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Publications:

Learning-by-doing: experience from 20 years of teaching LCA to future engineers

Purpose: In support of the sustainable development of our societies, future engineers should have elementary knowledge in sustainability assessment and use of life cycle assessment. Publications on pedagogical experience with teaching life cycle assessment (LCA) in high-level education are however scarce. Here, we describe and discuss 20 years of experience in teaching LCA at MSc level in an engineering university with the ambition to share our insights and inspire teaching of LCA as part of a university curriculum. Methods: We detail the design of an LCA course taught at the Technical University of Denmark since 1997. The course structure relies on (i) a structured combination of theoretical teaching, practical assignments and hands-on practice on LCA case studies, and (ii) the conduct of real-life LCA case studies in collaboration with companies or other organisations. Through the semester-long duration of the course, students from different engineering backgrounds perform full-fledged LCA studies in groups, passing through two iterations—a screening LCA supporting a more targeted LCA. Results and discussion: The course design, which relies on a learning-by-doing principle, is transparently described to inspire LCA teachers among the readers. Historical evolution and statistics about the course, including its 192 case studies run in collaboration with 105 companies and institutions, are analysed and serve as basis to discuss the benefits and challenges of its different components, such as the theory acquisition, the assignment work, the LCA software learning, the conduct of case studies, the merits of industrial collaborations and grading approaches. Conclusions: We demonstrate the win-win situation created by the setting of the course, in which the students are actively engaged and learn efficiently how to perform an LCA while the collaborating companies often get useful insights into their analysed case studies. The course can also be an eye opener for companies unfamiliar with LCA, who get introduced to life cycle thinking and the potential benefits of LCA. We have no hesitation in recommending industries and LCA teachers to engage into such collaborations even in the fundamental teaching of LCA techniques.

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Critical Review

Manipulation and mistakes in LCA studies are as old as the tool itself, and so is its critical review. Besides preventing misuse and unsupported claims, critical review may also help identifying mistakes and more justifiable assumptions as well as generally improve the quality of a study. It thus supports the robustness of an LCA and increases trust in its results and conclusions. The focus of this chapter is on understanding what a critical review is, how the international standards define it, what its main elements are, and what reviewer qualifications are required. It is not the objective of this chapter to learn how to conduct a critical review, neither from a reviewer nor from a practitioner perspective. The foundation of this chapter and the basis for any critical review of LCA studies are the International Standards ISO 14040:2006, ISO 14044:2006 and ISO TS 14071:2014.
Introduction to Part III: Application of LCA in Practice

While Part II of this book presents the theoretical foundation and methodology of LCA, Part III is dedicated to a comprehensive discussion of how this methodology has been adapted and applied in practice. The chapters of Part III provide an easily readable and accessible introduction to different fields of LCA application with their specific decision situations, user competences and stakeholder needs, and associated methodological challenges and adaptations.

LCA of Wastewater Treatment

The main purpose of wastewater treatment is to protect humans against waterborne diseases and to safeguard aquatic bio-resources like fish. The dominating environmental concerns within this domain are indeed still potential aquatic eutrophication/oxygen depletion due to nutrient/organic matter emissions and potential health impacts due to spreading of pathogens. Anyway, the use of treatment for micro-pollutants is increasing and a paradigm shift is ongoing — wastewater is more and more considered as a resource of, e.g. energy, nutrients and even polymers, in the innovations going on. The focus of LCA studies addressing wastewater treatment have from the very first published cases, been on energy and resource consumption. In recent time, the use of characterisation has increased and besides global warming potential, especially eutrophication is in focus. Even the toxicity-related impact categories are nowadays included more often. Application of LCA for comparing avoided against induced impacts, and hereby identifying trade-offs when introducing new technology, is increasingly used. A typical functional unit is the treatment of one cubic metre of wastewater which should be well defined regarding composition. Depending on the goal and scope of the study, all life cycle stages have the potential of being significant, though disposal of infrastructure seems to be the least important for the impact profile in many cases. No inventory data and none of the conventional impact categories (except stratospheric ozone depletion if emission of N2O is excluded) should be ruled out; but eutrophication and ecotoxicity are in many cases among the dominating ones.
Life Cycle Impact Assessment

This chapter is dedicated to the third phase of an LCA study, the Life Cycle Impact Assessment (LCIA) where the life cycle inventory's information on elementary flows is translated into environmental impact scores. In contrast to the three other LCA phases, LCIA is in practice largely automated by LCA software, but the underlying principles, models and factors should still be well understood by practitioners to ensure the insight that is needed for a qualified interpretation of the results. This chapter teaches the fundamentals of LCIA and opens the black box of LCIA with its characterisation models and factors to inform the reader about: (1) the main purpose and characteristics of LCIA, (2) the mandatory and optional steps of LCIA according to the ISO standard, and (3) the science and methods underlying the assessment for each environmental impact category. For each impact category, the reader is taken through (a) the underlying environmental problem, (b) the underlying environmental mechanism and its fundamental modelling principles, (c) the main anthropogenic sources causing the problem and (d) the main methods available in LCIA. An annex to this book offers a comprehensive qualitative comparison of the main elements and properties of the most widely used and also the latest LCIA methods for each impact category, to further assist the advanced practitioner to make an informed choice between LCIA methods.

Overview of Existing LCIA Methods—Annex to Chapter 10

The chapter gives an overview and a systematic comparison of a selection of the most used Life Cycle Impact Assessment (LCIA) methods, focusing on methods that have been implemented and made available in LCA software. Currently available midpoint and endpoint characterisation methodologies are presented and their specific properties are qualitatively compared in detailed tables.
Uncertainty Management and Sensitivity Analysis

Uncertainty is always there and LCA is no exception to that. The presence of uncertainties of different types and from numerous sources in LCA results is a fact, but managing them allows to quantify and improve the precision of a study and the robustness of its conclusions. LCA practice sometimes suffers from an imbalanced perception of uncertainties, justifying modelling choices and omissions. Identifying prevalent misconceptions around uncertainties in LCA is a central goal of this chapter, aiming to establish a positive approach focusing on the advantages of uncertainty management. The main objectives of this chapter are to learn how to deal with uncertainty in the context of LCA, how to quantify it, interpret and use it, and how to communicate it. The subject is approached more holistically than just focusing on relevant statistical methods or purely mathematical aspects. This chapter is neither a precise statistical method description, nor a philosophical essay about the concepts of uncertainty, knowledge and truth, although you will find a little bit of both. This chapter contains (1) an introduction of the essential terminology and concepts of relevance for LCA; (2) a discussion of main sources of uncertainty and how to quantify them; (3) a presentation of approaches to calculate uncertainty for the final results (propagation); (4) a discussion of how to use uncertainty information and how to take it into account in the interpretation of the results; and finally (5) a discussion of how to manage, communicate and present uncertainty information together with the LCA results.

Assessment of Metal Toxicity in Marine Ecosystems: Comparative Toxicity Potentials for Nine Cationic Metals in Coastal Seawater

This study is a first attempt to develop globally applicable and spatially differentiated marine Comparative Toxicity Potentials (CTPs) or ecotoxicity characterization factors for metals in coastal seawater for use in Life Cycle Assessment. The toxicity potentials are based exclusively on marine ecotoxicity data and take account of metal speciation and bioavailability. CTPs were developed for nine cationic metals (Cd, Cr(III), Co, Cu(II), Fe(III), Mn, Ni, Pb and Zn) in 64 Large Marine Ecosystems (LMEs) covering all coastal waters in the world. The results showed that the CTP of a specific metal varies 3-4 orders of magnitude across LMEs, largely due to different seawater residence time. Therefore the highest toxicity potential for metals was found in the LMEs with the longest seawater residence times. Across metals, the highest CTPs were observed for Cd, Pb and Zn. At the concentration levels occurring in coastal seaways, Fe acts not as a toxic agent but an essential nutrient and thus has CTPs of zero.
Contribution of waterborne nitrogen emissions to hypoxia-driven marine eutrophication: modelling of damage to ecosystems in life cycle impact assessment (LCIA)

Marine eutrophication refers to the ecosystem response to the loading of a growth limiting nutrient, typically nitrogen (N), to coastal waters, where it may cause several impacts. One of the possible impact pathways to these impacts involves the excessive depletion of dissolved oxygen (hypoxia) in bottom waters. Hypoxia is identified as an important and widespread cause of disturbance to marine ecosystems and has been linked to the increasing anthropogenic pressure. This is driven by environmental emissions of reactive nitrogen, mainly from N-containing fertilizers used in agriculture and atmospheric deposition as a consequence of fossil fuels combustion.

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Indoor Air Pollutant Exposure for Life Cycle Assessment: Regional Health Impact Factors for Households

Human exposure to indoor pollutant concentrations is receiving increasing interest in Life Cycle Assessment (LCA). We address this issue by incorporating an indoor compartment into the USEtox model, as well as by providing recommended parameter values for households in four different regions of the world differing geographically, economically, and socially. With these parameter values, intake fractions and comparative toxicity potentials for indoor emissions of dwellings for different air tightness levels were calculated. The resulting intake fractions for indoor exposure vary by 2 orders of magnitude, due to the variability of ventilation rate, building occupation, and volume. To compare health impacts as a result of indoor exposure with those from outdoor exposure, the indoor exposure characterization factors determined with the modified USEtox model were applied in a case study on cooking in non-OECD countries. This study demonstrates the appropriateness and significance of integrating indoor environments into LCA, which ensures a more holistic account of all exposure environments and allows for a better accountability of health impacts. The model, intake fractions, and characterization factors are made available for use in standard LCA studies via www.usetox.org and in standard LCA software.

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The Glasgow consensus on the delineation between pesticide emission inventory and impact assessment for LCA

Pesticides are applied to agricultural fields to optimise crop yield and their global use is substantial. Their consideration in life cycle assessment (LCA) is affected by important inconsistencies between the emission inventory and impact assessment phases of LCA. A clear definition of the delineation between the product system model (life cycle inventory—LCI, technosphere) and the natural environment (life cycle impact assessment—LCIA, ecosphere) is missing and could be established via consensus building. A workshop held in 2013 in Glasgow, UK, had the goal of establishing consensus and creating clear guidelines in the following topics: (1) boundary between emission inventory and impact characterisation model, (2) spatial dimensions and the time periods assumed for the application of substances to open agricultural fields or in greenhouses and (3) emissions to the natural environment and their potential impacts. More than 30 specialists in agrifood LCI, LCIA, risk assessment and ecotoxicology, representing industry, government and academia from 15 countries and four continents, met to discuss and reach consensus. The resulting guidelines target LCA practitioners, data (base) and characterisation method developers, and decision makers. The focus was on defining a clear interface between LCI and LCIA, capable of supporting any goal and scope requirements while avoiding double counting or exclusion of important emission flows/impacts. Consensus was reached accordingly on distinct sets of recommendations for LCI and LCIA, respectively, recommending, for example, that buffer zones should be considered as part of the crop production system and the change in yield be considered. While the spatial dimensions of the field were not fixed, the temporal boundary between dynamic LCI fate modelling and steady-state LCIA fate modelling needs to be defined. For pesticide application, the inventory should report pesticide identification, crop, mass applied per active ingredient, application method or formulation type, presence of buffer zones, location/country, application time before harvest and crop growth stage during application, adherence with Good Agricultural Practice, and whether the field is considered part of the technosphere or the ecosphere. Additionally, emission fractions to environmental media on-field and off-field should be reported. For LCIA, the directly concerned impact categories and a list of relevant fate and exposure processes were identified. Next steps were identified: (1) establishing default emission fractions to environmental media for integration into LCI databases and (2) interaction among impact model developers to extend current methods with new elements/processes mentioned in the recommendations.

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The USEtox story: A survey of model developer visions and user requirements

Purpose USEtox is a scientific consensus model for assessing human toxicological and ecotoxicological impacts that is widely used in life cycle assessment (LCA) and other comparative assessments. However, how user requirements are met has never been investigated. To guide future model developments, we analyzed user expectations and experiences and compared them with the developers’ visions.

Methods We applied qualitative and quantitative data collection methods including an online questionnaire, semistructured user and developer interviews, and review of scientific literature. Questionnaire and interview results were analyzed in an actor-network perspective in order to understand user needs and to compare these with the developers’ visions. Requirement engineering methods, more specifically function tree, system context, and activity diagrams, were iteratively applied and structured to develop specific user requirements-driven recommendations for setting priorities in future USEtox development and for discussing general implications for developing scientific models.

Results and discussion The vision behind USEtox was to harmonize available data and models for assessing toxicological impacts in LCA and to provide global guidance for practitioners. Model developers show different perceptions of some underlying aspects including model transparency and expected user expertise. Users from various sectors and geographic regions apply USEtox mostly in research and for consulting. Questionnaire and interview results uncover various user requests regarding USEtox usability. Results were systematically analyzed to translate user requests into recommendations to improve USEtox from a user perspective and were afterwards applied in the further USEtox development process.

Conclusions We demonstrate that understanding interactions between USEtox and its users helps guiding model development and dissemination. USEtox-specific recommendations are to (1) respect the application context for different user types, (2) provide detailed guidance for interpreting model and factors, (3) facilitate consistent integration into LCA software and methods, (4) improve update/testing procedures, (5) strengthen communication between developers and users, and (6) extend model scope. By generalizing our recommendations to guide scientific model development in a broader context, we emphasize to acknowledge different levels of user expertise to integrate sound revision and update procedures and to facilitate modularity, data import/export, and incorporation into relevant software and databases during model design and development. Our fully documented approach can inspire performing similar surveys on other LCA-related tools to consistently analyze user requirements and provide improvement recommendations based on scientific user analysis methods.
Characterization modelling of aquatic ecotoxicity from metal emission to be applied in Life Cycle Impact Assessment

Following the Apeldoorn Declaration (Aboussouan et al. 2004) and Clearwater Consensus (Diamond et al. 2010), Gandhi et al. (2010) developed a new method to calculate metals Characterization Factor (CF) in freshwater and applied it on six metals, considering metals speciation and its impacts on bioavailability. However, ecotoxicity of several metals that
commonly appear in Life Cycle Inventory (LCI) have not yet been characterized in freshwater by the novel method. Ecotoxicity CF in marine ecosystem has received even less attention. In the previous Life Cycle Impact Assessment (LCIA) model, marine CF is either lacking (e.g. USEtox, IMPACT 2002+), or derived by applying freshwater ecotoxicity data and ignoring metal speciation (e.g. USES-LCA). Moreover, the connection between freshwater and seawater, the estuary, which may act as a metal filter, is missing in the framework.

To solve the problems mentioned above, this Ph.D. project aims at developing aquatic CFs for metals, including freshwater CF for 14 metals (Al(III), Ba, Be, Cd, Co, Cr(III), Cs, Cu(II), Fe(II), Fe(III), Mn(II), Ni, Pb, Sr and Zn) and marine CF for nine metals (Cd, Co, Cr(III), Cu, Fe(III), Mn, Ni, Pb and Zn) both for emission to seawater and for emission to freshwater. The work builds on the method developed by Gandhi et al. (2010), accounting metals speciation and its impact on bioavailability but expands to ensure a broader coverage of metals and to cover the marine environment in addition to freshwater ecosystems. Metals speciation varies in different water chemistries. Thus for each metal spatially differentiated freshwater CF was developed in seven different EU freshwater archetypes. Considering that emission location is often unknown in Life Cycle Assessment (LCA) studies, different averaging principles were tested on the spatially differentiated freshwater CFs to derive generic freshwater CFs, and the best approach was identified. For similar reasons, spatially differentiated marine CF was developed first for 64 Large Marine Ecosystems (LMEs) covering all coastal seawaters in the whole world. Based on the spatially differentiated marine CFs, several generic CFs were developed applying different averaging principles and the generic marine CF most suitable for use in LCA was recommended. The new sets of generic metal CFs were then applied in a case study, to test the impacts of new CFs when assessing Freshwater Ecotoxicity (FE) and Marine Ecotoxicity (ME) Impact Score (IS).

CF was calculated as the product of Fate Factor (FF), Bioavailability Factor (BF) and Effect Factor (EF). The multimedia fate model embedded in USEtox (Rosenbaum et al. 2008) was modified and applied to calculate FF. The chemical speciation model WHAM VII (Tipping et al. 2011) was used to calculate BF and partitioning coefficients for use in the calculation of FF, and the Free Ion Activity Model (FIAM) was adopted to derive EF. The resulting freshwater CF shows up to 2-6 orders of magnitude variations across freshwater archetypes for metals that form stable hydroxides in slightly alkaline waters (Al(III), Be, Cr(III), Cu(II) and Fe(III)), but it varies less than one order of magnitude for the other metals (Ba, Cd, Co, Cs, Fe(II), Mn(II), Ni, Pb, Sr and Zn), showing a much lower relevance of water archetype differentiation. In slightly acidic water, Al(III) and Cu(II) have the highest CF of all the investigated metals, while Cd has the highest CF in other water types. The emission weighted freshwater CF was recommended to be applied as site-generic CF in the LCA studies where emission location and water chemistry of the receiving freshwater is unknown.

In marine ecosystems, the variation of marine CFs is up to 3-4 orders of magnitude for each metal cross LMEs, mainly caused by the variation in the residence time of seawater in each LME. In all LMEs the highest CF was observed for Cd, Pb or Zn. Fe has a true zero CF in all LMEs, since it is argued that it will not act as a toxic agent at the concentrations that occur in coastal seawaters, but rather as an essential nutrient to biota. For all metals investigated, the highest CF was observed in the LMEs that have the longest residence times and correspondingly the lowest CF appears in the LMEs with the shortest residence times.

Marine CF for Cd, Co, Mn, Ni and Zn emitted to freshwater is less than half an order of magnitude lower than marine CF for the same metals emitted to seawater. The difference is largely due to metal removal in the freshwater compartment on the way to the coast, with a minor contribution from estuary removal. For the metals that have strong tendency to complex with particles (e.g. Cr, Cu and Pb), the difference between the two marine CFs is 1.5 orders of magnitude. Here estuary removal noticeably reduces the fraction of metals that be transported to seawater by 25%-65%. Compared with freshwater CF, marine CF emitted to seawater shows a similar range for Cd, Co, Cr, Mn, Ni and Zn. But for Cu, freshwater CF is slightly higher than marine CF emitted to seawater, while for Pb freshwater CF is 1-4 orders of magnitude lower than marine CF emitted to seawater, depending on archetypes and LMEs.

For marine CFs both emitted to freshwater and seawater, weighting by the annual estuary discharge was recommended as averaging principle to calculate the sitegeneric CF to be applied in LCA studies where emission location is unknown. Compared with freshwater CFs calculated with the default parameter settings and databases in USES-LCA and USEtox, the recommended site-generic freshwater CFs in this study are mostly higher or similar, within ~2 orders of magnitude difference. The recommended site-generic marine CFs for emission to seawater in this study are 1-4 orders of magnitude lower compared with the USES-LCA default CF with an egalitarian perspective except for Pb, for which the USES-LCA CF is similar to the value found in this study. Marine CFs for emission to freshwater in this study are 1-2 orders of magnitude lower than USES-LCA CFs for Co, Cr, Cu and Ni. For the rest of the investigated metals the CFs are similar or slightly higher than previous values.

By applying the new CFs on a smartphone inventory, FE and ME IS were calculated. Metals still dominant toxicity impacts even with the revised CFs. Compared with IS calculated by default USES-LCA and USEtox CFs, the new ecotoxicity IS is 1.5 orders of magnitude higher in freshwater and half an order of magnitude lower in marine water. The uncertainty of IS caused by ignoring emission location is two orders of magnitude, indicating that the difference between IS calculated with new CFs and previous CFs is modest.

A number of relevant improvements on the developed method are discussed, mainly focusing on alternative metal speciation models, which may allow expanding the coverage of metals further, and an update of the ecotoxicity data. For future research, it is recommended to develop ecotoxicity CF for sediment both in freshwater and marine ecosystem, to complement the framework of ecotoxicity impacts in the aquatic ecosystem in LCIA.

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**Authors:** Dong, Y. (Intern), Rosenbaum, R. K. (Intern), Hauschild, M. Z. (Intern)
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Global guidance on environmental life cycle impact assessment indicators: findings of the scoping phase

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Authors: Jolliet, O. (Ekstern), Frischknecht, R. (Ekstern), Bare, J. (Ekstern), Boulay, A. (Ekstern), Bulle, C. (Ekstern), Fantke, P. (Intern), Gheewala, S. (Ekstern), Hauschild, M. Z. (Intern), Itsubo, N. (Ekstern), Margni, M. (Ekstern), McKone, T. E. (Ekstern), Canals, L. M. Y. (Ekstern), Posthuma, L. (Ekstern), Prado-Lopez, V. (Ekstern), Ridoutt, B. (Ekstern), Sonnemann, G. (Ekstern), Rosenbaum, R. K. (Intern), Seager, T. (Ekstern), Struijs, J. (Ekstern), Zelm, R. V. (Ekstern), Vigon, B. (Ekstern), Weisbrod, A. (Ekstern)
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Pursuing an ecological component for the Effect Factor in LCIA methods

Life Cycle Assessment quantifies the environmental impacts from emissions and resources consumption of human activities. Uncertainty in modelling natural processes and ecological regulation challenges the prediction of effects from further pressures. Ecosystems’ health and adaptation capacity may have also been altered by past impacts. Model frameworks are usually built on stability, linearity of causality and expectation of a safe return to stable states if the stressor is minimised. However, the command-and-control paradigm has
resulted in the erosion of natural resources and species diversity. Ecosystem-related impacts are traditionally benchmarked by potential loss of biological diversity as Potentially Disappeared Fraction of species (PDF) integrated over area and time, building on the biological sensitivity of species in each receiving ecosystem. For consistency among Life Cycle Impact Assessment (LCIA) methods midpoint indicators are shown in Potentially Affected Fraction of species (PAF), which implicitly suggests reversibility to previous stable states. Currently applied conversion factors from midpoint to endpoint (species loss, as PDF) range from 10 (NOEC-based), 2 (chronic EC50-based) or 1 (assuming that continuous stress affects reproduction rate), but these are all based on biological/physiological responses and do not add a true ecological component to the impact. Such factor simply changes the HC50 by 1 or 0.3 log units. A stressor with equal intensity in two differently disturbed ecosystems (close or distant to a threshold) and sharing similar biological communities should not result in, necessarily, the same impact potential. We suggest the introduction of an ecological term in the Effect Factor of the characterisation modelling for ecosystem quality-related indicators in LCIA. An application to a marine eutrophication indicator will be presented to show how impacts from nitrogen emissions vary with the individual receiving ecosystems’ health, by defining proxies for ecosystem’s state and resilience. These, express the pressure on the system and its propensity for regime shifting. Ultimately, the ecosystem’s capacity to tolerate the pressure, to adapt to the stress and minimise its effects should complement the biological response. In our view, adding an ecosystem-based approach to the damage estimation can positively contribute to the environmental relevance and spatial differentiation of the results.
Updated US and Canadian normalization factors for TRACI 2.1
When LCA practitioners perform LCAs, the interpretation of the results can be difficult without a reference point to benchmark the results. Hence, normalization factors are important for relating results to a common reference. The main purpose of this paper was to update the normalization factors for the US and US-Canadian regions. The normalization factors were used for highlighting the most contributing substances, thereby enabling practitioners to put more focus on important substances, when compiling the inventory, as well as providing them with normalization factors reflecting the actual situation. Normalization factors were calculated using characterization factors from the TRACI 2.1 LCIA model. The inventory was based on US databases on emissions of substances. The Canadian inventory was based on a previous inventory with 2005 as reference, in this inventory the most significant substances were updated to 2008 data. The results showed that impact categories were generally dominated by a small number of substances. The contribution analysis showed that the reporting of substance classes was highly significant for the environmental impacts, although in reality, these substances are nonspecific in composition, so the characterization factors which were selected to represent these categories may be significantly different from the actual identity of these aggregates. Furthermore the contribution highlighted the issue of carefully examining the effects of metals, even though the toxicity based categories have only interim characterization factors calculated with USEtox. A need for improved understanding of the wide range of uncertainties incorporated into studies with reported substance classes was identified. This was especially important since aggregated substance classes are often used in LCA modeling when information on the particular substance is missing. Given the dominance of metals to the human and ecotoxicity categories, it is imperative to refine the CFs within USEtox. Some of the results within this paper indicate that soil emissions of metals are significantly higher than we expect in actuality.
Addressing Geographic Variability in the Comparative Toxicity Potential of Copper and Nickel in Soils

Comparative toxicity potentials (CTP), in life cycle impact assessment also known as characterization factors (CF), of copper (Cu) and nickel (Ni) were calculated for a global set of 760 soils. An accessibility factor (ACF) that takes into account the role of the reactive, solid-phase metal pool in the soil was introduced into the definition of CTP. Geographic differences in fate, accessibility, bioavailability, and terrestrial toxicity were assessed by combining the USEtox characterization model, empirical regression models, and terrestrial biotic ligand models. The median CTPs for Cu and Ni with 95% geographic variability intervals are $1.4 \times 10^3$ ($1.7 \times 10^2$ to $2.0 \times 10^4$) and $1.7 \times 10^3$ ($2.1 \times 10^2$ to $1.1 \times 10^4$) m$^3$/kg·day, respectively. The geographic variability of 3.5 orders of magnitude in the CTP of Cu is mainly associated with the variability in soil organic carbon and pH. They largely influence the fate and bioavailability of Cu in soils. In contrast, the geographic variability of 3 orders of magnitude in the CTP of Ni can mainly be explained by differences in pore water concentration of magnesium (Mg$^{2+}$). Mg$^{2+}$ competes with Ni$^{2+}$ for binding to biotic ligands, influencing the toxicity. Our findings stress the importance of dealing with geographic variability in the calculation of CTPs for terrestrial ecotoxicity of metals.

General information
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Analytical Propagation of Uncertainty in Life Cycle Assessment Using Matrix Formulation

Inventory data and characterization factors in life cycle assessment (LCA) contain considerable uncertainty. The most common method of parameter uncertainty propagation to the impact scores is Monte Carlo simulation, which remains a resource-intensive option—probably one of the reasons why uncertainty assessment is not a regular step in LCA. An analytical approach based on Taylor series expansion constitutes an effective means to overcome the drawbacks of the Monte Carlo method. This project aimed to test the approach on a real case study, and the resulting analytical uncertainty
was compared with Monte Carlo results. The sensitivity and contribution of input parameters to output uncertainty were also analytically calculated. This article outlines an uncertainty analysis of the comparison between two case study scenarios. We conclude that the analytical method provides a good approximation of the output uncertainty. Moreover, the sensitivity analysis reveals that the uncertainty of the most sensitive input parameters was not initially considered in the case study. The uncertainty analysis of the comparison of two scenarios is a useful means of highlighting the effects of correlation on uncertainty calculation. This article shows the importance of the analytical method in uncertainty calculation, which could lead to a more complete uncertainty analysis in LCA practice.

**General information**
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Challenges in LCA-based decision making involving heavy metals long-term emissions from landfills

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Organisations: Department of Management Engineering, Quantitative Sustainability Assessment, Department of Environmental Engineering, Residual Resource Engineering
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Characterizing exposure of bystanders and residents to pesticides applied in agricultural fields

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Authors: Ryberg, M. (Intern), Fantke, P. (Intern), Rosenbaum, R. K. (Intern)
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Exploring parameter uncertainty and seasonal variability for human health intake fractions in life cycle assessment: Extended abstract

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IMPACT World+: Una nueva metodología global y regionalizada de Análisis del Impacto de Ciclo de Vida

La mayoría de los impactos ambientales modelados en el análisis del impacto del ciclo de vida (AICV) son regionales o locales. Sin embargo, las metodologías de AICV actuales ofrecen factores de caracterización genéricos, representando las condiciones medias de un área específica (país o continente), sin tener en cuenta la variabilidad espacial de los impactos. IMPACT World+ ha sido desarrollado en respuesta a la necesidad de evaluación regionalizada de los impactos ambientales. La nueva metodología es de alcance global y utiliza el estado del arte de la modelización ambiental. IMPACT World+ es una actualización substancial de las metodologías IMPACT 2002+, EDIP y LUCAS. Entre otras innovaciones, proporciona información sobre la incertidumbre de los modelos de caracterización del AICV y sobre la variabilidad espacial de los factores de caracterización; asimismo, incluye factores de caracterización para cada (sub)continente, lo que permite una evaluación de los impactos de cualquier emisión/uso de recursos geo-referenciados.

Las novedades introducidas en IMPACT World+ son numerosas: importantes mejoras en el modelado del uso del suelo, del uso del agua y del uso de recursos; mejora de la modelización del destino atmosférico en el impacto de acidificación; regionalización del impacto de eutrofización con un modelo mundial de 0,5 x 0,5 grados de resolución espacial; factores de efecto respiratorio actualizados, derivados a partir de nuevos factores epidemiológicos. En relación a los impactos tóxicos, el modelo USEtox proporciona factores específicos para cada (sub)continente y se han modelado los residuos de aplicación directa de plaguicidas en seis cultivos. IMPACT World+ es un nuevo método de AICV que incrementará la relevancia y el poder discriminativo de un ACV, evaluando las incertidumbres y la variabilidad espacial en todas las categorías de impacto.

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Keeping USEtox up-to-date: What is coming and how you can contribute

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Land use impacts on biodiversity in LCA: proposal of characterization factors based on functional diversity

The focus of land use modeling in life cycle impact assessment has been mainly on taxonomic measures of biodiversity, namely species richness (SR). However, increasing availability of trait data for species has led to the use of functional diversity (FD) as a promising metric to reflect the distinctiveness of species; this paper proposes the use of an FD index to calculate characterization factors (CFs) for land use impacts. Furthermore, we compare the results of the CFs to current practice and assess the increase in complexity introduced by the use of the new indicator. The model proposed is based on data compiled by previous regional meta-analysis on SR and FD, in different land use types in the Americas. The taxonomic groups included were mammals, birds, and plants. Within each study, calculated values for FD for different land use types were compared with the natural or close-to-natural state, taken as the reference situation. FD values among different land uses were standardized, and CFs were calculated. The final results were then analyzed and compared by analysis of variance and post hoc tests. A sensitivity analysis was also applied to verify the influence on the choice of the reference state. The results show that significant differences exist between CFs for SR and FD metrics. Across all taxa, CFs differ significantly between land use types. The results support the use of CF for FD, as a complement to current practice. Distinct CFs should be applied for at least six groups of land use categories. The choice of reference land use type did not significantly alter the results but can be a source of variability. A sensitivity analysis evaluating the impact of alternate land use types as reference types found only few significant changes on the results. Given the results, we believe the use of CFs based on FD can help on the establishment of possible links between species loss and key ecosystem functions, i.e., on the association between the midpoint indicator (e.g., biodiversity loss) and the damage caused to ecosystem quality, in terms of functions lost. Basing CFs on FD is not without challenges. Such indices are data hungry (requiring species composition and traits) require more complex calculations than current common practice, including decisions on the choice of a method to calculate FD and the selection of traits.

General information
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Life Cycle Risks and Impacts of Nanotechnologies

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Quantification of uncertainty and spatial variability of characterisation factors in the new global LCIA method IMPACT World+
Evaluation of spatial variability of metal bioavailability in soils using geostatistics

Soil properties show significant spatial variability at local, regional and continental scales. This is a challenge for life cycle impact assessment (LCIA) of metals, because fate, bioavailability and effect factors are controlled by environmental chemistry and can vary orders of magnitude for different soils. Here, variography is employed to analyse spatial variability of bioavailability factors (BFs) of metals at the global scale. First, published empirical regressions are employed to calculate BFs of metals for 7180 topsoil profiles. Next, geostatistical interpretation of calculated BFs is performed using ArcGIS Geostatistical Analyst. Results show that BFs of copper span a range of 6 orders of magnitude, and have significant spatial variability at local and continental scales. The model nugget variance is significantly higher than zero, suggesting the presence of spatial variability at lags smaller than those in the data set. Geostatistical analyses indicate however, that BFs exhibit no significant spatial correlation at a range beyond 3200 km. Because BF is spatially correlated, its values at unsampled locations can be predicted, as demonstrated using ordinary krigging method. Similar approach can be employed for analyzing spatial variability of terrestrial ecotoxicity characterization factors of metals. Predicted maps can be used to provide a set of regionalized factors at spatial scales that are both scientifically relevant and practically feasible in LCIA.

A Methodology for Inclusion of Terrestrial Ecotoxic Impacts of Metals in Life Cycle Impact Assessment

Terrestrial ecotoxicity is in most cases not addressed or to a very limited extent in life cycle assessment (LCA). We are developing a new method for calculating terrestrial ecotoxicity characterization factor (CF) of metals for application in life cycle impact assessment (LCIA). e method takes into account metal speciation and interactions with soil organic constituents, because these mechanisms control metal bioavailability and inuence their toxic properties. Transfer functions and geochemical speciation models are employed to calculate reactive and available fractions of metals in 1300 soils spanning a wide range of properties and pore water chemistry. Site-specific fate factors (FF), bioavailability factors (BF) and eect factors (EF) are then calculated for these soils. e biggest variability is observed for BF, which can vary from 2 to 6 orders of magnitude for the cases of Ni and Cu, respectively. eese variations are a result of variability in soil properties such as pH, organic carbon or clay content. Published terrestrial biotic ligand models (TBLM) and free ion activity models (FIAM) are next employed in order to derive terrestrial ecotoxicity EFs. Median EFs predicted with TBLMs for Cu and Ni correspond to average ecotoxicity (range) of 12.4 (6.6 – 364) and 1194 (62 – 42164) µg/L, respectively. EFs derived with FIAMs turn out to be 6.5 (Cu) and 7.5 (Ni) times higher than these derived with TBLMs. e ecotoxicity ratio of Cu to Ni is accurately predicted with both models and the contribution of EF to the CF is within the same order of magnitude or lower comparing to that of the BF. us, FIAMs can be employed to calculate EFs for metals for which TBLMs are not available. From a set of spatially explicit CFs, site-generic CFs can be derived at global or continental scales. For applications in
LCIA, the tradeoff between the level of geographical detail and the level of uncertainty in both spatially explicit and site-generic CFs remains to be investigated. The method highlights the importance of taking into account variability of soil properties in deriving operational characterization factors for terrestrial ecotoxicity of metals.

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**Are Free Ion Activity Models Sufficient Alternatives to Biotic Ligand Models in Evaluating Metal Toxic Impacts in Terrestrial Environments?**
Metal partitioning between solid and aqueous phases and speciation in soil pore water control the bioavailability of toxic forms of metals, while protons and base cations can mitigate metal ecotoxicity by competitive interactions with biotic ligands. The employment of BLMs to evaluate toxicity potential of metals in soils results in site-specific toxicity scores due to large variability of soil properties and differences in ionic composition. Unfortunately, terrestrial BMLs are available only for few metals and few organisms, thus their applicability to hazard ranking or toxic impact assessment is low and alternatives must be found. In this study, we compared published terrestrial BLMs and their potential alternatives such as free ion activity models (FIAM), for applicability in addressing metal toxic impacts in terrestrial environments. A set of 1300 soils representative for the whole world is employed to calculate EC50 and thereafter hazardous concentration HC50 (geometric mean of all EC50) for these terrestrial organisms, for which both TBLMs and FIAMs are available. Results showed that median HC50 for all soils predicted with BLMs range 2 and 3 orders of magnitude for copper and nickel, respectively. In all cases, predictions of FIAMs fall within the range of values predicted with BLMs, and toxicity ratio of copper to nickel is accurately predicted with both models. Thus, both models are able to distinguish between the two metals in terms of their average toxicity. Given that the calculated toxicity scores show large variability even for soils located in close proximity to each other, selection of FIAMs is also justified in deriving soil quality criteria. It remains to be investigated at what spatial scale the FIAMs are a good alternative to TBLMs in evaluating metal toxic impacts in terrestrial environments.

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Comparison of metal toxic impacts between aquatic and terrestrial organisms: is the free ion concentration a sufficient descriptor?

Characterization of metal toxic impacts in comparative risk assessment and life cycle impact assessment (LCIA) should take into account metal speciation and interactions with soil/water organic constituents, because these mechanisms control metal bioavailability and may influence their toxic properties. In a comparative context we are faced with the need to characterise thousands of substances, but the limitation of the available data calls for reliable indicators suitable for extrapolation from the limited data that is available. Indeed, free metal ion concentration has in some cases been shown to be a sufficient indicator of metal toxicity for both aquatic and terrestrial species. With the aim of deriving extrapolations to predict terrestrial toxic impacts of metals from aquatic effect data, we compared copper toxicity of aquatic organisms with that of terrestrial organisms, testing the hypothesis that the free metal ion is an appropriate 'general' descriptor of metal toxicity. Results for 128 laboratory tests on Daphnia magna exposed to copper ions (Cu²⁺) in water show that variation of several orders of magnitude are observed between the toxicity tests. These variations may be a result of the inability of the free metal ion concentration to reflect toxicity, as the presence of protons and other cations reacting with biological binding sites has been shown to affect the toxicity of copper to D. magna. Similar patterns, albeit with smaller variations, are observed for terrestrial organisms. Up to three orders of magnitude difference occur for the extreme case of barley (Hordeum vulgare). Given the scarcity of terrestrial effect data compared to aquatic data, reliable and transparent, mechanistic-based predictions of terrestrial toxic impacts from aquatic effect data would be an important step ahead in the context of LCIA or comparative risk. Here we demonstrate that the overall ability of the free metal ion to reflect toxicity of metals for aquatic and terrestrial organisms is limited. This has consequences if potential terrestrial toxic effects are based on extrapolations from aquatic data, because the use of more sophisticated models such as the Biotic Ligand Model (BLM) would be required. However, extrapolation models based on an improved free ion approach might still be a good proxy, particularly when the comparative nature of life cycle assessment is taken into account.

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Authors: Owsiainiak, M. (Intern), Rosenbaum, R. K. (Intern)
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Publication date: 2011
Normalization references for Europe and North America for application with USEtox™ characterization factors

Purpose: In life cycle impact assessment, normalization can be a very effective tool for the life cycle assessment practitioner to interpret results and put them into perspective. The paper presents normalization references for the recently developed USEtox™ model, which aims at calculating globally applicable characterization factors. Normalization references for Europe and North America are determined, and guidance for expansions to other geographical regions is provided. Materials and methods The base years of the European and North American inventories are 2004 and 2002/2008, respectively. Emission data were extracted from two literature sources referring to each of the considered regions. The inventory for North America was adapted to avoid extrapolation of data from other regions and thus bring consistency with the emission inventory for Europe. In spite of different inventory assumptions, a similar coverage of substances was obtained for both regions with relatively high representation of metals and a number of organic compounds, mainly consisting of non-methane volatile organic compounds and pesticides. The two inventory sets were eventually characterized with the characterization factors (CFs) calculated with the version 1.0 of the USEtox™ model and substance database; both interim and recommended CFs were used. Results and discussion: Normalization references are provided for Europe and North America for the three USEtox™ toxic impact categories; ratios between the normalization references for the two regions in all cases lie below a factor of 3. Causes for the observed discrepancies are found to be different inventory assumptions as well as variations in the type and intensity of actual emissions between the two regions. Additional causes are inventories that only cover a limited number of substances, and the characterization model, which can only provide interim factors for certain substances like metal compounds. Based on these causes and on a review of recent studies on normalization references, a list of substances to be prioritized when collecting emission data was built, demonstrating the importance of metals. Conclusions: In the perspective of further refining the presented normalization references and of calculating new references for other regions, guidance is provided including a list of priority substances that should be considered when building emission inventories for normalization references.
Normalization references for USEtox™-based toxic impact categories: North American and European economic systems

As an optional step of the life cycle impact assessment (LCIA) phase in the ISO standards, normalization aims to express the magnitude of the impacts by comparing the characterized results against a common reference situation - the normalization references. In this study, we used inventories of two economic regions, North America and Europe, to calculate normalization references for the three currently-modelled USEtox™-based impact categories, i.e. freshwater ecotoxicity, human toxicity, divided into cancer effects and non-cancer effects. Base years for the references are 2004 for Europe and 2006 for North America. The normalization references have been calculated using recommended factors as well as with interim factors, as needed. It is found that, in spite of different inventory assumptions, the normalization references fall within the same order of magnitude for both North America and Europe. By analysing the most contributing substances, metals turn out to dominate the impacts in both regions. This may be explained by the interim status of the characterization factors (CFs) for metals, which might be overestimated in the current model. Part of the explanation may also lie in the incomplete coverage of organics in both the inventory and the CF databases. With respect to the intended global character of the USEtox™ model, different approaches to determine normalization references of other economic systems (e.g. Asia or world) are discussed in relation to these findings. Overall, we thus recommend the use of the provided set of normalization references for USEtox™, but we also advocate 1) to perform an update as soon as a more comprehensive inventory can be obtained and as soon as characterization factors for metals are revised; 2) to consider
The USEtox model was developed in a scientific consensus process involving comparison of and harmonization between existing environmental multimedia fate models. For freshwater ecosystem toxicity, it covers the entire impact pathway, i.e., transforming a chemical emission into potential impacts based on quantitative modeling of fate, exposure, and ecotoxicity effects. Taken together, these are represented as chemical-specific characterization factors (CFs). Through analysis of freshwater CFs for approximately 2500 organic chemicals, with special focus on a subset of chemicals with characteristic properties, this work provides understanding of the basis for calculations of CFs in USEtox. In addition, it offers insight into the chemical properties and critical mechanisms covering the continuum from chemical emission to freshwater ecosystem toxicity. For an emission directly to water, the effect factor, which is obtained from laboratory measurements of substance toxicity to different phyla, strongly controls freshwater ecotoxicity, with a range of up to 10 orders of magnitude. Chemical-specific differences in multimedia transfer influence the CF for freshwater emissions by less than two orders of magnitude. However, for an emission to air or soil, differences in chemical properties may decrease the CF by up to 10 orders of magnitude, as a result of intermedia transfer and degradation. This result brings new clarity to the relative contributions of fate and freshwater ecotoxicity to the overall characterization factor.
USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties

Purpose The aim of this paper is to provide science-based consensus and guidance for health effects modelling in comparative assessments based on human exposure and toxicity. This aim is achieved by i) describing the USEtoxTM exposure and toxicity models representing consensus and recommended modelling practice, ii) identifying key mechanisms influencing human exposure and toxicity effects of chemical emissions, iii) extending substance coverage.

Methods The methods section of this paper contains a detailed documentation of both the human exposure and toxic
effects models of USEtoxTM, to determine impacts on human health per kg substance emitted in different compartments. These are considered as scientific consensus and therefore recommended practice for comparative toxic impact assessment. The framework of the exposure model is described in details including the modelling of each exposure pathway considered (i.e. inhalation through air, ingestion through i) drinking water, ii) agricultural produce, iii) meat and milk, and iv) fish). The calculation of human health effect factors for cancer and non-cancer effects via ingestion and inhalation exposure respectively is described. This section also includes discussions regarding parameterisation and estimation of input data needed, including route-to-route and acute-to-chronic extrapolations. Results and discussion For most chemicals in USEtoxTM, inhalation, above-ground agricultural produce, and fish are the important exposure pathways with key driving factors being the compartment and place of emission, partitioning, degradation, bioaccumulation and bioccentration, and dietary habits of the population. For inhalation, the population density is the key factor driving the intake, thus the importance to differentiate emissions in urban areas, except for very persistent and mobile chemicals that are taken in by the global population independently from their place of emission. The analysis of carcinogenic potency (TD50) when volatile chemicals are administrated to rats and mice by both inhalation and an oral route suggests that results by one route can reasonably be used to represent another route. However, we first identify and mark as interim chemicals for which observed tumours are directly related to a given exposure route (e.g. for nasal or lung, or gastrointestinal cancers) or for which absorbed fraction by inhalation and by oral route differ greatly. Conclusions A documentation of the human exposure and toxicity models of USEtoxTM is provided, and key factors driving the human health characterisation factor are identified. Approaches are proposed to derive human toxic effect factors and expand the number of chemicals in USEtoxTM, primarily by extrapolating from an oral route to exposure in air (and optionally acute-to-chronic). Some exposure pathways (e.g. indoor inhalation, pesticide residues, dermal exposure) will be included in a later stage. USEtoxTM is applicable in various comparative toxicity impact assessments and not limited to LCA.

**General information**

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Organisations: Quantitative Sustainability Assessment, Department of Management Engineering, Radboud University Nijmegen, University of Michigan, Ecole Polytechnique de Montreal, University of California at Berkeley, National Institute of Public Health and the Environment

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Analytical Uncertainty Propagation in Life Cycle Inventory and Impact Assessment: Application to an Automobile Front Panel

Background, aim, and scope
Uncertainty information is essential for the proper use of Life Cycle Assessment (LCA) and environmental assessments in decision making. So far, parameter uncertainty propagation has mainly been studied using Monte Carlo techniques that are relatively computationally heavy to conduct, especially for the comparison of multiple scenarios, often limiting its use to research or to inventory only. Furthermore, Monte Carlo simulations do not automatically assess the sensitivity and contribution to overall uncertainty of individual parameters. The present paper aims to develop and apply to both inventory and impact assessment an explicit and transparent analytical approach to uncertainty. This approach applies Taylor series expansions to the uncertainty propagation of lognormally distributed parameters. Materials and methods
We first apply the Taylor series expansion method to analyze the uncertainty propagation of a single scenario, in which case the squared geometric standard deviation of the final output is determined as a function of the model sensitivity to each input parameter and the squared geometric standard deviation of each parameter. We then extend this approach to the comparison of two or more LCA scenarios. Since in LCA it is crucial to account for both common inventory processes and common impact assessment characterization factors among the different scenarios, we further develop the approach to address this dependency. We provide a method to easily determine a range and a best estimate of a) the squared geometric standard deviation on the ratio of the two scenario scores, "A/B", and b) the degree of confidence in the prediction that the impact of scenario A is lower than B (i.e., the probability that A/B<75%). For the aluminum panel, the electricity and aluminum primary production, as well as the light oil consumption, are the dominant contributors to the uncertainty. The developed approach for scenario comparisons, differentiating between common and independent parameters, leads to results similar to those of a Monte Carlo analysis; for all tested cases, we obtained a good concordance between the Monte Carlo and the Taylor series expansion methods regarding the probability that one
scenario is better than the other. Discussion The Taylor series expansion method addresses the crucial need of accounting for dependencies in LCA, both for common LCI processes and common LCIA characterization factors. The developed approach in equation (8), which differentiates between common and independent parameters, estimates the degree of confidence in the prediction that scenario A is better than B, yielding results similar to those found with Monte Carlo simulations. Conclusions The probability distributions obtained with the Taylor series expansion are virtually equivalent to those from a classical Monte Carlo simulation, while being significantly easier to obtain. An automobile case study on an aluminum front end panel demonstrated the feasibility of this method and illustrated its simultaneous and consistent application to both inventory and impact assessment. The explicit and innovative analytical approach, based on Taylor series expansions of lognormal distributions, provides the contribution to the uncertainty from each parameter and strongly reduces calculation time.

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Development of Normalization Factors for Canada and the United States and Comparison with European Factors

In Life Cycle Assessment (LCA), normalization calculates the magnitude of an impact (midpoint or endpoint) relative to the total effect of a given reference. The goal of this work is to calculate normalization factors for Canada and the US and to compare them with existing European normalization factors. The differences between geographical areas were highlighted by identifying and comparing the main contributors to a given impact category in Canada, the US and Europe. This comparison verified that the main contributors in Europe and in the US are also present in the Canadian inventory. It also showed that normalized profiles are highly dependent on the selected reference due to differences in the industrial and economic activities. To meet practitioners' needs, Canadian normalization factors have been calculated using the characterization factors from LUCAS (Canadian), IMPACT 2002+ (European), and TRACI (US) respectively. The main sources of uncertainty related to Canadian NFs are data gaps (pesticides, metals) and aggregated data (metals, VOC), but the uncertainty related to CFs generally remains unknown. A final discussion is proposed based on the comparison of resource extraction and resource consumption and raises the question of the legitimacy of defining a country by its geographical borders.

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Organisations: Quantitative Sustainability Assessment, Department of Management Engineering, Ecole Polytechnique de Montreal, U.S. Environmental Protection Agency
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The USEtox model was developed in a scientific consensus process involving comparison of and harmonization between existing environmental multimedia fate models. For life cycle impact assessment, USEtox may be used as a comparative tool for ecosystem and human toxicity. As a characterization model, it covers the entire impact pathway transforming a chemical emission into potential impacts on freshwater ecosystems based on quantitative modeling of fate, exposure and ecotoxicity effects. Taken together, these are represented as chemical-specific characterization factors (CFs). In the case of freshwater ecotoxicity, impacts are measured as potentially affected or disappeared species [PAF m3-day / kgemitted]. Through analysis of the freshwater CFs of over three thousand organic chemicals, this work provides insight into the chemical properties that most strongly influence freshwater ecosystem toxicity for a variety of emission scenarios. Furthermore, the analysis addresses the influence of chemical properties along the emission-fate-exposure-impact chain of events. The main trends are identified using results for the entire dataset of chemicals, and typical patterns are illustrated for a small selection of chemicals with characteristic combinations of properties. For an emission directly to water, the effect factor, which is obtained from laboratory measurements of substance toxicity to different trophic levels, strongly controls toxicity. Multimedia transfer affects the CF for these emissions by less than two orders of magnitude. However, for emission to air or soil, intermedia transfer and degradation may decrease the CF by up to 10 orders of magnitude. This result shows the importance of the Henry's law constant, the organic carbon and octanol-water partitioning coefficient, the degradation half-life in various media, and the treatment of intermittent rain in the model. The interplay between these parameters and the model, which assumes a typical ratio of water to land surface area, shows that direct air to water transfer is less important for many hydrophilic chemicals than might be suspected. As a result, for some compounds, second-order transfers, eg., from air to soil to water, are relatively more important. USEtox addresses some of the pressing problems in current life cycle impact assessment of chemical emissions by providing a consensus model that can calculate transparent chemical-specific characterization factors.
Using the Lashof Accounting Methodology to Assess Carbon Mitigation Projects Using LCA: Ethanol Biofuel as a Case Study

As governments elaborate strategies to counter climate change, there is a need to compare the different options available on an environmental basis. This study proposes a life cycle assessment (LCA) framework integrating the Lashof Mg-year accounting methodology that allows the assessment and comparison of different carbon mitigation projects (e.g. biofuel use, sequestering plant, afforestation project, etc.). The Lashof accounting methodology is chosen amid other methods of greenhouse gas (GHG) emission characterization for its relative simplicity and capability of characterizing all types of carbon mitigation projects. It calculates the cumulative radiative forcing caused by GHG emission within a predetermined time frame. Basically, the developed framework uses the Mg-year as a functional unit and isolates impacts related to the climate mitigation function with system expansion. The proposed framework is demonstrated with a case study of tree ethanol pathways (maize, sugarcane and willow). Study shows that carbon mitigation assessment through LCA is possible and that it could be a useful tool for decision makers as it can compare different projects regardless of their original context. Case study reveals that the system expansion scenario and the efficiency at reducing carbon emissions of the carbon mitigation project are critical factors having significant impact on results. Also, framework proves to be useful at treating land-use change emission as they are considered through the functional unit.

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The objective of this study is to increase the understanding and transparency of chemical biotransfer modeling into meat and milk and explicitly confront the uncertainties in exposure assessments of chemicals that require such estimates. In cumulative exposure assessments that include food pathways, much of the overall uncertainty is attributable to the estimation of transfer into biota and through food webs. Currently, the most commonly used meat and milk-biotransfer models date back two decades and, in spite of their widespread use in multimedia exposure models few attempts have been made to advance or improve the outdated and highly uncertain Kow regressions used in these models. Furthermore, in the range of Kow where meat and milk become the dominant human exposure pathways, these models often provide...
unrealistic rates and do not reflect properly the transfer dynamics. To address these issues, we developed a dynamic three-compartment cow model (called CKow), distinguishing lactating and non-lactating cows. For chemicals without available overall removal rates in the cow, a correlation is derived from measured values reported in the literature to predict this parameter from Kow. Results on carry over rates (COR) and biotransfer factors (BTF) demonstrate that a steady-state ratio between animal intake and meat concentrations is almost never reached. For meat, empirical data collected on short term experiments need to be adjusted to provide estimates of average longer term behaviors. The performance of the new model in matching measurements is improved relative to existing models—thus reducing uncertainty. The CKow model is straightforward to apply at steady state for milk and dynamically for realistic exposure durations for meat COR.

Keyword: biotransfer factor, BTF, carry over rate, COR, cow, cattle, dairy, milk, meat, Kow

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Scopus rating (2009): SJR 2.835 SNIP 1.803
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Integrating Indoor Air Pollutant Exposure within Life Cycle Impact Assessment

Neglecting health effects from indoor pollutant emissions and exposure, as currently done in Life Cycle Assessment (LCA), may result in product or process optimizations at the expense of workers’ or consumers’ health. To close this gap, methods for considering indoor exposure to chemicals are needed to complement the methods for outdoor human exposure assessment already in use. This paper summarizes the work of an international expert group on the integration of human indoor and outdoor exposure in LCA, within the UNEP/SETAC Life Cycle Initiative. A new methodological framework is proposed for a general procedure to include human-health effects from indoor exposure in LCA. Exposure models from occupational hygiene and household indoor air quality studies and practices are critically reviewed and recommendations are provided on the appropriateness of various model alternatives in the context of LCA. A single-compartment box model is recommended for use as a default in LCA, enabling one to screen occupational and household exposures consistent with the existing models to assess outdoor emission in a multimedia environment. An initial set of model parameter values was collected. The comparison between indoor and outdoor human exposure per unit of emission shows that for many pollutants, intake per unit of indoor emission may be several orders of magnitude higher than for outdoor emissions. It is concluded that indoor exposure should be routinely addressed within LCA.
Life Cycle Assessment of Mine Tailings Management in Canada

The effective management of mine tailings involves the control of several environmental impacts and legal requirements. Six tailings site management and closure scenarios were developed for a copper-zinc underground mine located in Quebec (Canada) and compared using life cycle assessment (LCA). Two options are considered for the mine operation: tailings can be sent to the tailings disposal area where they are submerged or they can be partly used for backfilling. For each of these two operation options, three alternatives are presented for mine closure: (a) submerged tailings, (b) partial desulphurization with a cover of desulphurized material and (c) a cover with capillary barrier effects (CCBE) made of natural soils followed by revegetation. The goals of the study were to draw the inventory of these management scenarios from the development to the post-closure phase, to assess and compare their environmental impacts and to determine the importance of the land-use impact category. The potential impacts for each scenario were evaluated using the IMPACT 2002+ LCIA method. The results of the performed LCA indicate that for mine development and operation, scenarios where tailings are partly used as backfill for underground stopes appear to lead to larger impacts in 11 of the 14 midpoint categories since the backfill plant operation consumes a greater amount of material and energy. For a site closure period of 2 years, the CCBE option creates the greatest impacts, since it requires much more effort than the other techniques. The results for the post-closure phase have been analysed separately since they have a larger uncertainty. They appear to modify the comparative assessment results. The various results presented in the paper show the importance of taking land-use impacts into account.

Keyword: Mine tailings management; Life cycle impact assessment; Acid mine drainage control; IMPACT 2002+; Land-use category

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Organisations: Ecole Polytechnique de Montreal
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Building a model based on scientific consensus for Life Cycle Impact Assessment of chemicals: The Search for Harmony and Parsimony

Achieving consensus among scientists is often a challenge - particularly in model development. In this article we describe a recent scientific consensus-building process for Life Cycle Impact Assessment (LCIA) models applied to chemical emissions - including the strategy, execution, and results of a process that used model comparison to achieve parsimony. This process has succeeded in establishing a transparent LCIA consensus model. We present the lessons that may be adapted by similar consensus processes in other fields.

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International consensus model for comparative assessment of chemical emissions in LCA

Under the UNEP-SETAC Life Cycle Initiative the six most commonly used characterisation models for toxic impacts from chemicals were compared and harmonised through a sequence of workshops removing differences which were unintentional or unnecessary. A parsimonious (as simple as possible but as complex as needed) and transparent consensus model, USEtox, was created producing characterisation factors that fall within the range of factors from the harmonised existing characterisation models. The USEtox model together with factors for several thousand substances are currently under review to form the basis of the recommendations from the UNEP-SETAC Life Cycle Initiative in this field.

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USEtox - The UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in Life Cycle Impact Assessment

Background, Aim and Scope. In 2005 a comprehensive comparison of LCIA toxicity characterisation models was initiated by the UNEP-SETAC Life Cycle Initiative, directly involving the model developers of CalTOX, IMPACT 2002, USES-LCA, BETR, EDIP, WATSON, and EcoSense. In this paper we describe this model-comparison process and its results—in particular the scientific consensus model developed by the model developers. The main objectives of this effort were (i) to identify specific sources of differences between the models’ results and structure, (ii) to detect the indispensable model components, and (iii) to build a scientific consensus model from them, representing recommended practice. Methods. A chemical test set of 45 organics covering a wide range of property combinations was selected for this purpose. All models used this set. In three workshops, the model comparison participants identified key fate, exposure and effect issues via comparison of the final characterisation factors and selected intermediate outputs for fate, human exposure and toxic effects for the test set applied to all models. Results. Through this process, we were able to reduce inter-model variation from an initial range of up to 13 orders of magnitude down to no more than 2 orders of magnitude for any substance. This led to the development of USEtox, a scientific consensus model that contains only the most influential model elements. These were, for example, process formulations accounting for intermittent rain, defining a closed or open system environment, or nesting an urban box in a continental box. Discussion. The precision of the new characterisation factors (CFs) is within a factor of 100-1000 for human health and 10-100 for freshwater ecotoxicity of all other models compared to 12 orders of magnitude variation between the CFs of each model respectively. The achieved reduction of inter-model variability by up to 11 orders of magnitude is a significant improvement. Conclusions. USEtox provides a parsimonious and transparent tool for human health and ecosystem CF estimates. Based on a referenced database, it has now been used to calculate CFs for several thousand substances and forms the basis of the recommendations from UNEP-SETAC’s Life Cycle Initiative regarding characterization of toxic impacts in Life Cycle Assessment. Recommendations and Perspectives. We provide both recommended and interim (not recommended and to be used with caution) characterisation factors for human health and freshwater ecotoxicity impacts. After a process of consensus building among stakeholders on a broad scale as well as several improvements regarding a wider and easier applicability of the model, USEtox will become available to practitioners for the calculation of further CFs.

General information

State: Published
Organisations: Quantitative Sustainability Assessment, Department of Management Engineering
Authors: Rosenbaum, R. K. (Intern), Bachmann, T. M. (Ekstern), Gold, L. S. (Ekstern), Huijbregts, M. A. (Ekstern), Jolliet, O. (Ekstern), Köhler, A. (Ekstern), Larsen, H. F. (Intern), MacLeod, M. (Ekstern), Margni, M. (Ekstern), McKone, T. E. (Ekstern), Payet, J. (Ekstern), Schuhmacher, M. (Ekstern), van de Meent, D. (Ekstern),
A flexible matrix algebra framework for the multimedia multipathway modeling of emission to impacts

When assessing human health or ecosystem impacts of chemicals several calculation steps need to be addressed. Matrix algebra solving techniques are a useful approach to structure and solve the system of mass balance equations assessing chemical fate in environmental multimedia models. We suggest expanding this matrix approach towards a framework which includes the exposure, effect, and damage assessment for human health and ecosystems, also applicable to spatial modeling. Special emphasis is laid upon interpretation of the physical meaning of different elements within the matrices. The proposed framework provides several advantages such as simplified updating or extending of models to new impact pathways, possibility of covering various models within the same framework and transparency. Interpretation of intermediate and final results is facilitated, e.g., allowing for direct identification of dominating exposure pathways. Model comparability and evaluation is well supported, as the four matrices contain all intermediate results in a clear and interpretable way, independent from parameters, such as amount and place of emission. Multidisciplinary work is strongly facilitated enabling the linkage of different models from various disciplines together, since each of its modules defines a clear interface of intermediate results. This framework was reviewed by an independent expert panel within a UNEP/SETAC workshop, and adopted as starting-point for new advances in modeling environmental toxic releases within the UNEP/SETAC Life Cycle Initiative.

Keyword: Life cycle impact assessment; Environmental risk assessment; Environmental multimedia modeling; Chemical fate; Human exposure; Human toxicity; Ecotoxicity; Matrix algebra; Spatial differentiation

General information
State: Published
Organisations: Ecole Polytechnique de Montreal, University of Michigan, Ecole Polytechnique Federale de Lausanne (EPFL)
Authors: Rosenbaum, R. K. (Intern), Margni, M. (Ekstern), Jolliet, O. (Ekstern)
Pages: 624-634
Publication date: 2007
Main Research Area: Technical/natural sciences

Publication information
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Volume: 33
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Web of Science (2017): Indexed yes
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Scopus rating (2016): CiteScore 7.33 SJR 2.465 SNIP 2.389
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 2.577 SNIP 2.129 CiteScore 6.49
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 2.714 SNIP 2.317 CiteScore 6.54
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 2.664 SNIP 2.209 CiteScore 6.06
ISI indexed (2013): ISI indexed yes
International consensus model for comparative assessment of chemicals

General information
State: Published
Organisations: Quantitative Sustainability Assessment, Department of Management Engineering
Publication date: 2007
Main Research Area: Technical/natural sciences
Publication: Research -> Poster – Annual report year: 2007

Towards a consensus model in chemical characterisation modelling for LCA: comparison and harmonisation of models for fate and ecotoxicity effects
Towards a consensus model in chemical characterisation modelling for LCA: comparison and harmonisation of models for human exposure and toxicity

Establishing a framework for Life Cycle Toxicity Assessment: Findings of the Lausanne review workshop
Multimedia and Food Chain Modelling of Toxics for Comparative Risk and Life Cycle Impact Assessment

The overall goal of this dissertation is to contribute to the development of best available practice in environmental multimedia fate and multipathway exposure modelling for human health and ecosystem impacts, addressing several important aspects. Environmental multimedia models relate environmental emissions to impacts (or risk factors) combining multimedia fate and multipathway exposure estimates with effect assessment data. Many organic chemicals formed in combustion and released to air as well as organic chemicals released to air, water, and soil from industrial activities enter humans primarily through food – in particular through meat and dairy products. Therefore, food chain modelling is of utmost importance for human exposure assessment. Model comparison and quantification of uncertainties of model results are vital for their correct interpretation. This leads to the following questions: 1. How would a model framework be structured favoring flexibility, transparency, comparability, interpretability, without limiting the capabilities of the model parts? 2. How can carry-over modelling of chemical biotransfer into biota such as meat or milk be improved considering limited data availability and high uncertainties? 3. How can environmental multimedia multipathway models be compared in a systematic and detailed way, and what are important sources of differences? 4. How to identify important sources of uncertainty in a model result, including regression models used for estimation and when modelling large sets of chemicals? In order to answer that, the following specific goals are addressed: 1. Develop a consistent matrix algebra framework for multimedia fate, multipathway exposure and toxicity effects models. 2. Review existing biotransfer models for chemical transfer into meat and milk and develop, compare and evaluate an improved carry-over model for meat and...
milk. 3. Compare selected multimedia fate, multipathway exposure and toxicity effects models on the level of final characterisation factors as well as for intermediate results. 4. Develop and test approaches to assess the uncertainty of model results accounting for regression model uncertainty and main parameters contributing to overall uncertainty.

Chapter 1 puts this dissertation into its context and introduces multimedia fate, multipathway exposure and human health and ecosystem effects modelling with a focus on the food chain exposure in the frame of comparative risk and Life Cycle Impact Assessment. Chapter 2 presents a framework for multimedia multipathway models entirely based on matrix algebra. When assessing human health or ecosystem impacts of chemicals several calculation steps need to be addressed. We suggest a matrix algebra framework which includes the fate, exposure, effect, and damage assessment for human health and ecosystems, also applicable to spatial modelling. Special emphasis is laid upon interpretation of the physical meaning of different elements within the matrices. Chapter 3 describes the development, comparison and evaluation of an improved carry-over model for chemical transfer into meat and milk. The objective of this study is to increase the reliability and transparency of chemical biotransfer modelling into meat and milk and explicitly confront the uncertainties in exposure assessments of chemicals that require such estimates. To address this we developed a dynamic three compartment cow model (called CKow), able to distinguish lactating and non-lactating cows, to more accurately track the transport of a chemical into meat fat and milk within the cow. Using the CKow model as base model we derived a simplified model proposing an improved, less uncertain regression model to predict COR for meat and milk based on Kow. Chapter 4 is a detailed comparison of four characterisation methods used in LCIA. The main objective was to investigate whether or not the models’ results agree with each other in terms of ranking as well as in absolute values and identify where differences come from. A comparison of characterisation factors and intermediate results of IMPACT 2002, CalTOX, USES-LCA, and EDIP97 has been performed for generic organic compounds. The comparison procedure was undertaken in three tiers: 1) comparison of available published factors, 2) calculated factors based on the harmonised chemical test set and 3) an in depth comparison revealing differences of the models on the level of processes and algorithms. Chapter 5 explores possibilities to estimate the uncertainty of results from multimedia fate and multipathway exposure models and to account for regression model uncertainty. Quantification and communication of uncertainties related to model results is vital for their correct interpretation and use. We explore and compare approaches to identify and quantify main sources of uncertainty, enabling to focus the data acquisition for the uncertainty assessment, especially when modelling large sets of chemicals. Chapter 6 presents general conclusions, wrapping up the achievements of this dissertation and answering the scientific questions raised above.

Keywords: life cycle impact assessment (LCIA); environmental risk assessment (ERA); environmental multimedia modelling; chemical fate; human exposure; human toxicity; ecotoxicity; matrix algebra; spatial differentiation; biotransfer factor (BTF); carry over rate (COR); cow; cattle; milk; meat; intake fraction; model comparison; uncertainty analysis

General information
State: Published
Organisations: Ecole Polytechnique Federale de Lausanne (EPFL)
Authors: Rosenbaum, R. K. (Intern)
Number of pages: 192
Publication date: 2006

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Main Research Area: Technical/natural sciences
Links: http://library.epfl.ch/theses/?nr=3539
Source: orbit
Source-ID: 257814
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An implemented approach for estimating uncertainties for toxicological impact characterisation
One approach accounting for parameter and model uncertainty is implemented in the LCIA (life cycle impact assessment) method IMPACT 2002. The uncertainty is estimated for intermediate results from the chemical fate, human intake fraction, and two toxicological effect modules. Overall uncertainty estimates are then arithmetically calculated. Results are presented for impact contributions in the contexts of aquatic ecosystems and human health. The approach of Hofstetter (1998) was adapted for estimating the uncertainty related to chemical fate and human intake fractions. A fundamental problem when estimating uncertainties for 1000’s of substances consists of the lack of uncertainty distributions for all of the input data and the need to have a practical approach to assign distributions to each chemical. Hofstetter (1998) proposed the use of fixed factors for clusters of substances. The choice of a factor is then dependent on the emission medium, exposure route, and the robustness of the model relative to the chemical being considered. The factors are initially determined for representative substances for each category using evaluation data, expert judgement, or approaches such as Monte Carlo. There is then no need to repeat the Monte Carlo calculations. Multiplying and dividing the geometric mean estimate by a factor provides an estimate of the upper and lower 95th percentile confidence interval bounds. The human health effect factor uncertainty is similarly defined and readily combined through addition with that of the intake fraction. Using expert judgement, three uncertainty classes were proposed to estimate uncertainty related to the
human effects input data. These effects data account for both the risk of an effect, as well as the potential consequences of population-based exposures. The uncertainty for ecotoxicological effects is currently related to the number of species tested for aquatic species in the water column. The more species test results available, the more robust the estimate of the ecotoxicological factor is assumed to be. For estimating the ecotoxicological effect factor uncertainty, the combined use of two distinct approaches was suggested, – the higher uncertainty estimate being adopted. The combination of both guaranteed more robust results compared to applying either method – both being based on differing assumptions related to the sample versus the population distribution. The presented approach proved to be very transparent, robust but while reflecting our current level of knowledge, quick to use, and is easily applied in practice to combine the uncertainty of the emissions inventory with those of the impact assessment phase in a life cycle assessment study.

Keyword: Uncertainty; LCIA; Toxicity; Multimedia Modelling

General information
State: Published
Authors: Rosenbaum, R. K. (Intern), Pennington, D. W. (Ekstern), Jolliet, O. (Ekstern)
Number of pages: 6
Publication date: 2004

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Place of publication: Manno, Switzerland
Publisher: International Environmental Modelling and Software Society, iEMSs
ISBN (Print): 88-900787-1-5
Main Research Area: Technical/natural sciences
Conference: 2nd Biennial Meeting of the International Environmental Modelling and Software Society, iEMSs, Osnabrück, Germany, 01/01/2004
Source: orbit
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2004

Bringing Science and Pragmatism together - a Tiered Approach for Modelling Toxicological Impacts in LCA
Goal, Scope and Background. The EU 5th framework project OMNIIOTOX will develop models calculating characterisation factors for assessing the potential toxic impacts of chemicals within the framework of LCA. These models will become accessible through a web-based information system. The key objective of the OMNIIOTOX project is to increase the coverage of substances by such models. In order to reach this objective, simpler models which need less but available data, will have to be developed while maintaining scientific quality. Methods. Experience within the OMNIIOTOX project has taught that data availability and quality are crucial issues for calculating characterisation factors. Data availability determines whether calculating characterisation factors is possible at all, whereas data quality determines to what extent the resulting characterisation factors are reliable. Today, there is insufficient knowledge and/or resources to have high data availability as well as high data quality and high model quality at the same time. Results. The OMNIIOTOX project is developing two inter-related models in order to be able to provide LCA impact assessment characterisation factors for toxic releases for as broad a range of chemicals as possible: 1) A base model representing a state-of-the-art multimedia model and 2) a simple model derived from the base model using statistical tools. Discussion. A preliminary decision tree for using the OMNIIOTOX information system (IS) is presented. The decision tree aims to illustrate how the OMNIIOTOX IS can assist an LCA practitioner in finding or deriving characterisation factors for use in life cycle impact assessment of toxic releases. Conclusions and Outlook. Data availability and quality are crucial issues when calculating characterisation factors for the toxicity impact categories. The OMNIIOTOX project is developing a tiered model approach for this. It is foreseen that a first version of the base model will be ready in late summer of 2004, whereas a first version of the simple base model is expected a few months later.

General information
State: Published
Organisations: Quantitative Sustainability Assessment, Department of Management Engineering, Innovation and Sustainability, USTUTT, P&G
Pages: 320-326
Publication date: 2004
Main Research Area: Technical/natural sciences

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Journal: International Journal of Life Cycle Assessment
Volume: 9
Comparison between three different LCIA methods for aquatic ecotoxicity and a product Environmental Risk Assessment – Insights from a Detergent Case Study within OMNIITOX

Background and Objective. In the OMNIITOX project 11 partners have the common objective to improve environmental management tools for the assessment of (eco)toxicological impacts. The detergent case study aims at: i) comparing three Procter & Gamble laundry detergent forms (Regular Powder-RP, Compact Powder-CP and Compact Liquid-CL) regarding their potential impacts on aquatic ecotoxicity, ii) providing insights into the differences between various Life Cycle Impact Assessment (LCIA) methods with respect to data needs and results and iii) comparing the results from Life Cycle Assessment (LCA) with results from an Environmental Risk Assessment (ERA). Material and Methods. The LCIA has been conducted with EDIP97 (chronic aquatic ecotoxicity) [1], USES-LCA (freshwater and marine water aquatic ecotoxicity, sometimes referred to as CML2001) [2, 3] and IMPACT 2002 (covering freshwater aquatic ecotoxicity) [4]. The comparative product ERA is based on the EU Ecolabel approach for detergents [5] and EUSES [6], which is based on the Technical Guidance Document (TGD) of the EU on Environmental Risk Assessment (ERA) of chemicals [7]. Apart from the Eco-label approach, all calculations are based on the same set of physico-chemical and toxicological effect data to enable a better comparison of the methodological differences. For the same reason, the system boundaries were kept the same in all cases, focusing on emissions into water at the disposal stage. Results and Discussion. Significant differences between the LCIA methods with respect to data needs and results were identified. Most LCIA methods for freshwater ecotoxicity and the ERA see the compact and regular powders as similar, followed by compact liquid. IMPACT 2002 (for freshwater) suggests the liquid is equally as good as the compact powder, while the regular powder comes out worse by a factor of 2. USES-LCA for marine water shows a very different picture seeing the compact liquid as the clear winner over the powders, with the regular powder the least favourable option. Even the LCIA methods which result in the same product ranking, e.g. EDIP97 chronic aquatic ecotoxicity and USES-LCA freshwater ecotoxicity, significantly differ in terms of most contributing substances. Whereas, according to IMPACT 2002 and USES-LCA marine water, results are entirely dominated by inorganic substances, the other LCIA methods and the ERA assign a key role to surfactants. Deviating results are mainly due to differences in the fate and exposure modelling and, to a lesser extent, to differences in the toxicological effect calculations. Only IMPACT 2002 calculates the effects based on a mean value approach, whereas all other LCIA methods and the ERA tend to prefer a PNEC-based approach. In a comparative context like LCA the OMNIITOX project has taken the decision for a combined mean and PNEC-based approach, as it better represents the ‘average’ toxicity while still taking into account more sensitive species. However, the main reason for deviating results remains in the calculation of the residence time of emissions in the water compartments. Conclusion and Outlook. The situation that different LCIA methods result in different answers to the question concerning which detergent type is to be preferred regarding the impact category aquatic ecotoxicity is not satisfactory, unless explicit reasons for the differences are identifiable. This can hamper practical decision support, as LCA practitioners usually will not be in a position to choose the ‘right’ LCIA method for their specific case. This puts a challenge to the entire OMNIITOX project to develop a method, which finds common ground regarding fate, exposure and effect modelling to overcome the current situation of diverging results and to reflect most realistic conditions.

General information
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Organisations: Innovation and Sustainability, Department of Management Engineering, Quantitative Sustainability Assessment, P&G
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Main Research Area: Technical/natural sciences

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Scopus rating (2016): CiteScore 3.43 SJR 1.328 SNIP 1.423
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.504 SNIP 1.554 CiteScore 3.49
IMPACT 2002+: A New Life Cycle Impact Assessment Methodology

The new IMPACT 2002+ life cycle impact assessment methodology proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories. For IMPACT 2002+, new concepts and methods have been developed, especially for the comparative assessment of human toxicity and ecotoxicity. Human Damage Factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities. The transfer of contaminants into the human food is no more based on consumption surveys, but accounts for agricultural and livestock production levels. Indoor and outdoor air emissions can be compared and the intermittent character of rainfall is considered. Both human toxicity and ecotoxicity effect factors are based on mean responses rather than on conservative assumptions. Other midpoint categories are adapted from existing characterizing methods (Eco-indicator 99 and CML 2002). All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources. Normalization can be performed either at midpoint or at damage level. The IMPACT 2002+ method presently provides characterization factors for almost
1500 different LCI-results, which can be downloaded at http://www.epfl.ch/impact
Keyword: Ecotoxicity - human toxicity - IMPACT 2002+ - life cycle impact assessment (LCIA) - midpoint/damage approach

**General information**

State: Published
Organisations: Ecole Polytechnique Federale de Lausanne (EPFL)
Authors: Jolliet, O. (Ekstern), Margni, M. (Ekstern), Charles, R. (Ekstern), Humbert, S. (Ekstern), Payet, J. (Ekstern), Rebiter, G. (Ekstern), Rosenbaum, R. (Intern)
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Main Research Area: Technical/natural sciences

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Scopus rating (2016): CiteScore 3.43 SJR 1.328 SNIP 1.423
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
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BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.736 SNIP 1.738 CiteScore 3.65
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.666 SNIP 1.979 CiteScore 3.35
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Web of Science (2013): Indexed yes
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Scopus rating (2012): SJR 1.515 SNIP 1.701 CiteScore 2.89
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Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 1.581 SNIP 1.716 CiteScore 2.82
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.447 SNIP 1.861
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.201 SNIP 1.592
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 0.863 SNIP 1.33
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.8 SNIP 1.22
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.6 SNIP 1.387
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.633 SNIP 1.742
Projects:

**Quantifying the Sustainability of Consumer Products: Focusing on Chemical Exposures**

Department of Management Engineering  
Period: 15/12/2013 → 23/03/2017  
Number of participants: 9  
PhD Student: Ernstoff, Alexi (Intern)  
Supervisor: Hauschild, Michael Zwicky (Intern)  
Jolliet, Olivier (Ekstern)  
Rosenbaum, Ralph K. (Intern)  
Trier, Xenia (Intern)  
Main Supervisor: Fantke, Peter (Intern)  
Examiner: Olsen, Stig Irving (Intern)  
Egeghy, Peter Paul (Ekstern)  
Hellweg, Stefanie (Ekstern)

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Institut stipendie (DTU)  
Project: PhD

**Impacts of waterbone nitrogen emissions to hypoxia-driven marine eutrophication: modelling of damage to ecosystems in life cycle impact assessment (LC IA)**

Department of Management Engineering  
Period: 15/12/2012 → 01/09/2016  
Number of participants: 7  
PhD Student: Cosme, Nuno Miguel Dias (Intern)  
Supervisor: Birkved, Morten (Intern)  
Rosenbaum, Ralph K. (Intern)  
Main Supervisor: Hauschild, Michael Zwicky (Intern)  
Examiner:
Laurent, Alexis (Intern)
Henderson, Andrew D. (Ekstern)
Verones, Francesca (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Life cycle impact assessment of long-term emissions from landfills
Department of Management Engineering
Period: 15/12/2011 → 22/06/2015
Number of participants: 7
Phd Student:
Bakas, Ioannis (Intern)
Supervisor:
Astrup, Thomas Fruergaard (Intern)
Rosenbaum, Ralph K. (Intern)
Main Supervisor:
Hauschild, Michael Zwicky (Intern)
Examiner:
Olsen, Stig Irving (Intern)
Finnveden, Göran (Ekstern)
Henderson, Andrew D. (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Development and application of a standardized methodology for the PROspective Sustainability assessment of Technologies
Department of Management Engineering
Period: 15/11/2010 → 23/02/2015
Number of participants: 6
Phd Student:
Dong, Yan (Intern)
Supervisor:
Rosenbaum, Ralph K. (Intern)
Main Supervisor:
Hauschild, Michael Zwicky (Intern)
Examiner:
Birkved, Morten (Intern)
Henderson, Andrew D. (Ekstern)
Lützhøft, Hans-Christian Holten (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Development of a methodology for inclusion of terrestrial ecotoxic impacts of metals in life cycle impact assessment
Department of Management Engineering
Period: 01/04/2010 → 12/12/2013
Number of participants: 6
Phd Student:
Owsianiak, Mikolaj (Intern)
Supervisor:
Rosenbaum, Ralph K. (Intern)
Main Supervisor:
Hauschild, Michael Zwicky (Intern)
Examiner:
Olsen, Stig Irving (Intern)
Diamond, Miriam Leah (Ekstern)
Lützhøft, Hans-Christian Holten (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Anden EU-finansiering
Project: PhD

LC-IMPACT: Development and application of environmental Life Cycle Impact assessment Methods for imProved sustAinability Characterisation of Technologies

Department of Management Engineering
Quantitative Sustainability Assessment
Radboud University Nijmegen
Swiss Federal Institute of Technology
Swedish Institute for Food and Biotechnology
PRé Consultants B.V.
International Institute for Applied Systems Analysis
Unilever
University of Stuttgart
Quantis
Leiden University
European Commission - Joint Research Center
Institute of Agri-food Research and Technology
University of Bayreuth
Period: 01/12/2009 → 31/05/2013
Number of participants: 6
LCA
Acronym: LC-IMPACT
Project participant:
Hauschild, Michael Zwicky (Intern)
Rosenbaum, Ralph K. (Intern)
Larsen, Henrik Fred (Intern)
Fantke, Peter (Intern)
Owsianiak, Mikolaj (Intern)
Cosme, Nuno Miguel Dias (Intern)

Relations
Parent project:
Development and application of environmental Life Cycle Impact assessment Methods for improved sustAinability Characterisation of Technologies
Project

Anden EU-finansiering

Department of Management Engineering
Quantitative Sustainability Assessment
Period: 01/12/2009 → 31/05/2013
Number of participants: 1
Acronym: LC-IMPACT
Number of related Ph.D. students: 1
Project Manager, organisational:
Rosenbaum, Ralph K. (Intern)

Relations
Activities:
LC-IMPACT: Outcomes work package 2: toxicity

Publications:
Addressing Geographic Variability in the Comparative Toxicity Potential of Copper and Nickel in Soils
Land use impacts on biodiversity in LCA: proposal of characterization factors based on functional diversity

Activities:

Scoping Workshop - Global guidance on environmental life cycle impact assessment indicators
Period: 16 May 2013 → 17 May 2013
Ralph K. Rosenbaum (Participant)
Department of Management Engineering
Quantitative Sustainability Assessment

Description
Workshop participant and co-chair of "ecosystem quality" working group

Related event

Scoping Workshop - Global guidance on environmental life cycle impact assessment indicators
16/05/2013 → 17/05/2013
Glasgow, United Kingdom
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.

LC-IMPACT: Outcomes work package 2: toxicity
Period: 15 May 2013
Ralph K. Rosenbaum (Speaker)
Department of Management Engineering
Quantitative Sustainability Assessment

Description
Final presentation of results from the work package "toxicity" of the EU project LC-IMPACT

Related event

SETAC Europe 23rd Annual Meeting: Building a Better Future: Responsible Innovation and Environmental Protection
12/05/2013 → 16/05/2013
Glasgow, United Kingdom
Activity: Talks and presentations › Conference presentations

Keeping USEtox up-to-date: What is coming and how you can contribute
Period: 14 May 2013
Ralph K. Rosenbaum (Speaker)
Department of Management Engineering
Quantitative Sustainability Assessment

Related event
Exploring parameter uncertainty and seasonal variability for human health intake fractions in life cycle assessment  
Period: 13 May 2013  
Ralph K. Rosenbaum (Speaker)  
Department of Management Engineering  
Quantitative Sustainability Assessment

Modelling human and ecosystems exposures and impacts for life-cycle assessment: the USEtox model  
Period: 12 May 2013  
Ralph K. Rosenbaum (Lecturer)  
Department of Management Engineering  
Quantitative Sustainability Assessment

Towards consensus about the delimitation between life cycle inventory and impact assessment in LCAs with pesticide and fertilizer use  
Period: 11 May 2013  
Ralph K. Rosenbaum (Organizer)  
Department of Management Engineering  
Quantitative Sustainability Assessment

Guideline committee VDI-Guideline 4601 "Environmental Indicators" (Richtlinienausschuss VDI-Richtlinie 4601 "Umweltindikatoren") (External organisation)  
Period: 1 Mar 2013 → 1 Mar 2016  
Ralph K. Rosenbaum (Participant)  
Department of Management Engineering
Quantitative Sustainability Assessment

**Description**
Expert member for Life Cycle Impact Assessment indicators in the guideline committee VDI-Guideline 4601 "Environmental Indicators" (Richtlinienausschuss VDI-Richtlinie 4601 "Umweltindikatoren")

Body type: VDI - Association of German Engineers
Degree of recognition: International

**Related external organisation**
Guideline committee VDI-Guideline 4601 "Environmental Indicators" (Richtlinienausschuss VDI-Richtlinie 4601 "Umweltindikatoren")
Activity: Membership › Membership of committees, commissions, boards, councils, associations, organisations, or similar

**International Journal of Life Cycle Assessment (Journal)**
Period: 2007 → …
Ralph K. Rosenbaum (Editor)
Department of Management Engineering
Quantitative Sustainability Assessment

**Description**
The International Journal of Life Cycle Assessment

Editor for Environmental fate and human exposure of chemicals; LCIA of Impacts on Human Health

Links:

**Related journal**

International Journal of Life Cycle Assessment
0948-3349
Central database
Activity: Research › Journal editor