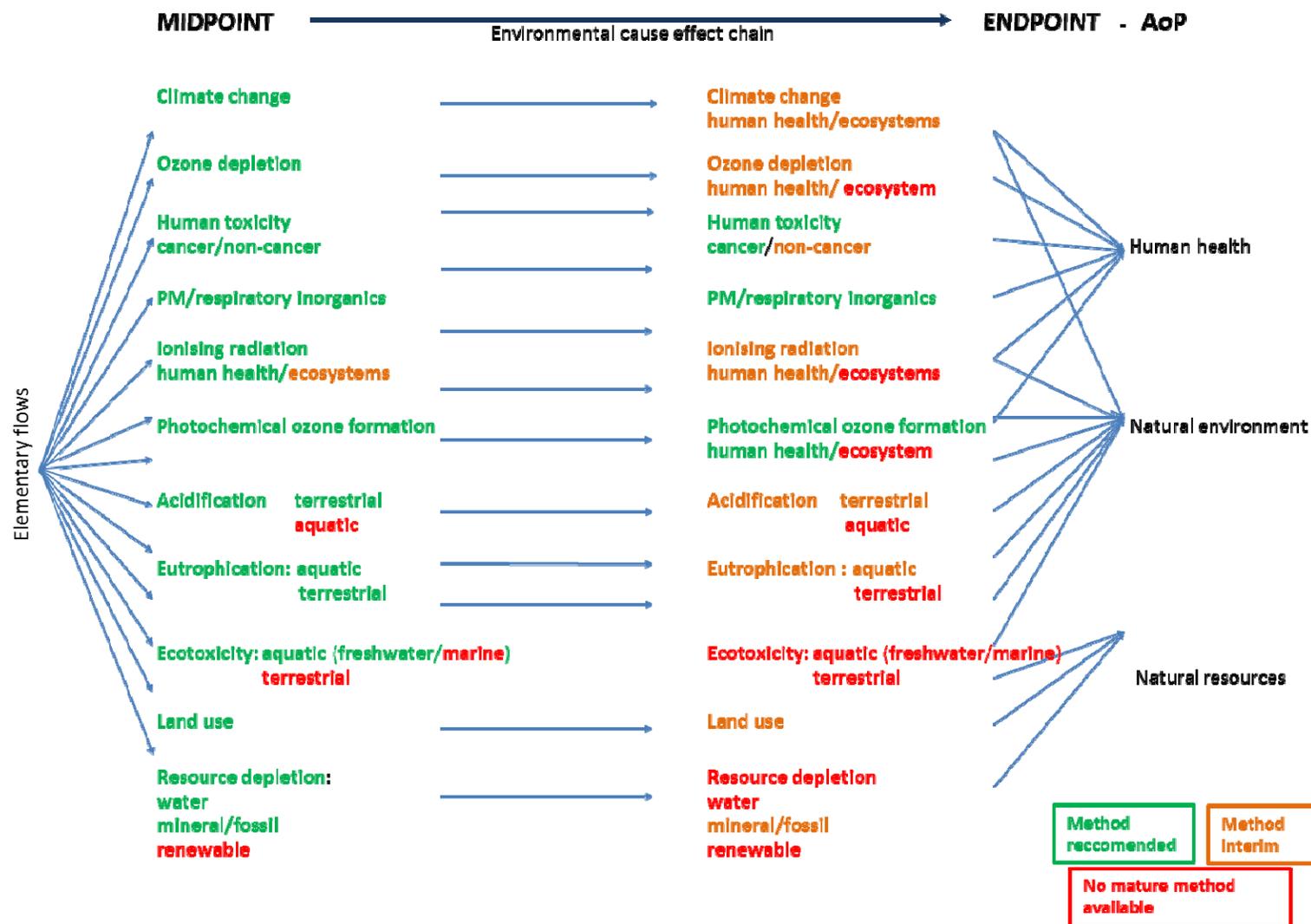
Several LCIA methods are available to analyse the emissions into air, water and soil, as well as the natural resources consumed in terms of their contributions to different impacts on human health, natural environment, and availability of resources, and there is not always an obvious choice amongst them. In spite of the similarities amongst some of them, there can be significant differences in their results. Those differences in LCIA methods can lead to different conclusions of the LCA depending on choice of the LCIA method [8].

Building on recommendations from SETAC and the UNEP/SETAC's Life Cycle Initiative's scientific working groups as an important starting point, the JRC-IES has enhanced the development of recommendations for LCIA through the International Reference Life Cycle Data System (ILCD). This was done in consultation amongst others with several non-EU countries, UNEP and scientific experts.

The ILCD Handbook on LCIA addresses the needs of clear guidance on models, indicators and characterisation factors that should be used in Life Cycle Impact Assessment (LCIA). It supports the calculation of indicators for different impacts such as climate change, ozone depletion, photochemical ozone formation, respiratory inorganics, ionising radiation, acidification, eutrophication, human toxicity, ecotoxicity, land use and resource depletion for use in a common integrated framework, such as LCA. The midpoint level as well as the endpoint level is assessed.

A scheme of the impact categories at midpoint and endpoint covered in the Handbook is provided in Figure 3.

**Figure.3:** Scheme of the impact categories were dealt with in ILCD Handbook on Life Cycle Impact Assessment .In green impact categories for which a method was identified and *recommended*, in orange, those for which a method is considered promising but not robust enough to be recommended (*interim*), in red, those for which *no mature method* is available.



Those guidelines and the selection of LCIA models and indicators has been developed in a “from science to decision support” process based on a set of scientific and stakeholder acceptance criteria and involving experts, advisory groups and the public.

The steps of evaluation are reported in three relevant ILCD Handbook documents dealing with LCIA:

- Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment [9].
- Framework and Requirements for LCIA models and indicators [10].
- Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment in European context [11].

In this process a number of research needs (e.g. issues not yet covered by existing methods, methodological limitation etc), critical issues and challenges for LCIA emerged and are reported in [9] to support LCIA further development.

#### *4.1. Method's selection*

Several methodologies have been developed for LCIA and some efforts have been made towards harmonisation. In order to support the selection of the methods, criteria for good characterisation modelling practice were developed in advance to be used in the evaluation and comparison of the selected methods. Starting from the first pre-selection of existing methods [9] and the definition of specific criteria [10], a set of recommended methods for each impact category at both midpoint and endpoint were selected [11].

The content of the three guidance documents is briefly presented.

The purpose of the Analysis of existing methods document [9], as a background document to the ILCD Handbook, was to provide an analysis of existing LCIA methods to identify differences in approaches and to select methods and models for more in depth evaluations for the final recommendations. The analysis also includes a number of models that cannot currently be found in the selected LCIA methodologies, but which have interesting features to be considered in the further development of LCIA models/methods.

In the Framework and requirements document [10], the core of the evaluation scheme is documented. The document contains:

- a description of the environmental mechanism (cause-effect chain) for each impact category to provide a common understanding of what needs to be modelled;
- a set of model requirements for the specific environmental impact categories that are commonly addressed in an LCA.
- a sets of criteria, sub criteria and recommendations against which models and indicators for use in LCIA should be evaluated for each impact categories. The criteria deal with required scientific qualities (completeness of scope; environmental relevance; scientific robustness and certainty; documentation, transparency and reproducibility; applicability), and the aspects that influence their acceptability to stakeholders;

In the Recommendation for LCIA document [11], the selected methods are presented and discussed against criteria and sub criteria. After the assessment of the best models amongst the other, several levels of recommendations are provided to reflect the different levels of robustness of various impact categories.

#### 4.1. Level of recommendation

The recommended characterisation methods (models and associated characterisation factors) are classified according to their quality into three levels: “I” (recommended and satisfactory), “II” (recommended but in need of some improvements) or “III” (recommended, but to be applied with caution). A detailed description of the levels is provided below:

- Level I: Recommended and satisfactory. These models and characterisation factors are recommended for all types of life cycle based decision support. Although further research needs may have been identified, these are not preventing the models/factors being seen as satisfactory given the current state-of-the art.
- Level II: Recommended, some improvements needed. The uncertainty of models and the resulting characterisation factors is to be more strongly highlighted. The need for dedicated further research is identified for these methods/factors to further improve them in terms of precision, differentiation, coverage of elementary flows etc.
- Level III: Recommended, but to be applied with caution. These models and characterisation factors are recommended to be used but only with caution given the considerable uncertainty, incompleteness or other shortcomings of the models and factors. These models/factors are in need of further research and development before they can be used without reservations for decision support especially in comparative assertions. It is also recommended to conduct sensitivity analyses applying – if available - other methods than the level III recommended ones and to discuss differences in the results, e.g. in the interpretation of the LCA. However, the level III recommended method should remain the baseline.
- Interim: immature for recommendation but the most appropriate among the existing approaches The methods and characterisation factors defined as interim are to be used only with extreme caution, and limited to in-house applications, given the considerable uncertainty, incompleteness or other shortcomings of the methods and factors.
- No recommendation. For some impact categories there were no existing models and factors that met the criteria for level III. For these impact categories no method is recommended in the ILCD System, as the level of maturity and/or available documentation is considered too limited to facilitate general use.

The fact that an impact category at midpoint or endpoint has no recommended methods hence does not mean that it is not relevant to include in a study but merely that at the moment no existing method was found mature for recommendation. In Figure 3, a list of the impact categories is reported, highlighting where methods are still immature to be recommended. This should not be taken as a recommendation to exclude this specific impact category, but to apply a method which has been identified by the practitioner as the current best practise for the specific application. However, in the study the uncertainties and the limitations have to be clearly stated, in particular for this impact category.

## 5. Consultation of stakeholders

At different stages various groups of stakeholders were invited to provide comments on the three ILCD Handbook documents dealing with LCIA. To understand the complexity and the relevance of this consultation, some of the topics highlighted by the by stakeholders are listed:

- Comprehensiveness of the set of impact categories. This refers to the need of identifying impact category at midpoint and endpoint in order to cover the environmental impacts
- Geographical coverage. This refers to the need of accounting for geographical validity of models and factors; Life Cycle Assessment typically has a global scope as the supply chains behind products tend to be global in nature. As far as available, global models have to be used – also for regional impacts. In absence of sufficiently sound global models, a choice had to be made in favour of models that represent large heterogeneous regions qualifying them as proxies of a global situation;
- Availability of inventory data for fulfilling the requirements of being ILCD compliant. So far, for some impact categories a lack in the completeness of the data collected in the inventory phase was reported.

In dealing with comments and input received it was often a not trivial task to find the right balance between e.g.:

- Scientific robustness versus applicability and feasibility aspects
- Making limited assessments on a few impact categories with a high degree of certainty versus making more comprehensive assessments including impact categories with a lower degree of certainty whilst being transparent about their need for improvement
- Cementing the status quo versus encouraging further improvements related to both LCIA method development and related LCI data availability and quality
- Enhancing the comparability of LCAs by being prescriptive versus providing the required flexibility

In these evaluations one guiding principle was the question how the robustness and quality of LCA and specifically LCIA can be further improved to lead to better informed decisions in policy in business.

While the "Analysis of existing methods" [9] and "Framework and requirements for LCIA" [10] documents have been already subject to a peer review by a panel of reviewers, for the Recommendations document [11] the peer review is in the planning phase at the time of writing this contribution.

#### **4. Outlook and prospects**

Enhancing sustainability requires more and more the adoption of methodologies for integrated assessment. In the context of environmental sustainability, major challenges are posed by actual feasibility of integration of models and methods towards a harmonised framework. The current development of LCIA is focused on ensuring comprehensiveness in assessing impacts and in overcoming constraints and limitation of methods and models. From the policy making side, there is a need to balance the stability of the recommendation (to be applied in a business and policy context) and the thriving scientific development in the field of impact assessment. Furthermore, finding the best solution to guarantee comparability among studies and being open to updated models and factors is of paramount importance.

The guidelines for LCIA derived also from the comments provided by stakeholders involved in the public consultation. The process has focused a number of critical issues and research needs to achieve a complete and robust framework for LCIA as well for other integrated environmental assessment procedures. Robustness of models and reliability of characterisation factors must be the basis for

further development in LCIA. To foster the robustness and acceptability of existing and new methods, some of the points under discussion were:

- Further developing the completeness and robustness of endpoint methods, which are not entirely satisfactory at their current development level. Indicators and factors are presented at both midpoint and endpoint in a consistent framework, but the latter are in many cases still immature to be recommended for use;
- Integrating impact categories that are not widely agreed or under development and that don't have yet complete models and factors (such as noise, accidents, salination)
- Establishing a common framework and glossary to enhance the possibility for domain experts outside LCIA to understand how to contribute to the further development of LCIA;
- Developing characterisation factors; some promising models with potential for application in the context of LCIA lack algorithms or proposals on how to calculate characterisation factors. Even if the models are scientifically robust a straightforward integration into LCIA and application in LCA is not feasible without characterisation factors;
- Fostering the geographical and temporal differentiation within methods, to better integrate different levels of impact evaluations: from the global to the regional/local scale.
- Developing a structured framework for addressing uncertainties
- Further improving the decision support function of LCA and LCIA, e.g. by developing and agreeing ways to communicate LCA results in a way that they are more condensed and easier to understand

The goal of a harmonized and robust methodology for LCIA has significant implications for environmental sustainability, moving from domain specific models and methods towards comprehensive and integrated environmental assessment of products and options.

### **Acknowledgments**

The presented process was co-financed by DG Environment through several Administrative Arrangements.

The authors wish to thank the drafting team of the Handbook and all the stakeholders contributing to the public consultation.

### **Conflict of Interest**

"The authors declare no conflict of interest".

### **References and Notes**

1. Finkbeiner, M.; Schau, E.M.; Lehmann, A.; Traverso, M. Towards Life Cycle Sustainability Assessment. *Sustainability* **2010**, *2*, 3309-3322
2. Kloepffer, W. Life Cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* 2008, *13* (2), 89-95
3. Rubik, F. *Integrierte Produktpolitik*; Metropolis: Marburg, Germany, **2002**.
4. EC, Communication on Integrated Product Policy. COM **2003** 302

5. EC, Communication on the sustainable consumption and production and sustainable industrial policy action plan. COM, **2008**; 397 final
6. EC- JRC, European Platform on Life Cycle Assessment <http://lct.jrc.ec.europa.eu/assessment/projects#c> (accessed October 2011)
7. ISO, Environmental management - life cycle assessment - Life cycle impact assessment (ISO 14044). 2006. ISO, Geneva.
8. Finnveden, G; Hauschild M.Z.; Ekvall T.; Guinee J.; Heijungs R.; Hellweg S.; Koehler A.; Pennington D.; Suh S. Recent developments in life cycle assessment, *Journal of Environmental management* , **2009** ,91,1–21
9. EC-JRC, ILCD Handbook. Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment. **2010**, p115. Available at <http://lct.jrc.ec.europa.eu>
10. EC- JRC, ILCD Handbook. Framework and Requirements for LCIA models and indicators. **2010**, p112. Available at <http://lct.jrc.ec.europa.eu>
11. EC-JRC, ILCD Handbook. Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment in European context. **2011**, p150. Available at <http://lct.jrc.ec.europa.eu>

© 2011 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/3.0/>).