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Communication

Research Needs and Challenges from Science to Decision Support. Lesson Learnt from the Development of the International Reference Life Cycle Data System (ILCD) Recommendations for Life Cycle Impact Assessment

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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 quantitative, integrated environmental assessment and promoting the use of these methodologies in different domains. In the context of Life Cycle Assessment (LCA) of products, in recent years, several methodologies have been developed for Life Cycle Impact Assessment (LCIA). The Joint Research Center of the European Commission (EC-JRC) led a "science to decision support" process which resulted in the International Reference Life Cycle Data System (ILCD) Handbook, providing guidelines to the decision and application of methods for LCIA. The Handbook is the result of a comprehensive process of evaluation and selection of existing methods based on a set of scientific and stakeholder acceptance criteria and involving review and consultation by experts, advisory groups and the public. In this study, we report the main features of the ILCD LCIA recommendation development highlighting relevant issues emerged from this "from science to decision support" process in terms of research needs and challenges for LCIA.

Comprehensiveness of the assessment, as well as acceptability and applicability of the scientific developments by the stakeholders, are key elements for the design of new methods and to guarantee the mainstreaming of the sustainability concept.

Keywords: life cycle impact assessment; science for policy support; integrated environmental assessment; environmental sustainability

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 relating to the environmental dimension of sustainability (e.g., [1]), despite some limitations [2,3] and unresolved issues [4,5]. LCA 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 various features, e.g., [6]:

- Life cycle perspective: all phases ("from the cradle to the grave") of the life cycle of a product (goods or service) are assessed with regard to all relevant material and energy flows from the extraction and processing of the resources, production and further processing, distribution and transport, use and consumption to recycling and disposal.
- 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 into air, water and soil, including waste and physical impacts).

LCA represents an integrated methodology for environmental assessment, in which a wide number of scientific domains and expertise are involved. The capitalization of existing sectorial scientific knowledge, its cross-cutting integration and the provision of robust support to decision making are the key challenges for increasing strength and credibility of LCA also as key tools for sustainability assessment.

Several methodologies have been developed for Life Cycle Impact Assessment (LCIA) and some efforts have been made towards the harmonization of methodologies such as, for example:

- The Life Cycle Initiative partnership of the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC), which has enhanced the role of life cycle based approaches and thinking in several ways since the late 1990s [7]. An example of model harmonization was the development of the USEtox model, a scientific consensus model developed with several toxicity model developers.
- The recent development of ReCiPe methodology, which resulted from the implementation of a collection of LCIA methods that have been harmonized in terms of modeling principles and choices [8].

Apart from efforts towards harmonization at the methodological/scientific level, it is considered of the utmost relevance to develop a science-to-policy interface, due to the broad implications of the decisions supported by LCA.

In the Communication on Integrated Product Policy (IPP) [9], the European Commission committed itself to produce a handbook on best practices in LCA. The Sustainable Consumption and Production (SCP) Action Plan [10] confirmed that "(…) consistent and reliable data and methods are required to assess the overall environmental performance of products (…)".

In this context, the Joint Research Centre of the European Commission (EC-JRC) led a "science-to-policy" process: gathering, capitalizing and evaluating existing knowledge in order to provide robust support to policy decision making. This resulted in the International Reference Life Cycle Data System (ILCD) Handbook. The ILCD Handbook is a series of detailed technical documents, providing guidance for good practices in LCA in business and government, serving as a "parent" document for the development of sector- and product-specific guidance documents, criteria and simplified tools. For LCIA, the Handbook provides guidelines for methods and assessments to analyze the emissions into air, water and soil, as well as the consumption of natural resources and assess them in terms of their contributions to different impacts on human health, natural environment, and availability of resources. Various 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. In order to support the comparison of the methods and the selection of those which represented the best practices, criteria for good characterization modeling practices were developed in advance for each category of impact. The criteria include scientific, applicability and stakeholder acceptance issues.

The guidelines for LCIA thus represent the result of a comprehensive process of evaluation and selection of methods based on a set of scientific and stakeholder acceptance criteria and involve extensive consultations with domain experts, advisory groups and the public, during a public consultation. In this process a number of research needs, critical issues and challenges for Life Cycle Impact Assessment were identified to improve the robustness of the models and the reliability of characterization factors which form the basis for further development in LCIA.

The purpose of this communication is twofold: (i) reporting the peculiar elements of the ILCD process, its context of development and the stakeholder involvement; (ii) presenting and discussing the critical issue merged from the process and the consultation, in order to identify research needs, outlook and prospects towards comprehensiveness in dealing with environmental sustainability.

The document is organized as follows: in Section 2, the overall context of the development of the ILCD Handbook entailing the European Platform on LCA and the ILCD data network; in Section 3, the peculiarity of the LCIA recommended methods choice and the contribution of stakeholders; finally, in Section 4, we discuss the research needs and the challenged emerged from the process and useful as starting point for future developments.

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

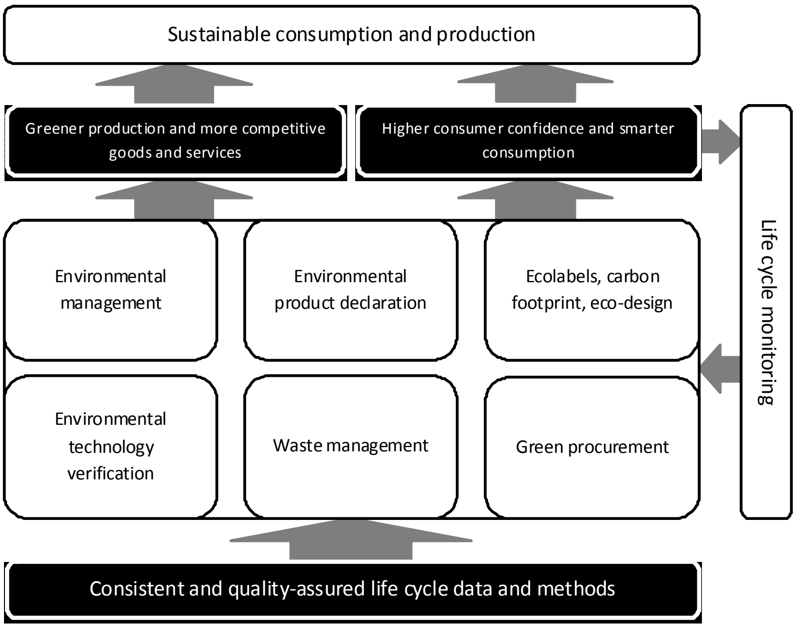
LCA is successfully used in the private sector, e.g., for: continuous environmental improvement of products; internal strategic decision support; evaluating risks and opportunities along the supply chain;

communication on strategic aspects with stakeholders at company and association level and communication with customers on products, e.g., via Environmental Product Declarations (EPD), carbon labels and footprints.

Despite the current use of LCA, a wider mainstream of life cycle thinking as key approach to environmental sustainability is still needed. This requires increasing the interaction among stakeholders involved in the development, application and use of the LCA results (such as the scientific community, business associations and policy makers) [3].

Since 2005, the JRC-IES set up the European Platform on LCA [11]: to improve the credibility, acceptance and use of LCA in business and public authorities; to ensure greater coherence across LCA-based instruments, and to provide robust decision support to a range of environmental policies and business instruments (see Figure 1).

Figure 1. Life cycle data and methods are the basis for supporting sustainable production and consumption tools/approaches such as: ecolabels, green public and private procurement, environmental product declarations, *etc.*



The activities and deliverables of the European Platform on LCA aim at:

- improving the quality and reliability of life cycle data and assessments, ensuring scientific robustness;
- increasing the availability of life cycle data, supporting practicality and affordability;
- facilitating knowledge exchange, capitalizing on existing practices and knowledge;
- promoting networking amongst various stakeholder to reflect current best practices and improve their overall acceptance in order to achieve the best attainable consensus. 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 Program (UNEP); an Advisory Group of European-level

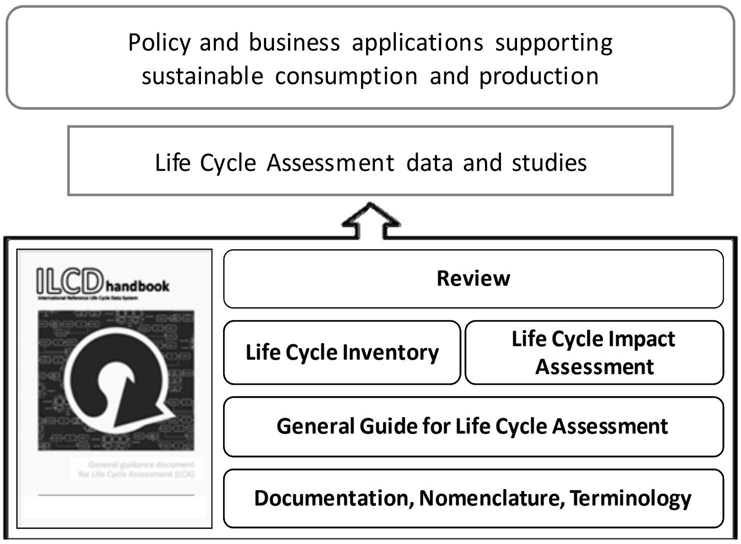
business associations; an Advisory Group of LCA software and database developers; and an Advisory Group of LCIA method developers;
- providing long-term support.

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.

2.1. ILCD Handbook.

The ILCD Handbook has been built upon the ISO standards for LCA (ISO 14040 series [12]) and provides detailed technical guidance on all steps required in an LCA, providing the basis for developing consistent and quality-assured life cycle data and assessments. The ILCD has been developed in coordination by the EC-JRC (Institute for Environment and Sustainability), the Directorate-General Environment (DG ENV) and through a series of invited and public consultations with global outreach. The aim of the process had been to reach the best-attainable consensus, reflecting best available practices in industry and government. It has to be noted, that the objective was not to create new methods during this process but to build on the best elements from existing practices. The structure of the ILCD Handbook is presented in Figure 2. Guidance is available on documentation, nomenclature and terminology for LCA studies, review requirements, LCI, and LCIA.

Figure 2. Overview of the structure of the International Reference Life Cycle Data System (ILCD) Handbook.



2.2. ILCD Data Network

The upcoming ILCD Data Network will provide consistent and quality-assured data on resource consumption and emissions (Life Cycle Inventory—LCI) based on requirements of the ILCD Handbook. The ILCD Data network is a decentralized network, open to all providers globally, such as businesses, national LCA projects, researchers and consultants on their own terms and conditions (e.g., free or for a fee). 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, properly documented and independently reviewed, and for emissions and resource consumption they must use the common ILCD elementary flows as specified in the ILCD elementary flow database. As one foreseen contribution those data sets contained in the European Reference Life Cycle Database (ELCD) that fulfill 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.

3. ILCD Handbook on Life Cycle Impact Assessment: From Scientific Literature to Identifying Best Practices

Several LCIA methods are available to assess the different potential impacts on human health, the natural environment, and the natural resources, from the inventory flows of the life cycle. There is not always an obvious best choice amongst them. In spite of similarities amongst some of them, there can be significant differences in their results [13,14], therefore differences in LCIA methods may lead to different conclusions of the LCA depending on the choice of the LCIA method [15].

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

The resulting ILCD Handbook on LCIA addresses the need of clear guidance on models, indicators and characterization factors that should be used in LCIA. It supports the calculation of indicators for different impacts such as climate change, ozone depletion, photochemical ozone formation, respiratory inorganics, ionizing 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 are addressed in the recommendations.

A scheme of the impact categories at midpoint and endpoint covered in the Handbook is provided in Figure 3, differentiating those categories for which a robust method exists and those for which no method was considered robust enough to be recommended.

These guidelines and the selection of LCIA models and indicators are the result of 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 [16].
- Framework and Requirements for LCIA models and indicators [17].
- Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment in the European context [18].

In this process a number of research needs (e.g., issues not yet covered by existing methods, methodological limitations *etc.*), critical issues and challenges for LCIA emerged and were identified [16] to support the further development of LCIA. Some of the central research needs are addressed in on-going research projects under the EU's Seventh Framework Program, such as LC-IMPACT [19] and PROSUITE [20].

3.1. Development of Recommendations

As mentioned above, several methodologies have been developed for LCIA and some efforts have been made towards harmonization. In order to support the selection of the methods for each environmental impact category, criteria for good characterization modeling practices were developed in advance to be used in the evaluation and comparison of the methods that passed over three stages, starting from the first pre-selection of existing methods [16] and the definition of specific criteria [17] to the comparative evaluation of the pre-selected methods against these criteria to arrive at a set of recommended methods addressing each impact category at both midpoint and endpoint [18].

The content of the three guidance documents is briefly presented.

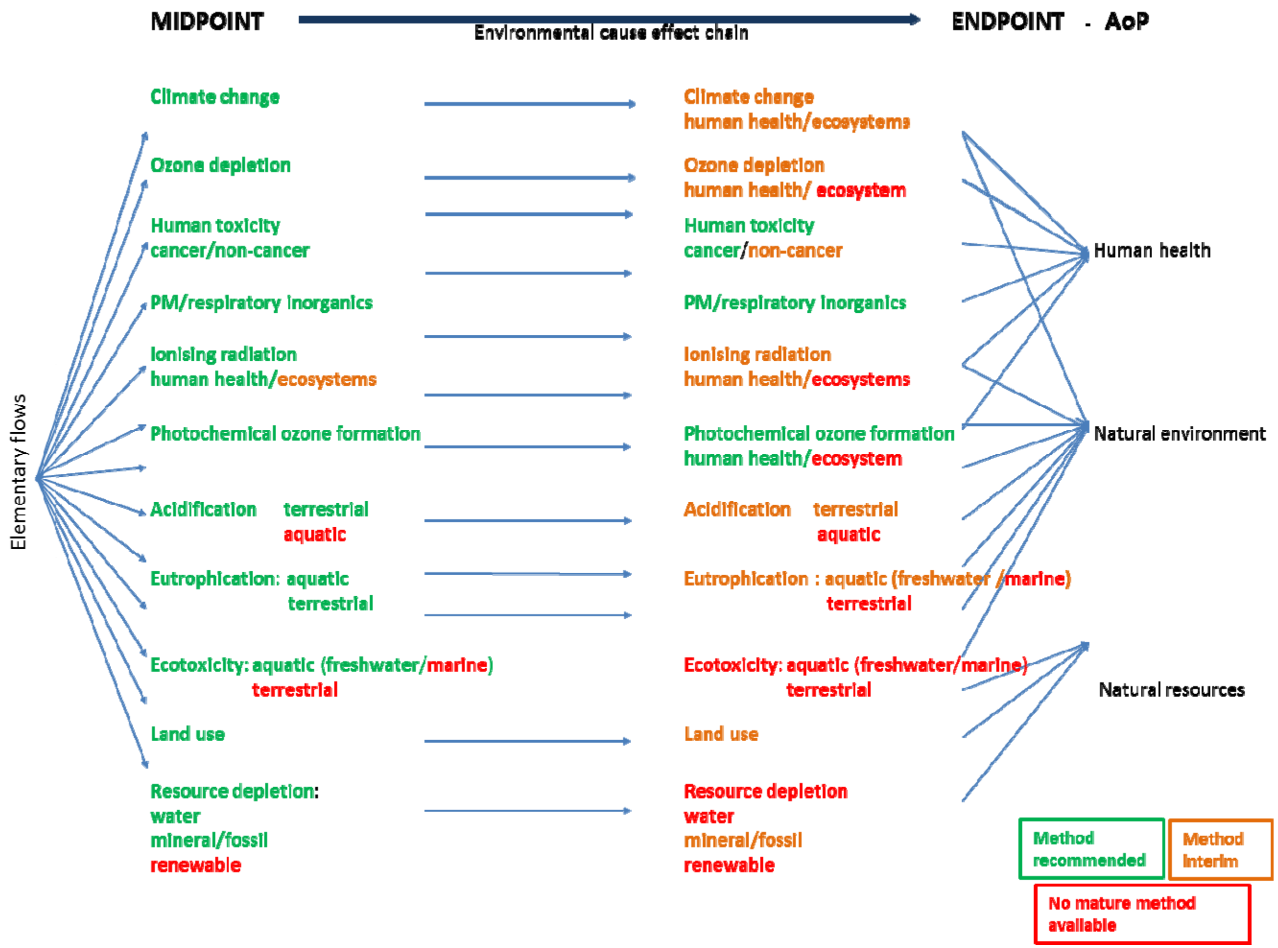
The purpose of the Analysis of the existing methods document [16], as a background document to the ILCD Handbook, was to provide an analysis of existing LCIA methods to identify differences in approaches and to select methods and models for more in depth evaluations for the final recommendations. The pre-selection 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 [17], the core of the evaluation scheme is documented, entailing:

- a description of the environmental mechanism (cause-effect chain) for each impact category to provide a common understanding of what needs to be modeled;
- a set of model requirements for the specific environmental impact categories that are commonly addressed in an LCA;
- a set of criteria, sub criteria and recommendations against which models and indicators for use in LCIA should be evaluated for each impact category. 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. The main criteria were detailed into a number of sub-criteria, some of which are specific to the considered impact category. The total number of sub-criteria varied between 35 and 50 for the different impact categories.

In the Recommendations for LCIA document [18], the selected methods are presented and assessed against criteria and sub-criteria. The assessment leads to the identification of the best existing models, and this is the basis for recommendations which can be given at several levels respecting the different levels of robustness of the methods for the various impact categories.

Figure 3. Scheme of the impact categories dealt with in ILCD Handbook on Life Cycle Impact Assessment at midpoint and at endpoint. 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.



3.2. Levels of Recommendation

The recommended characterization 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 characterization factors are recommended for all types of life cycle based decision support. Although further research needs may have been identified, these needs do not prevent the models/factors from being seen as satisfactory given the current state-of-the art.
- Level II: Recommended, some improvements needed. The uncertainty of models and the resulting characterization factors are 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 characterization 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 those recommended at level III 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.

Two further classifications exist for methods that are identified as the best among the existing but not of a sufficient quality to support a recommendation:

- Interim: immature for recommendation but the most appropriate among the existing approaches. The methods and characterization 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 the state of the models was so immature that it was considered irrelevant to even identify the best among the existing. For these impact categories, no method is mentioned—even as interim—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 to be mature enough for recommendation. In Figure 3, all the impact categories covered by the Handbook are reported highlighting where methods are still too immature to be recommended or missing maturity to even support an identification of the best among the existing. 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 relevant for the specific application. However, in the study the uncertainties and the limitations have to be clearly stated and considered in the interpretation of the results, in particular for this impact category.

3.3. Consultation of Stakeholders

At different stages various groups of stakeholders were invited to provide comments on the three ILCD Handbook documents dealing with LCIA. The points emerged by the public consultation contributed to the identification of research needs (presented in detail in the recommendations report [18]) and of the challenges posed by the science-to-policy interface. To understand the complexity and the relevance of this consultation, some of the topics highlighted by the stakeholders are reported:

- availability of inventory data for fulfilling the requirements of being ILCD compliant. So far, for some impact categories incomplete data was reported in the inventory phase.
- comprehensiveness of the set of impact categories. This refers to the need to identify impact category at midpoint and endpoint in order to comprehensively cover the environmental impacts;
- geographical coverage. This refers to the need to account 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 possible, global models have to be used—also for regional impacts. In absence of sufficiently sound global models, a choice has to be made in favor of models that, apart from representing the state-of-the art in environmental modeling for the concerned impact category, represent large heterogeneous regions qualifying them as proxies for a global situation.

In dealing with comments and inputs received, in order to integrate them in the final recommendations as far as possible, it was often a critical task to find the right balance between e.g.,

- scientific robustness of available models *versus* applicability and feasibility aspects;
- allowing limited assessments on a few impact categories with a high degree of certainty *versus* pushing towards more comprehensive assessments including impact categories with a lower degree of certainty whilst being transparent about their need for improvement;
- cementing the status quo, towards "stability" of the recommendations over time, *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 order to apply LCIA for many different types of applications.

The abovementioned aspects are crucial for any sustainability assessment methods and requires actions by several stakeholders (from methods developer to policy making) to ensure applicability and efficacy. In these evaluations, one guiding principle was the question of how the robustness and quality of LCA and specifically LCIA can be further improved to lead to better informed decisions in policy and in business. Furthermore, the three LCIA Handbooks [16–18] have already been subject to a peer review by a panel of reviewers in order to ensure the robustness of the overall process of recommendation development.

4. Outlook and Prospects

Enhancing the environmental pillar of sustainability assessment increasingly requires the adoption of methodologies for environmental integrated assessment. In the context of environmental sustainability, major challenges are posed by the actual feasibility of integrating models and methods towards a harmonized framework.

LCIA is an active field of research, and for some impact categories, new developments have already been published [21]. On-going research activities address some of the shortcomings identified during the development of the evaluation and recommendations of models and methods [19,20]. The current development of LCIA is focused on ensuring comprehensiveness in assessing impacts and in overcoming constraints and limitation of methods and models. Identified gaps for covering the environmental dimension of sustainability are related to several aspects, e.g.,

- the number of substances/flows covered by existing methods, e.g., number of chemical substances in the ecotoxicity and human toxicity models cover a relatively small percentage of the overall existing chemicals (around 3000 have characterization factors compared to 90,000 chemicals registered in the EU for the REACH directive [22]; or comprehensive coverage of resources (not only minerals and fossil fuels but also critical raw materials, not only abiotic but also biotic, not only mineral stock but also anthropogenic) [23];
- the target of impacts: e.g for ecotoxicity, the models mainly cover freshwater ecotoxicity. Epigean and hypogean terrestrial ecotoxicity and marine are still less developed;
- the number of impact categories: e.g., to tackle emerging issues, such as noise, desertification, indoor impacts and work related impacts, accidents, GMO's;
- cause–effect modeling: as completeness and robustness of endpoint methods 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 too immature to be recommended for use;
- capability of integrating the carrying capacity concept into the impact assessment (so far, few attempts have been made).

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 are of paramount importance. In this context, this work also contributes to other activities within the Commission, such as the development of a method for measuring Environmental Footprints of Products and Organizations [23].

The guidelines for LCIA also derived from the comments provided by stakeholders involved in the public consultation. The process has pinpointed a number of critical issues and research needs which must be addressed in order to achieve a complete and robust framework for LCIA, as well as for other integrated environmental assessment procedures. The robustness of models and the reliability of characterization 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 are:

- 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 too immature to be recommended for use;
- Integrating impact categories that are not widely agreed upon or are still under development and that do not yet have 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 characterization factors; as some promising environmental models with potential for application in the context of LCIA lack algorithms or methodologies on how to calculate characterization factors. Even if the models are scientifically robust, and some broadly accepted within their scientific community, a straightforward integration into LCIA and application in LCA is not feasible without characterization factors;
- Fostering the geographical and temporal differentiation within methods, to better integrate different level of impact evaluations: from the global to the regional/local scale and impacts occurring in different geographical regions or continents.
- Developing a structured framework for addressing uncertainties
- Further improving the decision support function of LCA and LCIA, e.g., by developing and agreeing on ways to communicate LCA results so that they are more condensed and easier to understand.

As discussed by [3], LCA plays a crucial role as an integrated environmental sustainability assessment methodology. The ongoing developments should be in line with the most advanced scientific discussion on sustainability science. 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.

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