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Operational integration of time dependent toxicity impact category in dynamic LCA

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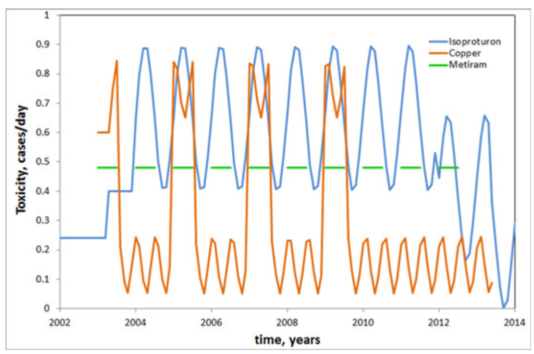
HIGHLIGHTS

- A method is proposed for calculating time dependent toxicity and ecotoxicity.
- Resolution of the dynamic fate model is combined with the USEtox® toxicity model.
- A current toxicity and a cumulated toxicity are calculated in function of time.
- The dynamic toxicity calculation is integrated in a dynamic LCA framework.

GRAPHICAL ABSTRACT



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ABSTRACT

Life Cycle Assessment (LCA) is the most widely used method for the environmental evaluation of an anthropogenic system and its capabilities no longer need to be proved. However, several limitations have been pointed out by LCA scholars, including the lack of a temporal dimension. The objective of this study is to develop a dynamic approach for calculating the time dependent impacts of human toxicity and ecotoxicity within LCA. A new framework is proposed, which includes dynamic inventory and dynamic impact assessment. This study focuses on the dynamic fate model for substances in the environment, combined with the USEtox® model for toxicity assessment. The method takes into account the noisy and random nature of substance emissions in function of time, as in the real world, and uses a robust solver for the dynamic fate model resolution. No characterization factors are calculated. Instead, a current toxicity is calculated as a function of time i.e. the damage produced per unit of time, together with a time dependent cumulated toxicity, i.e. the total damage produced from time zero to a given time horizon. The latter can be compared with the results obtained by the conventional USEtox® method: their results converge for a very large time horizon (theoretically at infinity). Organic substances are found to disappear relatively rapidly from the environmental compartments (in the time period in which the emissions occur) while inorganic substances (i.e. metals) tend to persist far beyond the emission period.

1. Introduction

Life Cycle Assessment (LCA) is a method that calculates potential impacts associated with products, processes and services over their entire

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life cycle. ISO standards14040–14044 specify the guide for conducting a LCA study, i.e. the four operational steps: the definition of the goal and scope, the construction of the Life Cycle Inventory (LCI) based on mass and energy balances over the whole system life cycle, the Life Cycle Impact Assessment (LCIA) based on various impact calculation models, and the interpretation step (ISO 14040:2006, 2006; ISO 14044:2006, 2006). Currently LCA is the most widely used methodology for evaluating the environmental performance of any anthropogenic system. Its capabilities no longer need to be proved but several limitations have been pointed out by LCA scholars. Among them, the lack of a temporal dimension is intrinsically related to the LCA background. In a state of the art review, Finnveden et al. (2009) argued that "the LCI results are also typically unaccompanied by information about the temporal course of the emission or the resulting concentrations in the receiving environment… The impacts, which can be calculated under such boundary conditions, thus represent the sum of impacts from emissions released years ago, from emissions released today and from emissions released sometime in the future." Here, two levels can be distinguished, which are related to the LCI and LCIA calculation steps in LCA.

Another time dependent aspect concerns the prospective evolution of systems over time, e.g. changes at the level of technologies or economic sectors. Such issues are resolved either by considering different scenarios at different time periods or by a radically different methodology i.e. Consequential LCA. This aspect is beyond the scope of this work, which focuses on the time dependency of inventory and impacts in Attributional LCA. Including the time dimension in LCA models is a challenge that has been taken up only recently and very little research is currently in progress.

The time dimension in the LCI step has been studied by Beloin-Saint-Pierre et al. (2014). These authors developed an approach called Enhanced Structure Path Analysis, in which environmental interventions (elementary flows, i.e. emissions and natural resources consumed) are distributed over time by considering the convolution product between temporal distributions related to the processes flows and temporal distributions related to elementary flows. However, this method still lacks a full and complete relationship with an LCA database.

To the best of our knowledge, only Tiruta-Barna et al. (2016) have provided a dynamic method for LCI, dealing with the complex supply chain and processes presented in an LCA study and linking the method to traditional LCA tools (databases). It enables easier implementation of temporal characteristics by LCA practitioners. In a recent study, Shimako et al. (2016) applied this method to bioenergy production from microalgae by calculating temporal LCI and coupling them with a temporal model of climate change.

In fact most studies dealing with temporal aspects in LCA are dedicated to climate change impact. For example, Cherubini et al. (2011) performed a calculation considering dynamic carbon removal by the biomass, which is a step prior to the calculation of the climate change impact. However, dynamic results for midpoint or endpoint climate change impact are not given as the calculated results are integrated in a single unit-based index. Levasseur et al. (2010) and Kendall (2012) studied time dependency in climate change impact by calculating temporal characterization factors (CF) for substances and applying them to dynamic emissions. Nonetheless, the authors focused on the LCIA step and modelled simple systems that did not present a complex network of processes (and emissions) as most LCA studies do. The fixed time step and simple input of data for the LCI did not allow the application of a more complex and complete dynamic LCI in their methods.

In traditional LCA, the mass of the emitted substance is proportionally linked to the impact by using characterization factors as proportionality constants, even though the fate of chemicals in the environment is determined by time-dependent processes such as mass transfer and chemical reactions, which produce non-linear distributions of remaining mass of substances in environment. An infinite time horizon is generally used for the calculation of CF for toxicity impact. This assumption is important for taking all long lasting impacts into account. However, predicting impacts for eternity is also illogical. Also, the consideration of an infinite time horizon may hide the potential impacts occurring over short periods of time in the assessment of a system, because of the different nature of substances considered in the assessment (Huijbregts et al., 2001). The evidence of such shortcomings determined LCA scholars to consider CFs for different time horizons. For toxicity calculations, Huijbregts et al. (2000a, 2000b, 2001) proposed characterization factors based on the USES-LCA model, which comprises fate, exposure and effect calculations. CFs for 20, 100 and 500 years were calculated to be in accordance with the horizon times used in global warming potentials as it was considered that they provided a useful interval for policy decisions.

Another method, proposed by Hellweg et al. (2003), tackles the lack of time influence by applying a discounting method, which considers that toxicity impact diminishes with time. Calculation of time dependent CFs was also the approach proposed by Lebailly et al. (2014) by evaluating the dynamics of substance fate in the environment. They used the USEtox® model and calculated the dynamic behaviour of substances for an initial unit load of substance by solving the fate model for these particular conditions. These authors calculated characterization factors at different time steps (starting from the initial emission), and used them for a temporal evaluation of the freshwater ecotoxicity of metals. They applied this method to the use of zinc as a fertilizer in agriculture in order to assess the temporal behaviour of the impact. Although it implements dynamics in the fate calculation for metals, the study lacks information on organic substances and, also, it does not implement complex, temporal LCIs, which may present dynamic features related to unit processes and supply chains involved in the life cycle of processes.

In conventional LCA, several toxicity models have been developed and used over the years. The Life Cycle Initiative (http://www.lifecycleinitiative.org/) programme of the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) developed the USEtox® consensual toxicity model for LCA. USEtox® development was based on the comparison of several toxicity models and on experts' recommendations (Jolliet et al., 2006; Ligthart et al., 2004; McKone et al., 2006). USEtox® provides toxicity characterization factors for human toxicity and freshwater ecotoxicity that are recommended by LCA scholars.

The objective of this study is to develop a dynamic approach for calculating time dependent toxicity and ecotoxicity impacts within LCA. The USEtox® model was chosen and adapted to include the time dimension. In the first part of the paper, the theoretical development is presented. Then, the method is applied to a testbed case, i.e. grape production, in order to emphasize the results of the proposed framework. This testbed case was chosen for a variety of reasons: i) agriculture employs potentially hazardous substances in the different production stages, so a temporal analysis of the LCI and environmental impacts is justified; ii) various substances are emitted into the environment by agricultural operations, i.e. metals and organic compounds with different types of harmful effects on humans and ecosystems.

2. Method

2.1. Toxicity impact assessment – USEtox® method

This subsection gives a brief presentation of the principles of the toxicity calculation methods in LCA, particularly for the USEtox® method. The toxicity calculation methods usually follow the approach used in methods for assessing chemical risk to human and ecosystem health, based on three steps following the causal chain: i) evaluation of the fate of chemicals in the environment, which leads to different concentrations/quantities of substances in different environmental compartments; ii) evaluation of the exposure of humans or ecosystems to a given substance, and iii) the effects that exposure might have on human or ecosystem health (Hauschild et al., 2008). Specific modelling