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Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability

Instrument: Co-ordination Action
Thematic Priority: Sustainable Development Global Change and Ecosystem

Critical review of current research needs and limitations related to ISO-LCA practice

Annex 2 – Reports of the topics and approaches analized

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LIFE CYCLE INVENTORY

I/O and HYBRID APPROACHES

- Phisical Input-Output Analysis
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[Phase/Topic/Approach]

Life Cycle Inventory/IO and Hybrid LCI/Physical Input-Output Analysis

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* In the course of the developments in LCA during the last decade, the economic discipline of IOA has been re-discovered as a valuable knowledge-base for various issues in LCA including allocation, dynamics, computation and analytical techniques. Indeed, however accurate these are, process-specific LCA is based on an incomplete system, since not all inputs and outputs are covered by the process-based system. In contrast, the prime merit of national input-output tables is that they fully cover the economic activities within the national borders, so that the system is relatively complete. However, the completeness in terms of a system boundary is acquired at the cost of poor resolution in terms of industry classification, as well as several years of base year difference and the loss of process specificity. The use of monetary input-output analysis integrated into/in combination with LCA framework has already been described, as a tool aiming at overcoming the LCA limitations like system boundaries and data availability. But we should consider that, among the several limitation represented by the application of the MIO framework, value in IOA implies that the analytical results obtained may be vulnerable to price fluctuations and non homogeneity (Suh, 2007); thus, important contribution may come from the physical input output (PIO) approach . Physical input-output tables (PIOTs) describe the flows of material and energy within the economic system and between the economic system and the natural environment [Wiedmann et al., 2006]. While the MIOT describes only internal flows of the economy, however, the PIOT also reports the exchanges taking place with the natural environment. Unlike the whole economy, individual industries have as sources of matter not only extraction and imports, but also other industries of the same economic system. Similarly, the outlets of each industry's production are not only the environment, the stocks and other economies but again other industries, and also consumers [Femia & Moll, 2005]. The PIOT is parallel to, and fully consistent with traditional MIOT but all flows are reported in physical units. They describe changes in the natural environment caused by human activities like using of natural assets as source of raw materials and as sink for residuals, on which is drawn less attention in traditional IOT because of the insufficient possibilities of a monetary valuation [2]. The economy is depicted as being embedded in the environment that is represented by the flows of primary inputs into the economy and waste flows out of the economy. A PIOT is not simply a unit conversion of a MIOT and cannot be derived only by multiplying the MIOT with a vector of prices per tons for each sector. This is mainly due to aggregation of non homogeneous products/sectors into one category. The higher the aggregation level, the more notable become the differences between MIOT and PIOT.

Deviations/developments with respect to ISO standard.

We cannot say anything of precise with reference to the ISO standard since PIOT applications described in the papers selected do not refer to possible integration with or combination to LCA. But in principle, we could take into account the assumption made for the MIOT, because PIOT is parallel to and fully consistent with traditional monetary IOT.

ISO series generally define the framework without specifying which computation method is to be used. Therefore, both LCI computation methods using process flow diagram and matrix representation are considered to be compatible with ISO standards. Methods that utilise IOA can be considered differently. According to ISO, LCA is compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Thus, what is so-called cradle-to-gate analysis, which is the case for IO-based LCI is not an LCA study in strict sense of ISO standards, since it does not contain the use and disposal phase within its scope. This implies that IO-based inventory alone is not considered as ISO compatible LCI in general sense.

However, if combined with inventory result from other stages of life cycle, as is the case for hybrid methods, the scope of the analysis is fully in line with the ISO standard. Then the ISO compliance of introducing external model such as IO accounts can be questioned for hybrid methods [5].

ISO 14041, clause 4.5. 'Modelling product systems' mentioned about the practical difficulties of describing all the relationships between all the unit processes in a product system and opens up possibilities of using models to describe key elements of physical system. Hence, in principle, there are no restrictions in using IO accounts to describe upstream process relationships if the model and assumptions are clearly noted. [5]

Although current ISO standards are based on process analysis, according to clause 4.5 of ISO 14041, they do not preclude an input-output model to be used in order to describe (part of) a product system. Moreover, as shown in the previous section, selecting a system boundary in compliance with ISO standards is, in practice, impossible without using the input-output model, and hybrid techniques using input-output analysis can therefore form a central element of ISO-compatible system boundary selection practices

Hence, input-output techniques should be introduced into current ISO standards through hybrid frameworks [5]

The selected papers don't describe the process of integration of PIOT into the LCA framework: the debate surrounding PIOTs is still very young and has so far mainly focussed on methodological issues surrounding the treatment of wastes in physical input-output models, as described in the following.

These first applications represent the starting point for a deeper evaluation of the role of PIOT applied to LCA framework.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. **General references**

- [5] S.Suh, G.Huppes, **Methods for Life Cycle Inventory of a product**, Journal of Cleaner Production 13 (687-697), 2005.

2. **Specific references**

- [1] K.Hubacek, S.Giljum, **Applying physical input-output analysis to estimate land appropriation (ecological footprint) of international trade activities**, Ecological Economics 44 (2003), 137-151
- [2] S.Suh, **A note on the calculus for physical input-output analysis and its application to land appropriation of international trade activities**, Ecological Economics 48 (2004), 9-17
- [3] S.Giljum, K.Hubacek, L.Sun, **Beyond the simple material balance: a reply to Sangwon Suh's note on physical input-output analysis**, Ecological Economics 48 2004), 19-22
- [4] H.Weisz, F.Duchin, **Physical and monetary input-output analysis: what makes the difference?**, Ecological Economics 57 (2006), 534-541

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

The reference [4] is our guiding paper since it summarises the debate raised by [1] on the application of PIOT to calculate the amount of land appropriation due to exports (so far all land related studies presented used MIOTs for attributing land to the different categories of final demand).
The authors in [1] analysed the use of input output models based on coefficient matrices derived from input-output tables in mass units (PIOTs for EU-15) for the computation of direct and indirect land requirements for the production of exports from EU-15 to the rest of the world and compared them to input-output models using coefficient matrices derived from monetary tables (MIOTs) and a vector of physical factor inputs per unit of output [4], arriving at substantially different numerical results concerning overall and sectoral land appropriation for exports.
The land use data has been integrated from a GIS database into a PIOT.

They suggested applying PIOTs for two main reasons:

- The most material intensive sectors are also the sectors with the highest land appropriation
- PIOA illustrates land appropriation in relation to the material flows of each the sectors, which is more appropriate from the point of view of environmental pressures than the land appropriation in relation to monetary flows of a MIOT.

In reply to this paper [2] demonstrated that waste is misspecified in the PIOT used by [1] and that this misspecification makes the PIOT inconsistent in terms of mass balance and as a consequence is a flawed physical model. Furthermore, it violates the fundamental assumption of input-output economics that each sector produces a homogeneous characteristic output. [2] proposed two alternative physical models which make use of PIOTs that consistently apply the mass balance assumption and comply with standard assumptions of input-output analysis, arriving at quite different

results from [1].
[2] determined that major differences in results obtained with Physical IO models and an extended monetary model are actually due to differences in the treatment of waste in PIOT and not to a superiority of the physical model. Furthermore, the differences between a monetary and a physical model may be relatively small if the treatment of waste is consistent in terms of mass balance and the underlying assumptions reasonably reflect real world conditions.

In particular, according to [2], in [1] the treatment of waste was inconsistent due to an inappropriate allocation of production waste in the PIOT because the wastes generated by each sector were added to its final deliveries in proportion to its use of primary inputs.

In contradiction with [2], [4] says that the basic reason for the differences in results is that both the MIOT and the PIOT they used contradict the assumption of a unique price for the characteristic output of a given industry.
The authors in [4] show that a basic static input-output model using a coefficient matrix derived from a MIOT is strictly equivalent to one where the coefficient matrix derived from an input-output table in physical unit, provided that the assumption of unique sectoral prices is satisfied.
They argue that the conceptual root of the differences in outcomes is explained by the fact that the two models are related by a price matrix rather than a price vector (i.e. single price for the characteristic output of each sector). That is, different unit prices are being assumed for different purchasers of a given sector's output.

Main advantages

The main advantages highlighted:

- major applicability of matrices with physical units for "prospective" analyses. When constructed for the past, these matrices will be exactly equivalent to monetised matrices given the assumption of a homogeneous price for each sector's output. When projected coefficient matrices for the future are required they are more readily constructed in physical units rather than monetary units, since the latter would require projections of future changes in relative prices as well as future changes in technologies [4].
- PIOTS allow a more accurate approximation to physical flows in the economy than analyses based on a MIOT. Especially for land related studies, using a physical multiplier is more appropriate, since land appropriation and material intensity among sectors are highly correlated [1]
- Using physical quantities, the accounting framework can be free from the price non homogeneity and fluctuation and different taxation schemes and subsidies, which may distort the actual physical flows between industries when a monetary unit alone is considered. However, for many industries, the monetary flows are more important than the physical flows in describing them [2].
- System boundary completeness.
- PIOT offers the information necessary to answer many of the questions concerning the direct contribution of the individual industries to environmental pressures [Femia & Moll, 2005].

Open questions

The weakness highlighted below refer to the PIOT methodology and not to the integration of PIOT and LCA.
Moreover, the overcoming of these obstacle will ensure a more practicability of the methodology, especially in terms of integration with other methodologies and data.

- The debate surrounding PIOTs is still very young and has so far mainly focussed on methodological issues surrounding the treatment of wastes in physical input-output models [Suh, 2007]
- Only a few PIOTs have been compiled to date and no standard methods for the compilation of PIOTs have yet been developed due to the relatively young history of physical input-output accounting.
  That means that it is highly likely that not only the factor input tables but also the interindustry and final demand tables of existing PIOTs differ in conventions and definitions both from each other and from MIOT, which have become much more standardised in the course of several decades of experience in compilation [4].
  The authors suggest also that IO coefficient matrices should me measured in mixed units, not in a single, aggregated mass unit nor in a single, aggregated monetary unit but rather the most appropriate unit for measuring the characteristic output of each sector.
- The main obstacle to the application of the approach is the very limited and restrictive data situation; thus, the results can only be regarded as a first and very rough estimation [1]. PIOTs have so far been compiled only for a very small number of countries.
- The major methodological weakness is that, unlike material flow analysis on the national level, no standardised methodology has jet been agreed upon. Existing PIOTs differ with regard to the number of sector reported, the disaggregation into producyt groups, as well as the inclusion or exclusion of specific materials. Moreover, a discussion about which materials should be separately balanced is currently missing at the theoretical level (in particular, the inclusion or exclusion of water and air dramatically changes the structure of the interindustry table and as a consequence also the results of input-output analysis based on these tables) [1]
- Due to the methodological limitation, it is a case specific question whether the benefits of using a PIOT outweigh its disadvantages. [2]
- Even though PIOTs can also be established on lower aggregation levels, this is an even more work intensive task and not always very likely to happen [2].

In addition to these weakness, we could assume that the majority of the limitations often referred to as obstacle of IOA for use in LCA, already described in the IO-LCA scheme, are still valid:

- Linear approximation in technical coefficients
- Static analysis
- It assumes that the environmental burden coefficients of imports are also well-approximated by the corresponding domestic industry sector. This may introduce errors in analyses of products with high import content and very different foreign production technologies.

- Aggregation of IO-data over different producers and over different products supplied by one industry
- Uncertainties of basic source data due to sampling and reporting errors

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

The main obstacle is that no standardised methodology has jet been agreed upon. Existing PIOTs differ with regard to the number of sector reported, the disaggregation into product groups, as well as the inclusion or exclusion of specific materials. Moreover, a discussion about which materials should be separately balanced is currently missing at the theoretical level (in particular, the inclusion (or exclusion) of water and air dramatically changes the structure of the interindustry table and as a consequence also the results of input-output analysis based on these tables) [1]
Concepts, definitions and classifications are a theoretical reference point only. Flows from/to the natural environment do not have a monetary counterpart so that there is no reference rule in National Accounting for their identification/classification.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analised and the development trends.

Due to the relatively young history of physical input-output accounting, the R&D needs highlighted by the authors are numerous and refer to the following aspects:

- Investigating land appropriation in international trade is a new and challenging research topic, in which only a few exemplary studies have been presented so far. While the methodology for accounting material flows is already internationally standardized within the framework of economy-wide material flow accounting, this standardization is so far completely missing with regard to methodologies assessing direct and indirect land appropriation by applying input-output analysis [1].
- The main obstacle to the application of the approach is the very limited and restrictive data situation. PIOTs have so far been compiled only for a very small number of countries. Furthermore, these already published input-output tables differ with regard to the level of sectoral aggregation as well as the consideration of different material groups. In particular, the inclusion (or exclusion) of water and air dramatically changes the structure of the interindustry table and as a consequence also the results of input-output analysis based on these tables [1].

- Further development of PIOTs should focus on the definition of a standardised methodological procedure for setting up physical accounts on the national as well as supranational level.
- For the application of physical input-output analysis on a broader level, much more standardised primary data describing the physical structure of economic systems is necessary. Only then it will be clarified whether or not this methodology is an adequate approach for estimating land use pressures of economic activities [1].
- Developments in basic data and statistics [2]
- The mass balance principle so far has been related to national accounts. However, balancing inputs and outputs for the whole economy is still a challenging issue [2].
- Both theoretical and practical applications of PIOTs are needed for further development [2]

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

The theme of "integrated analysis" is a good perspective for the future and could be the correct approach in order to take into consideration the aspects of complexity and comprehensiveness of a broader and deeper evaluation system, but, also in this case, the problems of complexity and time-consuming of analysis exist.

The structure of the input-output is very flexible and allows for integration with various other methodologies and data but, regarding PIOTs, before investing resources in their development, a deeper evaluation should be done on the effective use of the PIOTs data, according to the different potential users.
Indeed, PIOT data are very detailed and as such they don't seem to be very useful for policy makers. Therefore, summary tools and analytical uses are essential to justify the compilation work and to communicate the results of PIOTs.

[Phase/Topic/Approach]
Life Cycle Inventory/IO and Hybrid LCI/IO LCA

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

Life Cycle Inventory (LCI) is the most time and resource consuming phase in Life Cycle Assessment (LCA). Various options, including streamlining techniques, have been discussed to reduce the amount of effort involved in LCI and maintain the quality of the results at the same time.
Recent studies have shown how economic Input-Output Analysis (IOA) may indicate useful directions for these attempts, since it is a top-down technique and it allows the entire economy to be considered as a system under study. In fact, all processes in an economy are directly or indirectly connected with each other. In that sense, process analysis based LCI is always truncated to a certain degree, since it is practically not viable to collect process-specific data for the whole economy, and this problem has led the use of IOA in LCI.
Thus input-output tables with additional environmental data can supply environmental information on economic activities based on a relatively complete system, while requiring relatively little time and resources.

Deviations/developments with respect to ISO standard.
ISO series generally define the framework without specifying which computation method is to be used. Therefore, both LCI computation methods using process flow diagram and matrix representation are considered to be compatible with ISO standards. Methods that utilise IOA can be considered differently. According to ISO, LCA is compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Thus, what is so-called cradle-to-gate analysis, which is the case for IO-based LCI is not an LCA study in strict sense of ISO standards, since it does not contain the use and disposal phase within its scope. This implies that IO-based inventory alone is not considered as ISO compatible LCI in general sense.
However, if combined with inventory result from other stages of life cycle, as is the case for hybrid methods, the scope of the analysis is fully in line with the ISO standard. [4].

Relevant references

The relevant references should be organised along two lines:
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- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. **General references**

- [3]. S.Suh, **Functions, commodities and environmental impacts in an ecological-economic model**, Ecological Economics 48 (451-467), 2004.
- [4] S.Suh, G.Huppes, **Methods for Life Cycle Inventory of a product**, Journal of Cleaner Production 13 (687-697), 2005.
- [8] A.M. Nielsen, B. Weidema, **Input/Output analysis - Shortcuts to life cycle data**, Environmental Project No. 581 2001

2. **Specific references**

- [1] S. Joshi, **Product Environmental Life-Cycle Assessment using Input-Output Techniques**, Journal of Industrial Ecology 3 (2-3), 2000.
- [2] J.Munksgaard, M.Wier, M.Lenzen and C.Dey, **Using input-output analysis to measure the environmental pressure of consumption at different spatial levels**, Journal of Industrial Ecology 9 (1-2), 2005.
- [5] G. Cicas, C.T. Hendrickson, A. Horvath, H.S.Matthews, **A Regional Version of a US Economic Input-Output Life Cycle Assessment Model**, Int J LCA 12 (6) 365-372, 2007.
- [6] I.Yi, N.Itsubo, A.Inaba, K.Matsumoto, **Development of the Interregional I/O based LCA Method Considering Region-Specifics of Indirect Effects in Regional Evaluation**, Int J LCA 12 (6) 353-364, 2007.
- [7] S.Suh, G.Huppes, **Missing Inventory Estimation Tool Using Extended Input-Output Analysis**, Int J LCA 7 (3) 134-140, 2002.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

In the course of the developments in LCA during the last decade, the economic discipline of IOA has been re-discovered as a valuable knowledge-base for various issues in LCA including allocation, dynamics, computation and analytical techniques.
Indeed, however accurate these are, process-specific LCA is based on an incomplete system, since not all inputs and outputs are covered by the process-based system. In contrast, the prime merit of national input-output tables is that they fully cover the economic activities within the national borders, so that the system is relatively complete. However, the completeness in terms of a system boundary is acquired at the cost of poor resolution in terms of industry classification, as well as several years of base year difference and the loss of process specificity. Thus, operational tools are required to combine process-based LCA with IOA, preferably using only the advantages of the two [7].

Input-Output Analysis (IOA) is an economic discipline that deals with the interdependencies between and within industries and households through producing and consuming products and services (in terms of monetary transaction flows), and covering the distribution of labour income and profits and investment of capitals.

The input-output model assumes that each industry consumes outputs of various other industries in fixed ratios in order to produce its own unique

and distinct output. Environmental extensions of IOA can easily be made by assuming that the amount of environmental intervention generated by an industry is proportional to the amount of output of the industry and the identity of the environmental interventions and the ratio between them are fixed. Since all transaction activities within a country are, in principle, recorded in the national IO table, it is often argued that the system boundary of an IO-based LCI is generally more complete than that of process analysis.
If input-output tables are completed with additional environmental data, they can supply environmental information on economic activities based on a relatively complete system, while requiring relatively little time and resources.
Several approaches have been proposed to combine the strengths of process-specific LCA and IOA: among which the Missing Inventory Estimation Tool (MIET) has been developed, to support process-specific LCA by enlarging the system boundary to include an entire national economy and to minimise the defects of IOA. MIET has been developed using the US input-output table and various environmental statistics based on an explicit distinction between commodity and industry output Entering the estimated price of a missing flow either in the producer's or the consumer's price. MIET supplies inventory results for missing flows as well as characterised results, using around 100 different impact assessment methods that are in common use [7].
(last version of MIET: 2004)

In Figure 1 [4] the main differences between the LCI based on process analysis and the Input-output based LCI are summarised.
Main advantages and shortcomings are reported in the following sections.

Comparison between methods for LCI compilation

	LCI based on process analysis		Input–output based LCI	Hybrid LCI		
	Process flow diagram	Matrix representation		Tiered hybrid analysis	IO-based hybrid analysis	Integrated hybrid analysis
Data requirements	Commodity and environmental flows per process	Commodity and environmental flows per process	Commodity and environmental flows per sector	Commodity and environmental flows per sector and process	Commodity and environmental. flows per sector and process-based LCIs	Commodity and environmental. Flows per sector and process
Uncertainty of source data	Low	Low	Medium to high	Depends[a]	Depends[a]	Low
Upstream system boundary	Medium to poor	Medium to poor	Complete	Complete	Complete	Complete
Technological system boundary	Complete	Complete	Medium to poor	Depends[a]	Depends[a]	Complete
Geographical system boundary	Not limited	Not limited	Domestic activities only	Depends[a]	Domestic activities only	Not limited
Applicable analytical tools	Rare	Abundant, e.g. in Heijungs and Suh [10]	Rare	Rare	Abundant (analytical tools for IOA disaggregated IO part)	Abundant (both analytical tools for IOA and LCA for entire system)
Time- and labour intensity	High	High	Low, if environm. data available	Depends[a]	Depends[a]	High
Simplicity of application	Simple	Simple	Simple	Simple	Complex	Complex
Required computational tools	Excel or similar (no matrix inversion)	Matrix inversion (e.g. MatLab, Mathematica.)	Excel or similar	Excel or similar	Matrix inversion (e.g. MatLab, Mathematica.)	Matrix inversion (e.g. MatLab, Mathematica.)
Available software tools	Most available LCA software tools	CMLCA	MIET, EIOLCA	MIET+LCA software tool	–	CMLCA

[a] Dependant upon the shares of process analysis and IO-based system.

Figure 1 - Comparison between methods for LCI compilation [4]

Several case studies exist that apply the IOA framework to LCA, and new approaches are moving towards the setting out of input-output analysis combined with LCA for analysis with a regional resolution. The main feature of region-based LCA is that it can consider the structural and environmental characteristics of regions that are directly and indirectly affected by regional activity. Region-based LCA, meanwhile, which includes a lot of Product LCA, requires a greater amount of time, cost, and work on inventory analysis.

Starting from the consideration that both process LCA and EIO-LCA have been important decision making tools, neither of them has been able to perform regional and state level analyses efficiently, [5] and [6] proposed two different approaches to the problem.
In [5] a regional US LCA model, Regional Economic Input-Output Analysis-based Life-cycle Assessment (REIO-LCA) has been developed: it enables regional (multi-state in the US) and state- level analyses and allows decision-makers to estimate both the economic and the environmental implications of changes in a regional economy. The national model is based on the US 491 by 491economic input-output model, and uses sectoral energy consumption and emission factors to approximate the environmental effects of production and services.

The model proposed in [6] is a region-based LCA method which can, by using IO table, reflect the differences of regional characteristics for direct and indirect effects of regional activities. The Life Cycle Region-specific Assessment Method (LCRAM) is
a site-specific LCA method that consists of a regional database and an analysis method (EIOM).
In order to reflect the regional characteristics, including structural (regional production and consumption, interregional trade, and the structure of energy consumption) and environmental features (geographical location, climate, natural conditions, and population density), first a regional database has been constructed. This includes an Interregional Trade Matrix (ITM), Regional Environmental Burden Coefficients (REBC), and Regional Damage Factors (RDF). Second, for considering the regional characteristics by using the regional database to the each region, it is a necessary to identify the environmental burden emitting regions (Emitting Regions) of indirect effects due to regional activity. To do this, the Expanded Interregional Input Output Method (EIOM) has been developed, to take the place of the Multi-Regional Input Output method (Multi-Regional IO) by applying the Two-Regional IO method and the ITM.

Main advantages

The advantages of combining LCA with IOA are summarised below:

- IO-LCA takes a top-down approach and treats the whole economy as the boundary of analysis, methods that utilises IOA show higher completeness regarding upstream system boundary, while process-based analyses are generally superior for other system boundaries
- IO-based LCI can provide information on the environmental aspects of a commodity on the basis of a reasonably complete system boundary using less resources and time [4]
- compared to process-based analyses, methods that utilise IOA generally show smaller data requirements, that is assuming that IO-based LCIs are already available [4].

Regarding the regional model, it is highlighted that a region-based LCA could properly reflect regional characteristics, because the results of regional evaluations noticeably differ among the regions.

The main advantage of LCRAM model are [6]:

- its ability to reflect the characteristics of each region for the direct and indirect effects, through all stages of activity;
- its ability to quantify the interdependent effects and transportation-effects due to interaction among the regions that have been not reflected in conventional region-based LCA.
- It enables users to apply a regional evaluation for many more regions and the details of industry classification that has been impossible to reflect with an existing Multi-Regional IO method.

Open questions

Despite its strengthens, IO-LCA it is still subjected to several limitations [1]:

- The product of interest is approximated by its commodity sector, that is a broad aggregate that includes a large number of products;
- IOA method itself can provide LCIs only for pre-consumer stages of the product life cycle, while the rest of the product life cycle stages are outside the system boundary of IOA [4].
- Linear approximation in technical coefficients
- Static analysis
- It assumes that the environmental burden coefficients of imports are also well-approximated by the corresponding domestic industry sector. This may introduce errors in analyses of products with high import content and very different foreign production technologies. For a commodity of which the product system heavily relies on imports and newly developed technologies, however, applicability of IO based LCI methods is rather limited [4].
- Uncertainties, raising from the following sources [8]:
  - uncertainties of basic source data due to sampling and reporting errors
  - assumption that foreign industries producing competing imports exhibit the same factor inputs as domestic industries,
  - assumption that foreign industries are perfectly homogeneous,
  - assumption of proportionality between monetary and physical flow,
  - aggregation of IO-data over different producers and (over different products supplied by one industry.
- Data of IO-based LCI is normally older than process-based one, since it takes 1e5 years to publish IO tables based on industry survey [4].
- There are inconsistencies in the industry classification system between the input-output tables and environmental emission data: the input-output table is generally calculated on the basis of producer's prices, but the price information that LCA practitioners obtain from procurement records refers to consumer's prices. By using consumer's prices, input-output based LCIs will always result in underestimation. Calculation of consumer's prices requires data on retail and wholesale trade margins and transportation cost, which is not generally known to purchasers [7].

The system that IOA and LCA deal with have a lot in common. Despite the similarities, however, the systems that LCA deals with also have more than a few important differences: there are no annual 'transaction' records available, quantities are in physical units, it concerns the direction of physical flows instead of that of money flows, it contains use and end-of-life stages, it primarily concerns the function of a system etc. These differences provided enough reasons for LCA researchers to dependently develop slightly different computational structures from that of IOA [3]. Those unique features indeed make it difficult for an LCA to be directly integrated with IOA in current form.

Regarding the regional model, limitations are due to the limited number of environmental burdens considered, due to lack of regional database.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

The two main aspects of interest are data availability and software tools.

- Data availability and the lack of consistency among the different input-output table available (due to the different resolution) hamper the consistency of the methods. Data of IO-based LCI is normally older than process-based one, since it takes 1e5 years to publish IO tables based on industry survey.
- Regarding tools and database, there are several computational tools and databases. Economic Input-Output Life Cycle Assessment (EIOLCA) is a web-based IO-based inventory calculator that provides the amount of water usage, conventional pollutants emission, global warming gas releases and toxic pollutants emissions per sector output in monetary unit. Abundant analytical tools from both matrix representation of product system as well as IOA can be applied to integrated hybrid analysis. MIET (Missing Inventory Estimation Tool) is a software tool for tiered hybrid analysis to provide both inventory and environmental impact scores of the processes for which more reliable data are not available. MIET has been developed using the US input-output table and various environmental statistics based on an explicit distinction between commodity and industry output Entering the estimated price of a missing flow either in the producer's or the consumer's price. MIET supplies inventory results for missing flows as well as characterised results, using around 100 different impact assessment methods that are in common use [7].(last version of MIET: 2004)

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

3rd Part: COMMENTS

R&D needs and trends
One of the main lines of recent methodological development is the hybrid method [7], intended as a framework in which detailed unit processes level information in physical quantities is fully incorporated into the input-output model, which in turn represents the surrounding economy that embeds the process-based system. Another recommended direction of research is building reliable and publicly available environmental intervention databases for the input–output table. Although a number of national and international projects are in progress to incorporate environmental variables in national accounts the number of pollutants covered and the resolution of the commodity classification are rather limited for LCA purposes. This would be particularly useful for the analysis at regional level, hampered by the lack of reginal data on production and environmental emissions. For the LCRAM model, a possible improvement could be represented by combining it with WIO (Waste Input Output model), in order to grasp circulation for the products and waste between basic industries and waste management industries can be applied.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. Despite the advantages of using IO based LCI, due to the higher completeness regarding upstream system boundary and to the support in overcoming the problem of lack of data for all the processes analysed, IO based LCI could be suggested only as a first proxy. No research lines seem to exist on uncertainty factors for IO data but this will be of great interest, due to the repercussions of the methodology (in terms on Integrated Hybrid Analysis) in large scale application. Furthermore, the high level of aggregation of sector represents an obstacle to the fully integration between the IO and LCA structure. The integrated hybrid analysis could be a good perspective for the future but also in this case, the problem of complexity and time-consuming of analysis still exist: efforts should be concentrated towards the simplification of the analysis in order to make it more practical.

[Phase/Topic/Approach]

Life Cycle Inventory/IO and Hybrid LCI/Hybrid LCI

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* Life Cycle Inventory (LCI) is the most time and resource consuming phase in Life Cycle Assessment (LCA). Two basic methods are used in practice for compiling an LCI: process analysis and input-output analysis. Process analysis can be performed both with the process flow diagram approach and the use of matrix annotation. In a process flow diagram approach, process-specific data for each process in a product system are compiled and remaining successive upstream inputs are considered to have negligible impact, so that the branches of the "process tree" come to a finite end. In this approach both the number of processes that are involved in the product system and the order of upstream processes are limited. Thus, an LCI compiled using a process flow diagram exhibits inherent system incompleteness. In the approach using matrix annotation, each column of the technology matrix is occupied by a vector of inputs and outputs per unit of operation time of each process, including the use and disposal phase. The LCI is calculated by inverting the technology matrix and multiplying it by an environmental matrix. This algorithm has advantages in representing infinite orders of upstream process relations, which cannot be achieved using the process flow diagram approach. However, those relations are limited to the processes that are included within the chosen system boundary; thus, the number of approaches involved is limited and inclusion or exclusion is decided on the basis of subjective choices. In contrast, economic input-output analysis is a top-down technique that uses sector monetary transaction matrixes describing complex interdependencies of industries within a national economy and is a suitable approach for LCI.[2] It allows the entire economy to be considered as a system under study: in fact, all processes in an economy are directly or indirectly connected with each other. In that sense, process analysis based LCI is always truncated to a certain degree, since it is practically not viable to collect process-specific data for the whole economy, and this problem has led the use of IOA in LCI. Thus input-output tables with additional environmental data can supply environmental information on economic activities based on a relatively complete system, while requiring relatively little time and resources. Attempts to overcome the disadvantages, while combining the advantages of both methods in LCA, are generally referred to as Hybrid LCA. The term "hybrid" is used in two different cases: one is for the use of both physical and monetary units and the other is for the integration of sector and process level data [2].

Deviations/developments with respect to ISO standard.

ISO series generally define the framework without specifying which computation method is to be used. Therefore, both LCI computation methods using process flow diagram and matrix representation are considered to be compatible with ISO standards. Methods that utilise IOA can be considered differently. According to ISO, LCA is compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Thus, what is so-called cradle-to-gate analysis, which is the case for IO-based LCI is not an LCA study in strict sense of ISO standards, since it does not contain the use and disposal phase within its scope. This implies that IO-based inventory alone is not considered as ISO compatible LCI in general sense.

However, if combined with inventory result from other stages of life cycle, as is the case for hybrid methods, the scope of the analysis is fully in line with the ISO standard. Then the ISO compliance of introducing external model such as IO accounts can be questioned for hybrid methods [1].

ISO 14041, clause 4.5. 'Modelling product systems' mentioned about the practical difficulties of describing all the relationships between all the unit processes in a product system and opens up possibilities of using models to describe key elements of physical system [40]. Hence, in principle, there are no restrictions in using IO accounts to describe upstream process relationships if the model and assumptions are clearly noted. [1]

Although current ISO standards are based on process analysis, according to clause 4.5 of ISO 14041, they do not preclude an input-output model to be used in order to describe (part of) a product system. Moreover, as shown in the previous section, selecting a system boundary in compliance with ISO standards is, in practice, impossible without using the input-output model, and hybrid techniques using input-output analysis can therefore form a central element of ISO-compatible system boundary selection practices

Hence, input-output techniques should be introduced into current ISO standards through hybrid frameworks [1]

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. General references

- [1] S.Suh, G.Huppes, **Methods for Life Cycle Inventory of a product**, Journal of Cleaner Production 13 (687-697), 2005.
- [5] A.M. Nielsen, B. Weidema, **Input/Output analysis - Shortcuts to life cycle data**, Environmental Project No. 581 2001
- [6] S. Joshi, **Product Environmental Life-Cycle Assessment using Input-Output Techniques**, Journal of Industrial Ecology 3 (2-3), 2000.

2. Specific references

- [2] S.Suh, M-Lenzen, G.Treloar, H.Hondo, A.Horvath, G.Huppes, O.Jolliet, U.Klann, W.Krewitt, Y.Moriguchi, J.Munksgaard, G.Norris, **System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches**, Environmental Science & Technology, vol. 38, No. 3, 2004.
- [3]. S.Suh, **Functions, commodities and environmental impacts in an ecological-economic model**, Ecological Economics 48 (451-467), 2004.

	- [4] M.Lenzen, **A guide for compiling inventories in hybrid life-cycle assessment: some Australian results**, Journal of Cleaner Production 10, 545-572, 2002.
	- [7] S.Suh, G.Huppes, **Missing Inventory Estimation Tool Using Extended Input-Output Analysis**, Int J LCA 7 (3) 134-140, 2002.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. In the course of the developments in LCA during the last decade, the economic discipline of IOA has been re-discovered as a valuable knowledge-base for various issues in LCA including allocation, dynamics, computation and analytical techniques. Indeed, however accurate these are, process-specific LCA is based on an incomplete system, since not all inputs and outputs are covered by the process-based system. In contrast, the prime merit of national input-output tables is that they fully cover the economic activities within the national borders, so that the system is relatively complete. However, the completeness in terms of a system boundary is acquired at the cost of poor resolution in terms of industry classification, as well as several years of base year difference and the loss of process specificity. Input-Output Analysis (IOA) is an economic discipline that deals with the interdependencies between and within industries and households through producing and consuming products and services (in terms of monetary transaction flows), and covering the distribution of labour income and profits and investment of capitals. The input-output model assumes that each industry consumes outputs of various other industries in fixed ratios in order to produce its own unique and distinct output. Environmental extensions of IOA can easily be made by assuming that the amount of environmental intervention generated by an industry is proportional to the amount of output of the industry and the identity of the environmental interventions and the ratio between them are fixed. Since all transaction activities within a country are, in principle, recorded in the national IO table, it is often argued that the system boundary of an IO-based LCI is generally more complete than that of process analysis. If input-output tables are completed with additional environmental data, they can supply environmental information on economic activities based on a relatively complete system, while requiring relatively little time and resources. Official input-output table cover the entire economy using detailed government statistics that are often inaccessible to the general public. Due to the wide coverage of the table and the use of enormous amount of data that are often sensitive, IOTs have to be aggregated, and it often takes a few years to process the data before a table is officially published. Therefore, relying only on IO data for detailed LCA is not desirable, which is certainly a limitation of IO-LCA. Using the hybrid approach, however, these problems can be resolved efficiently: sector resolution is selectively gained to the level necessary for the foreground system using detailed, process-specific information, while the background system still covers the entire national economy represented by

an IOT. The possibility of combining the two systems with different resolution in a consistent framework offers a great advantage for both the IO and LCA sides (Suh).

So far hybrid analysis has been adopted to LCI compilation in different ways, that will be distinguished here as tiered hybrid analysis; IO-based hybrid analysis; and integrated hybrid analysis [1].

Tiered hybrid analysis utilises process-based analysis for the use and disposal phase as well as for several important upstream processes, and then the remaining higher order input requirements (e.g., materials extraction and manufacturing of raw materials) are imported from an IO-based LCI. Tiered hybrid analysis can be performed simply by adding IO-based LCIs to the process-based LCI result.

Tiered hybrid analysis provides reasonably complete and relatively fast inventory results. However, the following aspects should be considered:

- the border between process-based system and IO-based system should be carefully selected, since significant error can be introduced if important processes are modelled using the aggregated IO information.
- there are some double-counting problems in tiered hybrid analysis. In principle, the commodity flows of the process-based system are already included in the IO table, so that those portions should be subtracted from the IO part.
- the tiered hybrid model deals with the process-based system and the IO-based system separately, so that the interaction between them cannot be assessed in systematic way. For example, the effects of different options at the end of the product life cycle, which can change the industry-interdependence by supplying materials or energy to the IO-based system, cannot be properly modelled using the tiered hybrid method.

The **IO-based hybrid approach** is carried out by disaggregating industry sectors in the IO table in case more detailed sectoral monetary data are available (in this way, detailed process-specific data can be fully utilized without double counting), while the tiered hybrid method is applied for the use and end-of-life stages of the product life cycle. Inventory results for the remaining stages of the product life cycle, including use and disposal, should be added manually. Since this approach partly utilises the tiered hybrid method, the interactive relationship between pre-consumer stages and the rest of the product life cycle is difficult to model.

The disaggregation procedure is the most essential part of IO-based hybrid approach. Joshi suggested to use existing LCIs for information sources of detailed input requirements, sales structure and environmental intervention.

The **Integrate hybrid analysis model** [2] is a hybrid model that integrates the computational structure of an LCA with an input-output analysis within a consistent mathematical framework throughout the whole life-cycle of a product. Integrated hybrids analysis relies on full process analysis, and then utilises IO-based LCI only for cut-offs

Indeed, so far the results of a hybrid analysis has been the simple sum of process analysis and input-output based analysis. In other words, the computational structure of LCA has not been fully integrated with that of IOA: hybrid utilised matrix representation only for the input–output part, while process analysis is dealt with separately by using a process flow diagram approach. This separation in the computational structure imposes several constraints on hybrid models.

In the integrated hybrid analysis model, the process-based system is represented in a technology matrix by physical units per unit operation time of each process while the input-output system is represented by monetary units. This model is derived from a make and use framework (*the format of the input-output table used is the commodity by commodity format. The industry by industry format is less applicable in the current model, due to the aggregation of commodities in an industry output. Moreover, the industry that produces an input material for a process is generally less fully known to the LCA practitioners than the commodity itself*) for both the process-based and the input-output-based system by linking them through flows crossing the border between the two systems. Using the integrated hybrid analysis, detailed unit process level information in physical quantities is fully incorporated into the input-output model, which in turn represents the surrounding economy that embeds the process-based system. This approach enables a consistent allocation method throughout the hybrid system and avoids double counting by subtracting the commodity flows in a process-based system from the input-output system.

An application of this model to a case study shows that on average, the results from hybrid LCA and input-output LCA were higher than the process-based results.

Starting from the consideration that information from IO accounts is less reliable than process-specific data - *due to temporal differences between IO data and current process operation, aggregation, import assumptions etc.* - the IO table is interconnected with the matrix representation of the physical product system only at upstream and downstream cut-offs where better data are not available. Since information on the process-based system is gathered by direct inspections and questionnaires, purchase and sales records for cut-offs required to link the process-based system with the IO table may be relatively easy to obtain.

In Figure 1 [4] the main differences among hybrid LCI are summarised.
Main advantages and shortcomings are reported in the following sections.

Comparison between methods for LCI compilation

	LCI based on process analysis		Input–output based LCI	Hybrid LCI		
	Process flow diagram	Matrix representation		Tiered hybrid analysis	IO-based hybrid analysis	Integrated hybrid analysis
Data requirements	Commodity and environmental flows per process	Commodity and environmental flows per process	Commodity and environmental flows per sector	Commodity and environmental flows per sector and process	Commodity and environmental. flows per sector and process-based LCIs	Commodity and environmental. Flows per sector and process
Uncertainty of source data	Low	Low	Medium to high	Depends[a]	Depends[a]	Low
Upstream system boundary	Medium to poor	Medium to poor	Complete	Complete	Complete	Complete
Technological system boundary	Complete	Complete	Medium to poor	Depends[a]	Depends[a]	Complete
Geographical system boundary	Not limited	Not limited	Domestic activities only	Depends[a]	Domestic activities only	Not limited
Applicable analytical tools	Rare	Abundant, e.g. in Heijungs and Suh [10]	Rare	Rare	Abundant (analytical tools for IOA disaggregated IO part)	Abundant (both analytical tools for IOA and LCA for entire system)
Time- and labour intensity	High	High	Low, if environm. data available	Depends[a]	Depends[a]	High
Simplicity of application	Simple	Simple	Simple	Simple	Complex	Complex
Required computational tools	Excel or similar (no matrix inversion)	Matrix inversion (e.g. MatLab, Mathematica.)	Excel or similar	Excel or similar	Matrix inversion (e.g. MatLab, Mathematica.)	Matrix inversion (e.g. MatLab, Mathematica.)
Available software tools	Most available LCA software tools	CMLCA	MIET, EIOLCA	MIET+LCA software tool	–	CMLCA

[a] Dependant upon the shares of process analysis and IO-based system.

Figure 2 - Comparison between methods for LCI compilation [1]

With time and money available, the choice clearly is for the integrated hybrid analysis. However, a rational strategy at a case level could be to consider a step-wise approach, where tiered hybrid approach is performed first by specifying upstream cut-offs. With additional resources and time available, then the next step will be specifying downstream cut-offs and further disaggregating IO table. The step-wise approach can start with a few important processes worked out in detail, that is quite cheap and fast. Then, focussed on where main contributions and uncertainties are, a stepwise build-up of resolution can follow, until a sufficient quality of result has been developed. In this development, there always is a full and consistent system definition, with resolution being added as required [1].

TABLE 1. Comparison between Hybrid Approaches

approach	strengths	weaknesses	methodological reference	case studies
tiered hybrid	easy to use	problem of double counting	Bullard et al. (*34*)	Moriguchi et al. (*12*), Marheineke et al. (*38*), Hondo et al. (*46*), Munksgaard et al. (*42, 47*)
	literatures, databases and case studies well documented	recurring flows are not properly described by process-flow diagram approach		
input–output based hybrid	avoid double counting	use and end-of-life phase are externally added to the main system	Joshi (*43*).	Joshi (*43*)
	process part and input–output part are described in a consistent framework	recurring flows between the main system and use and end-of-life phase are not properly described		
		should be combined with other methods if the national economy is highly dependent upon imports		
integrated hybrid	consistent mathematical framework for the whole life-cycle	relatively complex to use	Suh (*16*)	Suh and Huppes (*53*), Suh (*63*)
	avoid double counting.	high data and time requirements		
	easy to apply analytical tools			

Figure 3 – Comparison between Hybrid Approaches [2]

In a hybrid assessment, aggregated data in the input output part are substituted consecutively by specific, detailed process data for the most important lower order requirements, thus continuously making the inventory more reliable and accurate. Whenever process data or resources are unavailable or the required level of uncertainty is achieved, the process part can be truncated and the remaining requirements covered by input-output analysis. Thus, the boundary delineation of a hybrid assessment task can be elegantly tailored to suit requirements of specificity, accuracy, cost, labour, and time. It should be noted, however, that different hybrid approaches have different strengths and weaknesses, and the choice of method should be made considering various factors, including data requirements, required time and resources, the relevance of imports for a national economy, and the level of aggregation in a national input-output table [2].

New approaches to hybrid analysis have been proposed in [4], by applying the structural path analysis (SPA) as a guide to be employed for the design of a data collection and boundary selection strategy for inventories in hybrid LCAs (more details on the topic of system boundary are available in the related scheme).
The author employs an algorithm for scanning, extracting and ranking input paths but extended from imported commodities as well as domestically produced and imported capital. The results of these computations are sector and factor specific top-ranking input paths, which can be used as a guide for the preliminary identification and the coverage of the most important items for LCA inventories, and for completing existing process-based inventories.
The use of structural path analysis can assist LCA: by estimating the coverage of a given inventory, the boundary between the process analysis and input-output part of the hybrid assessment can be deliberately set in order to achieve a given level of accuracy.

Main advantages

In addition to the general advantages of combining LCA with IOA, the main advantages of the hybrid approaches highlighted by the authors are the following:

- integrated hybrid analysis has a clear advantage in terms of the quality of the result, especially in terms of system completeness. With information on the monetary value only for cut-off flows and with improved availability of environmentally extended IO data, preferably regionalised, the additional data requirements and the added complexity both may become quite limited. This seems a best choice for the future, if not for now already. However, it adds to the cost of already expensive and time-consuming full process LCA.
- The IO-based hybrid analysis is conceptually more mature. Although use and post-use processes are not incorporated in the IO part, and the links between the systems remains external, the IO-based hybrid analysis shows higher resolution for the IO-based system and does not have problems of overlap: the processes based system does not contain commodity flows represented in the IO table.
- Input-output analysis can take into account capital goods and overheads (such as head offices, marketing, company cars, lunchrooms, etc.) as inputs to a product system, which are often deliberately left out by most of process LCIs [2].
- The use of integrated hybrid model is recommended especially for comparative LCA studies. Equivalence of system boundaries has been on of the main obstacles in comparative studies. The integrated hybrid model provides a fairly neutral and complete background system for LCA practitioners, enabling a comparative study on the basis of equivalent system boundaries. [3]

Open questions
The weakness that are often referred to as obstacles of IOA for use in LCA have been addressed in the IO-LCI scheme. What can be considered valid also for hybrid approach is: ▪ Linear approximation in technical coefficients ▪ Static analysis ▪ It assumes that the environmental burden coefficients of imports are also well-approximated by the corresponding domestic industry sector. This may introduce errors in analyses of products with high import content and very different foreign production technologies. ▪ Additional uncertainties: o uncertainties of basic source data due to sampling and reporting errors o assumption that foreign industries are perfectly homogeneous, o assumption of proportionality between monetary and physical flow, o aggregation of IO-data over different producers and over different products supplied by one industry. ▪ Data of IO-based LCI is normally older than process-based one, since it takes 1e5 years to publish IO tables based on industry survey . ▪ There are inconsistencies in the industry classification system between the input-output tables and environmental emission data: the input-output table is generally calculated on the basis of producer's prices, but the price information that LCA practitioners obtain from procurement records refers to consumer's prices. By using consumer's prices, input-output based LCIs will always result in underestimation. Calculation of consumer's prices requires data on retail and wholesale trade margins and transportation cost, which is not generally known to purchasers . Other unresolved issues that are more persistent and for which continued efforts should be made (Suh): - as international trade has grown to be an integral part of the global economy, applicability of a national input output table and analyses thereof is becoming increasingly limited for addressing global challenges; - lack of comparability between IOTs of different countries also makes it difficult to compare IO-LCA results of different countries; - quantitative uncertainty analysis has rarely been attached to IO-LCA, as basic uncertainty information for individual elements of an IOT is generally unavailable. Other aspects to be considered: - Although hybrid approaches can in general substantially reduce the systematic truncation problem that is caused by an arbitrary system boundary selection, the question of locating the boundary between the process system and the input-output system still remains. - The results of a hybrid LCA with only a few processes will be similar to that of an input-output LCA, but it can gain resolution when the process part becomes larger, and process-specific data substitute for input-output data. However, one should be aware that expanding the process part also means increasing data requirements, and therefore, a balance should be considered in determining the boundary between the process part

and the input-output part. The advantage is, however, that at any time the assessment is complete in terms of upstream requirements.

- In terms of the simplicity of computation both IO-based and integrated hybrid analysis are considered to be more complicated than other methods, since these two approaches require some understanding on IOA.
- The tiered hybrid analysis has the appeal of easy extension on existing simple partial LCA systems in filling in the gaps. However, the connection between the two inventory subsystems is made externally, 'by hand'. The only partial links between the systems remain a source of error which is difficult to assess
- For both tiered hybrid and IO-based hybrid analysis, there are several criteria for which judgement can be case specific, since the boundary between detailed process-based analysis and IO-based analysis may vary. For example, time and labour intensity will rise, and source data uncertainty will be lowered as the process-based part becomes larger for these methods

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

The two main aspects of interest are data availability and software tools.

- Data availability and the lack of consistency among the different input-output table available (due to the different resolution) hamper the consistency of the methods. Data of IO-based LCI is normally older than process-based one, since it takes 1e5 years to publish IO tables based on industry survey.
- Regarding tools and database, there are several computational tools and databases. Chain Management by Life Cycle Assessment (CMLCA) is a software tool originally developed for education purposes although it can be successfully utilised for real case studies. Abundant analytical tools from both matrix representation of product system as well as IOA can be applied to integrated hybrid analysis. MIET (Missing Inventory Estimation Tool) is a software tool for tiered hybrid analysis to provide both inventory and environmental impact scores of the processes for which more reliable data are not available. MIET has been developed using the US input-output table and various environmental statistics based on an explicit distinction between commodity and industry output. Entering the estimated price of a missing flow either in the producer's or the consumer's price, MIET supplies inventory results for missing flows as well as characterised results, using around 100 different impact assessment methods that are in common use [7].(last version of MIET: 2004)

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

The integrated hybrid model is also generically applicable to studies on broad interindustry interdependence on which some parts of the system deserves special attention.

3rd Part: COMMENTS

R&D needs and trends
Beyond methodological developments, on which still several efforts are necessary, prerequisites for this highly important development are in the field of databases and software. LCA databases are to be adapted to the integrated hybrid method by supplying monetary data on process flows. IO databases, still available mainly at the single country level, should develop into a regionalised, trade-linked global system. High-quality IO database can be set up on the basis of supply and use tables, with detailed commodity flows available in most primary data sources where the supply and use tables are constructed from Also, the environmental data in the IO part, present now for a few countries only in greater detail, can become available for many more countries. Since most commercially available LCA software is not able to handle matrix inversion for LCI computation, a software tool development that enables hybrid analysis by broader LCA users is also required. [1] Other aspects to consider: • Hybrid LCA is still considered a complex tool even to those who already have used LCA. Efforts should be made to draft case studies, disseminate useful findings, and develop user-friendly software that enables hybrid LCA. [2] • research efforts should be devoted further to develop well-structured, environmentally augmented input-output tables: To do so, efforts should be made in the direction of developing better statistics on environmental emissions and resources use that can be used in input-output LCA. In the long term, the development of a multinational environmental input-output model with complete trade links is very desirable, especially in connection with regionalized LCIA methods that will result in a complete system with regional specification [2] The EXIOPOL (A New Environmental Accounting Framework Using Externality Data and Input Tools for Policy Analysis) project is working on this: among the several goals of the project, one is related to setting up an environmental extended (EE) Input Output (IO) framework for the EU-25 in a global context, in order to take pollution and externalities embedded in imports to the EU25 into account, and also to analyse the effects of sustainability measures taken in Europe on the economic competitiveness of the EU25. • future research with regard to structural path analysis as a guide for LCA could concentrate on developing a sound basis for quantifying the uncertainty of path values [4] In order to reduce errors of path values, the following improvements in the underlying data are desiderable: - environmentally important industry sectors should not be classified within another aggregate, but separately, in order to reduce the allocation error; - a multi-region input–output framework should be set up including national data on resource use and pollution in order to reduce the error associated with the imports assumption; - an input–output table for domestically produced as well as imported capital flow should be estimated by statistical offices regularly.
Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

No research lines seem to exist on uncertainty factors for IO data but this will be of great interest, due to the repercussions of the methodology in large scale application.
Furthermore, the high level of aggregation of sector represents an obstacle to the fully integration between the IO and LCA structure.

The integrated hybrid analysis could be a good perspective for the future but also in this case, the problem of complexity and time-consuming of analysis still exist: efforts should be concentrated towards the simplification of the analysis in order to make it more practical.

[Phase/Topic/Approach]

Life Cycle Inventory/IO and Hybrid LCI/Waste Input-Output Analysis

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

Recently there has been an increasing studies on what is called hybrid analysis, i.e. an analysis in which process-based LCA and IOA are combined in order to overcome the limitations (incompleteness due to cut offs, lack of process specificity) and combine the advantages (high level of detail and completeness in system boundaries) of both methods. But when waste treatment methods have to be evaluated in the analysis, there is a need of a more tailored methods.
Indeed, the conventional IOA was originally developed to represent the intersectoral flow of goods and hence is not designed to take into account the flow of waste associated with it. Consequently, in its conventional form IOA is not able to take proper account of the effects that result from the interaction between the flow of goods and wastes, issue that would be of fundamental importance for the purpose of LCA of waste management.
Because waste treatment is expected to accept whatever waste is generated by industry and households, a proper consideration of this feature is vital for LCA of waste management. Indeed, the main concern of LCA of waste management consist of the economic and environmental impacts that may result from the introduction of alternative waste-recycling methods and/or alternative waste treatment methods., i.e. the LCA of waste management deals with the case in which le level and composition of waste treatment, as well as the allocation pattern of wastes to treatment methods change; thus the WIO model allow to take account of the interdependencies between the flow of goods and wastes, by establishing a correspondence between waste generation and its treatment at the level of each sector [1].

The approach is quite new, and all the (few) references founded belong to the same authors but, nevertheless its relevance has been highlighted also in the work funded by DEFRA "Sustainable Consumption and Production – Development of an Evidence Base" (authors: T. Wiedmann, J. Minx, J. Barrett, R. Vanner, P. Ekins).
A WIO model has been developed by the same authors in order to perform a life-cycle cost analysis of the recycling of end-of-life electrical home appliances. This approach is described in the LCC scheme.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. **General references**

-
2. Specific references
- [1] S. Nakamura, Y. Kondo, **Input-Output Analysis of Waste Managemen**t, Journal of Industrial Ecology vol. 6 (1) 39-63, 2002.
- [2] K. Takase, Y. Kondo, A. Washizu, **An Analysis of Sustainable Consumption by the Waste Input-Output Model**, Journal of Industrial Ecology vol.9 (1-2), 201-219, 2005. - [3] Y. Kondo, S. Nakamura, **Evaluating Alternative Life-Cycle Strategies for Electrical Appliances by the Waste Input-Output Model**, Int J LCA 9 (4) 236-246, 2004. - [4] Y. Kondo, S. Nakamura, **Waste Input-Output Linear Programming Model with its Application to Eco-Efficiency Analysis**, Economic Systems Research Vol. 17, No. 4, 393-408, 2005.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

The WIO is a hybrid methodology of LCA that takes into account the interdependencies between the flow of goods and waste, where the technology matrix of a product system in LCA (in particular the foreground system that refer to waste management and recycling, described in physical units) is fully integrated with technical coefficients matrix of an economy (the background processes that refer to the traditional flow of goods and services) in IOA.
It is capable of taking into account all the phases of life cycle, production, use, and end of life (EoL). Exclusion of the EoL phase used to be mentioned as a limitation of IO analysis (IOA) for LCA (while the conventional IOA does not cover the use phase as well, its incorporation is rather straightforward). It, however, does not apply to the WIO because of its explicit consideration of the flow of waste and waste management activities including waste recycling.

To be noted that in the WIO model, waste are defined in a broad sense and contains both by-products and waste in a "narrow" sense that refers to waste for treatment.

The model has two main features:

- It expands the Leontief environmental input-output (EIO) model with respect to waste flows. It turns out that the EIO model is a special case of the WIO model in which there is a strict one-to-one correspondence between waste types and treatment methods, providing a general framework for LCA of waste management.
- It takes into account the dynamics of waste management treatment because the input-output relationships of waste treatment are significantly affected by the level and composition of waste feedstock, by incorporating an engineering process model of waste treatment and by including an

allocation matrix (a matrix that provide a means to represent a change in the allocation of waste to different treatment methods). For engineering models of waste management, the level and composition (calorific value, water and ash content, and other aspects) of waste feedstock entering into the system are exogenously given. Integrated into the WIO model these variables become endogenous and can be determined by the interaction between goods production and waste treatment for a given level and composition of the final demand.
The model was developed by using Japanese IO tables, data on the generation, recycling and treatment of waste and an engineering model of waste management.

Additional features of the model :

- The number of waste types and of treatment methods can be arbitrary
- It can handle the case in which a single treatment method is applied to multiple types of waste
- It can handle the case in which several treatment methods are jointly applied to a single type of waste, provided that the combinations are technically feasible.
- In the WIO model, the extended parts referring to waste flow and management are measured in physical units, and are consistent with a mass balance condition. For each type of waste, the mass balance condition is satisfied, because the amount of its net generation (generation minus recycling) is equal to the amount of its treatment. For each waste treatment process, its feedstock is set equal to the amount of recovered waste materials and residues, and hence the mass balance condition is met. When it comes to the good producing sectors, however, the mass balance condition between input and output in physical terms (physical inputs = physical outputs + process waste) is not considered because the flow of good is measured in monetary units following the convention of IOA.
- WIO model has a nonlinear nature in the sense that its coefficients can be affected by a change in waste management policy. It remains linear so far as the characteristics of waste allocated to each of the treatment methods are fixed. When these characteristics are altered, however, the coefficients of model may also change and the linearity may no longer hold. This nonlinear nature of waste treatment has been taken into account by the definition of an engineering model of individual processes describing the quantitative relationships between characteristics of waste feedstock, inputs of utilities and of chemicals, specification of the equipment and the generation of treatment residues.

The WIO model has been further developed in order to analyse **households' sustainable consumption patterns** **[2]**. Indeed, the WIO model is much more suitable for the analysis of sustainable consumption than the conventional input-output model because it can deal with the disposal stage of consumed goods as well as the purchase and use stages.
The conventional IO model, as well as the WIO model, is useful for evaluating the purchase stage of consumption because it is suited to taking upstream repercussions into account; but it cannot be applied straightforwardly to an assessment of a disposal stage that causes downstream repercussions, at least in its original form. The WIO model does not suffer from such a shortcoming because of its distinguishing feature mentioned above. Thus, it evaluates both the purchase and disposal stages properly, whereas the conventional IO model analyzes only the purchase stage.
A simple method for evaluating incoming rebound effects within the WIO framework has been also introduced, by assuming that households face a fixed budget, and then adjusting the new consumption pattern so that it has the same total expenditure as the old consumption pattern, which means

that the leftover budget is allocated proportionally to all goods in the new consumption pattern.
This method indicates equal income elasticises for all goods in this case

The authors presented also an **analytic extension of the waste input output model, based on the method of linear programming [4]**. The resulting model, the Waste Input Output Linear Programming model (WIO-LP), allows one to automatically obtain an optimal waste management and recycling strategy for among a given set of alternative feasible strategies.
In addition, an eco-efficiency maximising frontier (or environmental impact minimising frontier) can be obtained quantitatively by a repeated use of the WIO-LP model. A point on the frontier is given as an optimal solution to the WIO-LP model in which the objective function is one of the environmental emissions selected and an upper bound is provided to the other environmental emission. Therefore an eco-efficiency maximising frontier can be obtained by repeatedly solving the WIO-LP model.
A single point on the frontier will be selected by explicitly stating the priority of policy objectives. The selected point is also a scenario that consists of a combination of alternative options.
The WIO-LP model, namely, enables one not only to identify a goal of reducing environmental emissions or improving eco-efficiency but also to formulate a quantitatively concrete waste management strategy to accomplish the goal.
The obtained frontier can be used to check whether a given waste management and recycling strategy is inefficient, efficient or infeasible.

The model thus can explore the extent to which a given measure of eco-efficiency can be maximised by an appropriate combination of existing (technological and resources) potentials. In addition, the model provides a flexible framework to incorporate not only the average technologies given by the public IO table but also any technology that is feasible in the sense of engineering.

Main advantages

Several advantages have been highlighted by the authors:

- It can deal with an arbitrary combination of treatment methods applied to an arbitrary combination of waste types provided that the combinations are technically feasible.
- The number of waste types and treatment methods can be set arbitrarily and are not required to be equal.
- It can take account of waste generated from virtually any waste source in the economy, including municipal solid waste (MSW) from final demand sectors, industrial and commercial waste from the goods and service producing sectors, and treatment residues from waste treatment sectors.
- It provide a means to evaluate some aspects of life cycle costing of waste management scheme through the use of the indicator of total employment: it can be considered as a first order measure of the economic efficiency of a particular waste management scenario.
- Methodology easiness in implementing a wide range of alternative scenarios with regard not only to the manufacturing phase, but also to the phase of use and end of life [3].

Open questions

The main open question that recurs in all the papers in the lack of data. in particular,. This situation caused several limitations in the analyses performed, in particular:

- Also that the number of environmental loads in the WIO model is not limited in principle, only carbon dioxide and landfill consumption have been considered;
- The factors concerned with human toxicity and ecotoxicity were not considered
- The model described the relationship between the purchase and disposal stages of consumption properly, although it could have dealt with the use stage of consumption for all goods if sufficient data were available for the use stage.

Furthermore:

- The WIO model is an open model that has no linkage between the final demand (consumption and investment) for durables and the accumulation and discarding over time of durables.
- Taking environmental impacts other than co2 and landfill consumption into consideration is one of the remaining issues to be researched.
- Accounting for the three stages of consumption jointly as well as building relevant databases for each stage also awaits for further research.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

The lack of appropriate data prevents from considering a large number of environmental load.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Waste sector.
The WIO framework has been applied also for a life cycle cost analysis. Information on this topic are available in the LCC scheme.

3rd Part: COMMENTS

R&D needs and trends

Referring to the open questions described above, the main research lines should focus on data:

- Taking environmental impacts other than co2 and landfill consumption into consideration
- Accounting for the three stages of consumption jointly as well as building relevant databases for each stage

Other aspects:

- The analysis has been static, and no aspect of the dynamic process, where goods are transformed into waste was considered. Proper consideration of this dynamic aspects is of great importance for analyzing issues of durable waste such as building, structures, automobiles and appliances.
- To establish a linkage between the final demand (consumption and investment) for durables and the accumulation and discarding over time of durables.
- Important future directions for research related to the WIO-LP model deal with the final demand vector as a choice variable that can be optimized in eco-efficiency analysis. Indeed, it is desiderable to move the eco-efficiency maximizing frontier to the northeast direction in order for a sustainable society to materialize: carrying out a waste management strategy lying on a given frontier corresponds to attaining the best available eco-efficiency level, while moving the frontier to the northeast direction corresponds to raising the best available eco-efficiency level. Important points to investigate are which constraints should be relaxed, and what strategies are effective for raising the best available eco-efficiency

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

Because the concept of the WIO table is a new and original one, a corresponding public national accounting system does not exist; thus it has been developed by using a large number of data materials taken from various sources including public sources, industry associations, and a literature survey.
Stating this situation, an uncertainty analysis should be performed in order to evaluate the results obtained.

Furthermore, more case studies should be carried out in order to better highlight its capacity.

LIFE CYLE INVENTORY

CONSEQUENTIAL LCI

- Choice between consequential and attributional LCA
- Marginal data
- Partial equilibrium modelling
- Experiences curves
- Rebound effects

[Phase/Topic/Approach]

Inventory analysis/Consequential LCI/Selection

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

The appropriate methodological choices in an LCA depend on the purpose of the study. Various attempts have been made to structure the various applications of LCA and to describe the connection between the study goal and the methodological choices that should be made in the LCA.

Many application typologies include approximately the same distinction between attributional and consequential LCA. Different words are used to denote the two types of LCA (2:1), and there are slight differences between the distinctions presented in different publications. Essentially, however, attributional LCA aims at describing the environmentally relevant physical flows to and from a life cycle. Consequential LCA aims at describing how the environmentally relevant flows from the technological system as a whole change in response to possible changes in the life cycle (1:3).

The choice between attributional and consequential LCA affects, for example, the definition of system boundaries, allocation approaches, and the selection of data (1:1). It can also affect the choice of functional unit (1:2). This dependency on the purpose of the study is not accounted for in the international standard on LCA.

The literature selected is restricted to include mainly peer-reviewed journal papers published since the year 2000. Most typologies of this kind were presented before that, and often in conference proceedings or PhD theses.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. **General references**

1. Tillman, A.-M. (2000) Significance of decision-making for LCA methodology, Environmental Impact Assessment Review 20:113-123.
2. Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt W-P, Suh S, Weidema BP, Pennington DW. (2004) Life Cycle Assessment – Part 1: Framework, Goal & Scope Definition, Inventory Analysis, and Applications. Environment

International 30(5):701-720.
3. Ekvall T, Weidema BP. (2004) System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. International Journal of Life Cycle Assessment, 9(3):161-171.
4. Sandén B, Karlström M. (2007) Positive and negative feedback in consequential life-cycle assessment. Journal of Cleaner Production 15(15):1469-1481.

2. Specific references

1. Wenzel, H. Application Dependency of LCA Methodology: Key Variables and Their Mode of Influencing the Method. Int. J. LCA, Vol. 3, No. 5, pp. 281-288 (1998)
2. Weidema, B. Avoiding Co-Product Allocation in Life-Cycle Assessment. J. Ind. Ecol., Vol. 4, No. 3, pp. 11-33 (2000)
3. Ekvall T, Tillman A-M, Molander S. Normative ethics and methodology for life cycle assessment, J. of Cleaner Production, Vol. 13, No. 13-14, pp. 1225-1234 (2005)
4. Frischknecht, R. (2006) Notions on the Design and Use of an Ideal Regional or Global LCA Database. International Journal of Life Cycle Assessment 11(LCA Special 1):40-48.
5. Heijungs, R., Guinée, J.B. Allocation and "what-if" scenarios in life cycle assessment of waste management systems, Waste Management, Vol. 27, pp. 997-1005 (2007)

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

After several years were spent on discussing allocation and with the choice between marginal and average data, no agreement on what is the best LCI method had been obtained. It was then realised, or decided, that there are really two different LCA methods: one where allocation and average data are typically used, and one where system expansion and marginal data are often used. The focus of the debate then shifted to the question when each LCI method was the most appropriate. Meantime, it has become apparent that the aim of describing environmental consequences affects the methodology far beyond the issues of allocation and marginal data (1:3).

Main advantages

The distinction between attributional and consequential LCA helps structuring the discussion on a couple of methodological issues that have been debated for a very long time: allocation problems and the choice between marginal and average data (1:1). It also helps structuring the discussion on what knowledge an LCA generates (2:3).

Open questions

There is still no consensus regarding when the knowledge generated by attributional and consequential LCA is relevant (see below).

There is also no consensus regarding if the consequential LCA methodology is practicable (see below).

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

System expansion is the most common consequential approach to allocation problems. Heijungs & Guinée (2:4) argue that system expansion is impractical because of the large uncertainties involved. Weidema (2:2), on the other hand, argues that system expansion is always possible and rarely difficult.

It has also been argued that consequential LCA is difficult to perform because the systems investigated become more complex and because the marginal technology is often difficult to identify. Other authors argue that consequential LCA is easier to perform that attributional LCA because it is not necessary to collect data on the whole production systems; the investigation can be restricted to the marginal technology. It has also been argued that consequential LCA is conceptually easier because the focus on consequences give a clear guidance in methodological choices. Attributional LCA requires arbitrary choices, because

Most performed LCA can probably still be best described as attributional LCA, but the number of consequential LCAs grows steadily.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Some authors suggest that attributional LCA be used for learning purposes, while consequential LCA is used for generating information that is relevant for decisions. The rational is that attributional LCA describes a state, while consequential LCA is designed to describe the consequences of a decision. Tillman (1:1) further recommends attributional LCA for identifying hot spots and for developing market claims such as environmental product declarations.

Weidema (2:2), however, questions the relevance of attributional LCA for product declarations and for hot spot identification. Wenzel (2:1) claims

that consequential LCA generates the most relevant information, independently of the application, because an LCA is interesting only if it influences decisions. Ekvall et al. (2:3) argue that both attributional and consequential LCA can be used for decision-making, and also for learning purposes. Consequential LCA is valid to assess environmental consequences of individual decisions or rules. Attributional LCA, on the other hand, is valid for the purpose of avoiding connections with systems with large environmental impacts. Both purposes can be relevant according to this reference. Several authors have stated (e.g., 2:3) that attributional and consequential LCA can both be applied to investigate future as well as historic systems.

3rd Part: COMMENTS

R&D needs and trends
Tillman (1:1) states that further development is required in the methods for consequential LCI: modelling of marginal effects, system expansion, etc. She observes that the methods may depend on the goal and scope of the LCA and, in particular, on the decision at hand. Frischknecht (2:4) states that it will hardly be possible to reach consensus on what LCI methods are the best. Instead, we should strive at clarifying where there is consensus and where there is not. Where there is no consensus, we should strive at identifying a few standard choices.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. Besides the R&D needs identified by the authors above, there is an apparent need to further investigate the feasibility and relevance of consequential LCA. This is apparent from the widely differing views on these issues, presented by different authors. The feasibility can only be demonstrated through an accumulated experience from successful LCAs. To agree on the relevance of consequential LCA, further debate and analysis is required in the international LCA community.

[Phase/Topic/Approach]

Inventory analysis/Consequential LCI/Marginal

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

A consequential LCA often includes marginal data (1:1, 2:2). Marginal data, by definition, represent the effects of a small change in the output of products and/or services from a system on the environmental burdens of the system.

Several authors have presented and discussed different approaches for identifying the marginal technology (i.e., the technology affected by a small change in demand (2:1)). This issue is not addressed at all by the international standard on LCA.

The literature selected primarily includes peer-reviewed journal papers published since the year 2000. This selection covers most of the relevant lines of thought on this subtopic.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. General references

1. Tillman, A.-M. (2000) Significance of decision-making for LCA methodology, Environmental Impact Assessment Review 20:113-123.
2. Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt W-P, Suh S, Weidema BP, Pennington DW. (2004) Life Cycle Assessment – Part 1: Framework, Goal & Scope Definition, Inventory Analysis, and Applications. Environment International 30(5):701-720.
3. Ekvall T, Weidema BP. (2004) System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. International Journal of Life Cycle Assessment, 9(3):161-171.
4. Sandén B, Karlström M. (2007) Positive and negative feedback in consequential life-cycle assessment. Journal of Cleaner Production 15(15):1469-1481.

2. **Specific references**
1. Wedema BP, Frees N, Nielsen A-M. (1998) Marginal production technologies for life cycle inventories, International Journal of Life Cycle Assessment 4(1):48-56 2. Azapagic A, Clift R. (1999) Allocation of environmental burdens in multiple-function systems, Journal of Cleaner Production 7(2):101-119 3. Weidema B. (2000) Avoiding Co-Product Allocation in Life-Cycle Assessment, Journal of Industrial Ecology 4(3):11-33 4. Eriksson O, Finnveden G, Ekvall T, Björklund G. (2007) Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion, Energy Policy 35(2):1346-1362 5. Heijungs, R., Guinée, J.B. (2007) Allocation and "what-if" scenarios in life cycle assessment of waste management systems, Waste Management, 27:997-1005

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. Two methodological choices were initially identified as relevant for a consequential LCA: the use of marginal data and the expansion of systems to avoid allocation problems (1:1). These choices are connected: the system expansion should include the marginal technology, since this is the technology actually affected by the life cycle or decision at stake (2:1). However, a consequential LCA should include marginal data not only in the system expansions. Normally, marginal data are relevant to model all of the background system, since this is only marginally affected by the life cycle or decision at hand (2:2).
Main advantages
Consequential LCA aims at describing how the environmentally relevant flows from the technological system change in response to possible changes in the life cycle (1:3). Most changes will have a marginal effect on the background system, at least (2:2). Marginal data, by definition, represent these effects.
Open questions

The most fundamental open question is whether the identification of marginal technologies is practicable (see below).

Another open question is what type of marginal effects should be included in the consequential LCA. Short-term effects are changes in the utilisation of the existing production capacity in existing production plants. Long-term effects involve changes in the production capacity (2:1). Energy systems analyses typically focus on the short-term effects. Weidema et al. (2:1) suggests that the choice should be decided case by case, but states that the long-term effects are relevant in most cases. Other authors argue that the most complete description of the consequences is obtained if short-term and long-term effects are both accounted for (2:4).

There is also no consensus on how to identify the marginal technology. Different approaches have been presented, corresponding to the different opinions on what marginal effect is the most relevant. The short-term marginal technology is identified as the technology with the lowest running cost, where the capacity is not fully utilised. Weidema et al. (2:1) present a five-step procedure to identify the long-term marginal technology. The combination of short-term and long-term marginal effects is called complex marginal effects. Complex marginal effects on the Nordic electricity system have been investigated using a cost-optimising dynamic model of this system (2:4).

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Heijungs & Guinée (2:5) argue that system expansion is impractical because of the large uncertainties involved in identifying the marginal technology. Weidema (2:3), on the other hand, argues that identifying the marginal technology is always possible and rarely difficult.

Most LCA practitioners do not have any cost-optimising dynamic model readily available. No LCA practitioner can be expected to have cost-optimising dynamic models of all parts of the background system. For this reason, if nothing else, the identification of complex marginal effects in an LCA is impractical. In principle, the complex marginal effects can be investigated in separate studies and compiled in a database for use in LCA case studies (2:4). A drawback is that the complex marginal effects identified in a separate study might not be fully consistent with the LCA where they are applied (2:4). Furthermore, the only complex marginal effects that have been published, so far, concern electricity production in Scandinavia.

The five-step procedure to identify the static long-term marginal technology is publicly available (2:1). Applying this procedure can still be difficult for an LCA practitioner, because it requires an analysis of the market and of the economy of different technologies. Such analyses also typically involve large uncertainties. The long-term marginal technology has been identified for several products (2:3), however. Results from such studies can be used by LCA practitioners, if caution is taken to account for the uncertainties involved.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose. Marginal data are relevant to model environmental burdens from all production systems that are marginally affected by possible changes in the life cycle. This is typically true for all large production systems, i.e. system with large production volume: the production of bulk materials (e.g., steel, aluminium and polyethylene), energy carriers (e.g., electricity, fuel oil and petrol), etc. In an LCA such systems commonly appear in the background system and in system expansions.

3rd Part: COMMENTS

R&D needs and trends
Tillman (1:1) states that further work is needed to "describe in greater detail how use of marginal capacity should be modeled (what type of marginal) depending on which decision is being considered".
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. Besides the R&D needs identified by the authors above, there is an apparent need to further investigate the feasibility of handling the uncertainties involved in the identification of marginal technologies. This is apparent from the widely differing views on these issues, presented by different authors (2:3, 2:5). It is also important to develop approaches to systematically evaluate and handle these uncertainties.

[Phase/Topic/Approach]

Inventory analysis/Consequential LCI/Partial equilibrium modelling

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

Partial equilibrium modelling describes the balance between supply for and demand of specific products. It can be applied to investigate how this balance is shifted by a change in price of the products, or by a change on the supply or demand side.

Partial equilibrium modelling is not mentioned in the international standard on LCA.

The literature selected includes nearly all identified scientific papers where the combination of partial equilibrium models and LCA is discussed. It also includes all identified scientific papers presenting case studies where LCA and partial equilibrium models are combined.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. General references

1. Tillman, A.-M. (2000) Significance of decision-making for LCA methodology, Environmental Impact Assessment Review 20:113-123.
2. Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt W-P, Suh S, Weidema BP, Pennington DW. (2004) Life Cycle Assessment – Part 1: Framework, Goal & Scope Definition, Inventory Analysis, and Applications. Environment International 30(5):701-720.
3. Ekvall T, Weidema BP. (2004) System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. International Journal of Life Cycle Assessment, 9(3):161-171.
4. Sandén B, Karlström M. (2007) Positive and negative feedback in consequential life-cycle assessment. Journal of Cleaner Production 15(15):1469-1481.

2. Specific references

1. Ekvall T. (2000) A market-based approach to allocation at open-loop recycling, Resources, Conservation and Recycling 29(1-2):93-111.
2. Bouman M, Heijungs R, van der Voet E, ven den Berg JCJM, Huppes G. (2000) Material flows and economic models: an analytical comparison of SFA, LCA and partial equilibrium models, Ecological Economics 32: 195-216.
3. Weidema B. (2003) Market information in life cycle assessment. Environmental Project no. 863, Danish Environmental Protection Agency, Copenhagen, Denmark. Url: http://www2.mst.dk/udgiv/publications/2003/87-7972-991-6/pdf/87-7972-992-4.pdf.
4. Ekvall T, Andrae A. (2006) Attributional and consequential environmental assessment of the shift to lead-free solders, International Journal of Life Cycle Assessment, 11(5):344-353.
5. Lesage P, Ekvall T, Deschenes L, Samson R. (2007) Environmental assessment of brownfield rehabilitation using two different life cycle inventory models: Part I - Methodological Aproach, International Journal of Life Cycle Assessment, Online First.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Consequential LCA aims at describing how the environmentally relevant flows from the technological system change in response to possible changes in the life cycle (1:3). An increase in the use of a good in the life cycle typically can contribute to increasing the market price of this good. This not only stimulates the production of the good, but also reduces the use of the good in other life cycles (1:3). Partial equilibrium modelling describes both of these effects through the concept of own-price elasticity of demand and supply.

Main advantages

In a traditional LCA model, the unit processes are directly connected by physical flows. By introducing partial economic models, the LCA model accounts for the fact that these physical flows are traded on a market (2:1).

Open questions

It is an open question if partial equilibrium models should be integrated into LCA. Bouman et al. (2:2) argue that partial economic models give information that is different and complementary to LCA results, and that specific advantages of the different tools might be lost if they are integrated. Ekvall & Weidema (1:3), on the other hand, argue that integration of partial equilibrium models into LCA "would result in a new tool with specific advantages with regard to modelling the consequences of changes".

It is also an open question when partial equilibrium modelling is relevant. Weidema (2:3) argues that long-term prices are in many cases not affected by demand, but determined by the long-term marginal production cost. This holds, he states, "on competitive, unconstrained markets (i.e. where there are no market imperfections and no absolute shortages or obligations with respect to supply of production factors, so that production factors are fully elastic in the long term". When the price is not affected by the demand, an increase in the use of a good in a life cycle does not affect the long-term use of the good in other life cycles. In such cases, the use of a partial equilibrium model is irrelevant. The question is how common these cases are, and when they occur.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

A more practical question concerns the feasibility of partial equilibrium modelling. Partial equilibrium modelling can be expected to require economists. Economists with relevant expertise are typically not readily available to LCA practitioners. The question is how to involve more economists in the LCA community and in the LCA projects.

Partial equilibrium modelling adds to the complexity and cost of the LCA. When the complexity increases, the risk for calculation errors and other mistakes also increases. The study also becomes more difficult to interpret and report in a transparent manner.

Partial equilibrium modelling also adds to the uncertainty of the LCA. There are typically large uncertainties in the estimated own-price elasticity of demand and supply (2:1).

Introducing partial equilibrium models in LCA becomes more feasible, and much less costly, if own-price elasticities from the literature can be used in case studies. Using literature data increases the uncertainty, however. Own-price elasticities depend on case-specific factors such as the time and place, and also on whether the study focuses on short-term or long-term effects.

The cost and complexity can both be reduced by focussing on the parts of the technological and economic system where the most important consequences are expected to occur. This means that the life cycle model is reduced to include only the flows and processes where changes are expected to be important for the results and conclusions, and that partial equilibrium models are added only when effects on other life cycles are expected to be very important for the results and conclusions.

This solution has the weakness that the LCA will depend more heavily on what is expected to be important in advance of the study. This problem is probably general: when more impact categories and/or causal mechanisms are added to the LCA methodology, each study can afford to include fewer aspects that are expected to be insignificant.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

As stated above, the applicability of partial equilibrium models in LCA is an open question. Bouman et al. (2:2) argue that partial equilibrium models should perhaps not be integrated into LCA at all. Weidema (2:3) argue that they are not applicable for goods that are traded on competitive, unconstrained markets. Ekvall (2:1) suggests that partial equilibrium models of scrap markets can be applied to handle cases of open-loop recycling. Ekvall & Andrae (2:4) use a semi-quantitative partial equilibrium model of the lead market to investigate the effects of a global shift to lead-free solders. Lesage et al. (2:5) use a partial equilibrium model of the housing market to investigate the land-use effects of a case of brownfield rehabilitation.

Outside LCA, partial equilibrium modelling is an established tool in the area of environmental economics. It has been used to assess the environmental consequences of policy decisions and other strategic decisions. The studies often focus on the effects on fuel and electricity demand and on CO2 emissions from the energy sector.

3rd Part: COMMENTS

R&D needs and trends

Ekvall (2:1), who models open-loop recycling, states that it is an important research task to calculate the elasticities of supply and demand for the most important markets for recovered material, to facilitate such modelling.

Bouman et al. (2:2) state that the combination and integration of tools such as LCA, partial equilibrium models, and substance flow analysis is a field of research which is still wide open.

Ekvall & Andrae (2:3) observes that price elasticity estimates seem to be available in the literature for a few goods only. They also present the hypothesis that the marginal alternative use of materials outside the life cycle investigated is often not very important, environmentally, but states that many more case studies are required to test this hypothesis.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

Besides the R&D needs identified by the authors themselves, the open issues mentioned above also need further attention:
- Should partial equilibrium models be integrated into LCA, or used in parallel to LCA?
- For what types of good does a change in demand in a life cycle affect the demand in other life cycles?

To make the combination of LCA and partial equilibrium models feasible, the price elasticity of demand and supply need to be estimated for many more products. To make the estimates available to LCA practitioners, they should be compiled in databases that are posted in connection to ordinary LCI databases.

[Phase/Topic/Approach]

Inventory analysis/Consequential LCI/Experience curves

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

Learning curves describe how an individual or production process becomes more efficient as a function of the accumulated experience (2:1). The function is a log-log function with a constant progress ratio: for each doubling of the accumulated experience, the time and/or cost required for a process is reduced by a specific percentage (typically 5-35%). The initial time and cost and the progress ratio are empirically measured. The learning curve can then be extrapolated into the future to estimate further expected improvements.

Experience curve is a similar concept, but on a higher systems level: they describe how a technology becomes less expensive as the production of the technology grows more efficient with accumulated experience (2:2). The term "learning curve" is sometimes used to denote both of these concepts.

It has been demonstrated that not only the cost but also the efficiency (2:2) and environmental performance (2:3) of a technology improves with accumulated experience. This development can also be described using experience curves.

Experience curves or learning curves are not mentioned in the international standard on LCA.

The selected references include all identified texts discussions on the integration of experience curves in LCA. It also includes a thesis that discusses experience curves in general.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. General references

1. Tillman, A.-M. (2000) Significance of decision-making for LCA methodology, Environmental Impact Assessment Review 20:113-123.

2. Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt W-P, Suh S, Weidema BP, Pennington DW. (2004) Life Cycle Assessment – Part 1: Framework, Goal & Scope Definition, Inventory Analysis, and Applications. Environment International 30(5):701-720.
3. Ekvall T, Weidema BP. (2004) System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. International Journal of Life Cycle Assessment 9(3):161-171.
4. Sandén B, Karlström M. (2007) Positive and negative feedback in consequential life-cycle assessment. Journal of Cleaner Production 15(15):1469-1481.

2. Specific references

1. Wright, TP. (1936) Factors affecting the costs of airplanes. Journal of the Aeronautical Sciences 3:122-128.
2. Claeson, U. (2000) Analyzing Technological Change Using Experience Curves - A Study of the Combined Cycle Gas Turbine Technology. Lic Eng Thesis, Chalmers University of Technology, Gothenburg, Sweden.
3. Pento T, Karvonen MM. (2000) Long-term determinants of emission coefficients and their effects on life cycle inventory (LCI) calculations. In Karvonen (2000) An industry in Transition. Environmental significance of strategic reaction and proaction mechanisms of the Finnish pulp and paper industry. PhD thesis, University of Jyväskylä, Jyväskylä, Finland:67-76.
4. Weidema BP, Ekvall T, Pesonen H-L, Rebitzer G, Sonnemann G W, Spielmann M. (2004) Scenarios in life-cycle assessment. SETAC, Pensacola.
5. Ekvall T, Mattsson N, Münter M. (2005) System-wide environmental consequences of Vistar combustion in Stenungsund - Feasibility study. Report 2005:1. Division of Energy Technology, Chalmers University of Technology, Gothenburg, Sweden.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Consequential LCA aims at describing how the environmentally relevant flows from the technological system change in response to possible changes in the life cycle (1:3). A decision to invest in a new technology can have a large impact on the future of this specific technology. It increases the accumulated experience on the technology. This makes subsequent investments in the technology less expensive and, hence, more likely. Over time, a snowball effect can occur, giving the technology a much higher market share than it would have had without the initial investment (2:5). If this effect is taken into account, it can have a huge effect on the LCA results (1:4).

The fact that technologies tend to get more efficient and perform better environmentally can be relevant to take into account in consequential as well as attributional LCAs. It is particularly relevant for case studies with a long time horizon and case studies with new and immature technologies.

Main advantages

Experience curves make it possible to estimate the possibly huge environmental effect of investments in new technologies. An experience curve also facilitates forecasting of future emissions from a specific technology.

Open questions

The accumulated experience is not a perfect basis for estimating future improvements. Improvements occur not only as a result of investments in the specific technology but also through learning from other, related technologies, and from research. It might be possible to define a better basis for estimating future improvements, but no such suggestion has been established yet.

When experience curves are used for making forecasts of future emissions, it is necessary to make an assumption or forecast about the future investments in the technology. It is an open question how to make these forecasts.

It is also an open question how to use experience curves for estimating the effect of investments in new technologies. Two approaches have been presented so far. Ekvall et al. (2:5) suggest using a dynamic model of the market where the technology has a share. This model has market-share functions that describe how the market-share of the technology depends on the difference in cost compared to other technologies. Such a model gives an estimate of the consequence of an individual investment in any of the technologies on the market. The drawback of this approach is that it requires expertise not only in experience curves but also in dynamic modelling.

Sandén & Karlström (1:4) use a simplified approach. They estimate:
- the total learning investment, i.e., the investment that is required to make the new technology economically competitive with the traditional technology on the market,
- the environmental impact that occurs if the new technology takes over the market, and
- the probability that this will occur.

Then they divide the estimated impact by the total learning investment, and multiply by the probablility that the new technology will take over the market. The result is presented as the estimated consequence of a unit investment. This approach does not require advanced modelling. On the other hand, it is not accurate for estimating the consequence of an individual investment. Instead, it allocates the impacts of the total learning investment in proportion to the size of the individual investment.

It is also an open question if the concepts of experience curves and learning investments should be integrated into the LCA. They make a consequential LCA more comprehensive and accurate in the aim of describing how the environmentally relevant flows from the technological system change. On the other hand, they add complexity, cost and uncertainty to the study.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

As stated above, the approach of Ekvall et al. (2:5) requires expertise in dynamic modelling. The approach of Sandén & Karlström (1:4) is more feasible. It still requires expertise in the area of experience curves and learning investments to make estimates of the progress ratio and learning investments.

As also stated above, experience curves adds to the complexity, cost and uncertainty of the LCA. When the complexity increases, the risk for calculation errors and other mistakes also increases. The study also becomes more difficult to interpret and report in a transparent manner.

Introducing experience curves in LCA is more feasible, and much less costly, for technologies where the progress ratio has already been estimated. This is the case for many energy technologies (2:4).

The cost and complexity can both be reduced by focussing on the parts of the technological and economic system where the most important consequences are expected to occur. This means that the life cycle model is reduced to include only the flows and processes where changes are expected to be important for the results and conclusions, and that experience curves are applied only when effects on technological development are expected to be very important for the results and conclusions.

This solution has the weakness that the LCA will depend more heavily on what is expected to be important in advance of the study. This problem is probably general: when more impact categories and/or causal mechanisms are added to the LCA methodology, each study can afford to include fewer aspects that are expected to be insignificant.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

The use of experience curves to estimate the future consequences of investments adds most value to the consequential LCA where effects on technological development are expected to be very important for the results and conclusions. This is typically the case for new, immature technologies in important parts of the life cycle.

The use of experience curves to estimate future efficiency and emissions of processes in the life cycle adds most value to LCAs where the time horizon is long and there are new, immature technologies in important parts of the life cycle.

The use of experience curves is more easily defended for technologies where the progress ratio has already been estimated. Defining the progress ratio as part of an LCA project will probably often be considered too difficult and expensive.

3rd Part: COMMENTS

R&D needs and trends

Claeson (2:2) states that further research is required on how transfer of knowledge and experience between technologies and between geographical regions should be accounted for when applying experience curves. Further developments are also required to decide on how knowledge generated through research, as opposed to investments, should be accounted for.

The approach of Ekvall et al. (2:5) as been outlined in a pilot study only. Real case studies are required to test and illustrate this approach.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

Besides the R&D needs identified by the authors themselves, the open issues mentioned above also need further attention:
- Should experience curves be integrated into LCA?
- If so, what approach should be used in what circumstances?

To make the combination of LCA and experience curves feasible, experience curves need to be established for more technologies. For each technology, the experience curves can be uniquely described through
- the cost, efficiency, or environmental performance at a specified starting time,
- the accumulated experience at this starting time, and
- the progress ratio.

These data can be compiled in databases that are posted in connection to ordinary LCI databases, to make the experience curves available to LCA practitioners.

[Phase/Topic/Approach]

Inventory analysis/Consequential LCI/Rebound effects

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* An LCA calculates the environmental burdens per functional unit. It typically aims at comparing systems with the same functional output. Such a comparison does not take into account the fact that a change in the life cycle investigated might affect the functional output from the life cycle and from technological system as a whole. This can happen for many reasons. All of these effects can be denoted rebound effects (RE) or ripple effects (2:3): RE1. The demand for a specific product, and hence its production, can increase when a change in the life cycle reduces the price of the product (2:1) or when it enhances the quality or function the product (2:2). RE2. A reduction in the price of a specific product X (e.g., a car) can also affect the demand for other products. The demand for competing products (e.g., a car of a different brand) decreases, because they become less competitive compared to product X (1:4, 2:1). This offsets part of RE1. On the other hand, the demand for complementary products (e.g., tyres) increase when the demand for product X increases. RE3. When the price of a product is reduced for a consumer or industry, more money is available for this consumer or industry to spend on other products. Hence, the demand for other products in general can increase (2:1, 2:5). This adds to RE1. RE4. When the price of a specific product is reduced for an industry, it can reduce the price of its products. This can result in an increase in the use of these products, which means the industry grows. Consumers and industries where these products are used benefit from the secondary price reduction, and so on. Through this chain of cause and effects, the initial price reduction is likely to contribute to economic growth (1:4, 2:1). This also adds to RE1. RE5. A change in the price of a product can affect the technology development, consumption preferences and societal institutions (2:1). RE6. The demand for a specific product can increase when a change in the life cycle makes it less time-consuming to use and maintain. In addition, this will give consumers more time to spend on other kinds of consumption and other activities (2:4). RE7. The demand for a specific product, and other products, can also increase when a change in the life cycle makes the product smaller, easier to handle, etc. (2:4).

RE8. The demand for products can increase to compensate when a change in the life cycle reduces the quality or function of the product (2:2). When this happens to an industry, it is likely to reduce its output of products, reducing economic growth, and offsetting part of the increase in purchase to the industry.

RE9. The demand for products might increase to compensate when a change reduces the fulfilment of needs and/or reduces the happiness of consumers (2:4).

Rebound effects can be accounted for in a comparative LCA, if the functional unit does not quantify the functional output (e.g., use "person-year of transport" rather than "30 000 person-km of transport")(2:2). Different approaches are appropriate for quantifying the various ways in which the functional output from the technological system can be affected:

RE1. The effect of the price of a product (P_i) on the demand for this product (D) can be analysed using the concept of own-price elasticity of demand ($\square_i$): $\square_i = (\square D_i/D_i) / (\square P_i/P_i)$. This is a well established concept in economics (1:3).

RE2. The effect of the price of a product (P_i) on the demand for competing and complementary products (D_j) can be analysed using the concept of cross-price elasticity of demand ($\square_{ij}$): $\square_{ij} = (\square D_j/D_j) / (\square P_i/P_i)$. This is also a well established concept in economics (1:4)

RE3. The effect of the price of a product on the general demand for other products can be analysed using computable general equilibrium (CGE) models. These are top-down models of a full economy. A CGE model describes the interaction between different sectors in the economy, and the balance between the use of capital, labour and resources within each sector. It is an established tool in economics. The environmental impacts of the increase in demand can be assessed by identifying the marginal consumption in the economy affected (2:5).

RE4. The effect of the price of a product on the economic growth can also be analysed using CGE models (2:1).

RE9. The effect on the fulfilment of needs and/or reduces the happiness of consumers can be analysed using a step-wise procedure presented by Hofstetter et al. (2:4).

For other types of rebound effects, we have not found approaches to quantify the effects in the literature.

Rebound effects and the approaches mentioned here are not discussed in the international standard on LCA.

The literature selected includes nearly all identified scientific papers where the rebound effect is discussed in connection to LCA. It also includes an important paper that discusses the rebound effect without connection to LCA (2:1).

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. General references

1. Tillman, A.-M. (2000) Significance of decision-making for LCA methodology, Environmental Impact Assessment Review 20:113-123.
2. Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt W-P, Suh S, Weidema BP, Pennington DW. (2004) Life Cycle Assessment – Part 1: Framework, Goal & Scope Definition, Inventory Analysis, and Applications. Environment International 30(5):701-720.
3. Ekvall T, Weidema BP. (2004) System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. International Journal of Life Cycle Assessment, 9(3):161-171.
4. Sandén B, Karlström M. (2007) Positive and negative feedback in consequential life-cycle assessment. Journal of Cleaner Production 15(15):1469-1481.

2. Specific references

1. Greening LA, Greene DL, Difiglio C. (2000) Energy efficiency and consumption - The rebound effect - A survey. Energy Policy 28: 389-401.
2. Weidema B. (2003) Market information in life cycle assessment. Environmental Project no. 863, Danish Environmental Protection Agency, Copenhagen, Denmark. Url: http://www2.mst.dk/udgiv/publications/2003/87-7972-991-6/pdf/87-7972-992-4.pdf.
3. Hertwich E. (2005) Consumption and the Rebound Effect: An industrial ecology perspective. Journal of Industrial Ecology 9(1-2):85-98
4. Hofstetter P, Madjar M, Ozawa T. (2006) Happiness and Sustainable Consumption: Psychological and physical rebound effects at work in a tool for sustainable design. International Journal of Life Cycle Assessment 11(Special 1):105-115.
5. Thiesen J, Christensen TS, Kristensen TG, Andersen RD, Brunoe B, Gregersen TK, Thrane M, Weidema BP. (2007) Rebound Effects of Price Differences, International Journal of Life Cycle Assessment, Online First.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Consequential LCA aims at describing how the environmentally relevant flows from the technological system change in response to possible changes in the life cycle (1:3). Assuming that the functional output from the life cycle is unaffected by changes in the life cycle is a simplification. As stated above, a change that affects the price, quality, functionality, need for maintenance, etc. of a product, can influence the demand for this product. It can also affect the demand for other products. Different concepts and tools are effective for analysing different kinds of rebound effects:

- The own-price elasticity of demand is a useful concept in the analysis of how a change in price for a product affects the demand for this specific product (RE1).
- The cross-price elasticity of demand is a useful concept in the analysis of how a change in price for a product affects the demand for a small number of other products (RE2).
- General equilibrium models are useful whenever we wish to estimate the effect of changes in one part of the economy upon the rest of the economy (RE3 and RE4).
- The concept of marginal consumption is useful to analyse the environmental impact of a change in the money available for consumers to spend on other products (RE3).

Main advantages

Accounting for rebound effects makes a consequential LCA more accurate and comprehensive. An estimate of rebound effects is required to quantify effects on the functional output of the life cycle or the technological system. They are not accounted for, and easily forgotten, when the LCA implicitly assumes that the functional output is unaffected. This can lead to the environmental gain of improvements in the life cycle being overestimated as well as underestimated (2:3).

The concept of rebound effects also makes it possible for the LCA to highlight conflicts between environmental concerns and other goals, such as growth in the economy and consumption. This is because additional economic activity and increases in spending power of consumers typically are related to additional environmental burdens (2:1, 2:5). When rebound effects are accounted for, a change in the life cycle reduces total environmental impacts if it:

- reduces the environmental impact of the product itself,
- makes the product more expensive (RE1, RE3 & RE4)(2:1, 2:5),
- increases the time required to handle the product (RE6)(2:4), and/or
- makes the product larger or more difficult to handle (RE7)(2:4).

Open questions

There is no absolute consensus on the word “rebound”. It might be more adequate to talk about ripple effects (2:3), because it is not always easy to know in advance if these indirect effects increases or reduces the environmental impacts. If, for example, a product becomes cheaper, allowing consumers to spend money on other products, this is likely to increase environmental impacts (2:5). But if this money is spent on, e.g., increased insulation of a house, the environmental impacts are reduced (2:3).

The definition of the rebound effect vary in the literature and among researchers (2:1).

For several rebound effects, it is an open question how they should be quantified. Even when established tools such as price elasticity and CGE models can be applied, the quantification of rebound effects depend on important subjective methodological choices. For this reason, the magnitude of rebound effects is uncertain (2:1, 2:3).

It is also an open question if rebound effects should be accounted for in the LCA. It makes a consequential LCA more comprehensive and accurate in the aim of describing how the environmentally relevant flows from the technological system change. On the other hand, it adds complexity, cost and uncertainty to the study.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Accounting for rebound effects adds to the complexity, uncertainty and cost of the LCA. When the complexity increases, the risk for calculation errors and other mistakes also increases. The study also becomes more difficult to interpret and report in a transparent manner.

Estimating price elasticities and development and use of CGE models require economists. Economists with relevant expertise are typically not readily available to LCA practitioners. The question is how to involve more economists in the LCA community and in the LCA projects.

Quantifying RE1 and RE2 in LCA becomes more feasible, and much less costly, if price elasticities from the literature can be used in case studies. Using literature data increases the uncertainty, however. Price elasticities depend on case-specific factors such as the time and place, and also on whether the study focuses on short-term or long-term effects.

The cost and complexity can both be reduced by assuming different boundary conditions to be active. To analyse RE3 for a consumer product, the total spending of households can be assumed to be unaffected. This boundary condition reduces the analysis to identifying the marginal consumption mix (2:5).

The cost and complexity can also be reduced by focussing on the parts of the technological and economic system where the most important consequences are expected to occur. This means that the life cycle model is reduced to include only the flows and processes where changes are

expected to be important for the results and conclusions, and that rebound effects are accounted for only when effects on the functional output are expected to be very important for the results and conclusions.
This solution has the weakness that the LCA will depend more heavily on what is expected to be important in advance of the study. This problem is probably general: when more impact categories and/or causal mechanisms are added to the LCA methodology, each study can afford to include fewer aspects that are expected to be insignificant.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Rebound effects can occur whenever a change in the life cycle affects the product in any way (price, quality, size, etc.). As indicated above, the applicability of rebound effects in LCA is still an open question, because of the complexity, uncertainty and costs involved. Accounting for rebound effects adds most value to the consequential LCA when the rebound effects are expected to be important for the results and conclusions. They can be expected to be important when the product price is greatly affected, particularly if a group of consumers or companies spend a significant share of their budget on the purchase of this product.

Outside LCA, rebound effects have been much discussed and analysed in the context of energy systems analysis (2:1, 2:3). The aim of such analysis is often to quantify the net effect of improvements in energy efficiency that reduces the cost of energy services such as residential heating, transports etc.

3rd Part: COMMENTS

R&D needs and trends

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

Greening et al. (2:1) state that one of the primary tasks for further research is to agree on the definition of the rebound effect. They also state that more research is required to estimate the rebound effect in various cases related to energy use.

Hertwich (2:3) highlights the need for research on rebound or ripple effects in a broad sense, including effects on behaviour, technological spill-over and other posivite and negative, indirect effects of policy measures.

Hofstetter et al. (2:4) state that further research is needed to test their hypothesis that high levels of happiness will reduce the consumption of physical goods. They also acknowledge that their stepwise procedure for estimating RE9 needs to be refined and further tested.

Thiesen et al. (2:5) call for further research on marginal consumption and investment patterns. They also see the need for development of more precise methods for determining the marginal consumption, and for development of input-output tables for additional countries and regions in the world.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

This is a large field of research in the sense that it includes various types of cause-and-effect relations. It is also methodologically imature: for several rebound effects, no method has been found to quantify the effect. For other effects, only a single, first approach has been presented. And further research and development is required even when established tools such as price elasticity and CGE modelling can be applied. Hence, it is easy to conclude that much research remains to be done in this area.

LIFE CYLE INVENTORY

ALLOCATION

- multi-output processes
- multi-input processes
- open-loop recycling

[Phase/Topic/Approach]
Inventory analysis/Allocation/Multi-output processes

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* A multi-output process is an activity that generates more than one product. A useful distinction is made between combined production, where the volume of products from the process can be independently varied, and joint production, where the ratio of products is fixed (1:2, 2:1). An allocation problem arises in the LCA when one of the products is used in the life cycle investigated and a different product, or set of products, in other life cycles. The problem is to decide what share of the environmental burdens of the activity should be allocated to the life cycle investigated, i.e., included in the LCA of the product investigated. Many different solutions to the allocation problems have been suggested (1:5). The choice of solution can have a decisive impact on the results of an LCA. The international standard ISO 14044 requires the following stepwise procedure for dealing with allocation problems: 1. Allocation should be avoided, wherever possible, either a) through division of the multifunction process into sub-processes, and collection of separate data for each sub-process, or b) through expansion of the system investigated to include the additional functions related to the co-products. 2. Where allocation cannot be avoided, the allocation should reflect the physical relationships between the environmental burdens and the functions, i.e., how the burdens are changed by quantitative changes in the products delivered by the system. 3. Where such physical causal relationships alone cannot be used as the basis for allocation, the allocation should reflect other relationships between the environmental burdens and the functions, for example in proportion to the economic value of the products. This procedure has been criticized because it fails to account for the fact that different approaches to allocation might be adequate in different LCAs, depending on the purpose of the study. For example, it does not account for the distinction between attributional and consequential LCA, despite the fact that this distinction was explicitly agreed upon in order to resolve the debate on allocation and related methodological issues. The ISO procedure has also been criticized because it fails to account for the feasibility of the methods, the amount of work required, and the type of information resulting from the different methods (1:3). It also does not account for fairness or equity (2:1). The procedure has also been subject to conflicting interpretation. Researchers disagree on what approaches are allowed according to the ISO procedure. They also disagree on what approaches are possible (see Open questions, below). The references selected for the discussion on allocation at multi-output processes are a selection of reviewed papers from scientific journals. The

selection is based on an assessment of whether the authors are influential in the international debate on allocation and whether the specific papers are relevant examples on the different perspectives on allocation that are highlighted in this document.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

3. General references

1. Azapagic A, Clift R. (1999) Allocation of environmental burdens in multiple-function systems. Journal of Cleaner Production 7:101-119.
2. Weidema B. (2000) Avoiding Co-Product Allocation in Life-Cycle Assessment. Journal of Industrial Ecology 4(3):11-33.
3. Ekvall T, Finnveden G. (2001) Allocation in ISO 14041 – A Critical Review. Journal of Cleaner Production 9(3):197-208.
4. Guinée J, Heijungs R, Huppes G. (2004) Economic Allocation: Examples and Derived Decision Tree. International Journal of Life Cycle Assessment 9(1):23-33.
5. Curran MA. (2007) Co-Product and Input Allocation Approaches for Creating Life Cycle Inventory Data: A Literature Review. International Journal of Life Cycle Assessment 12(Special Issue 1):65-78.

4. Specific references

1. Frischknecht R. (2000) Allocation in Life Cycle Inventory Analysis for Joint Production. International Journal of Life Cycle Assessment 5(2):85-95.
2. Cederberg C, Stadig M. (2003) System Expansion and Allocation in Life Cycle Asessment of Milk and Beef Production. International Journal of Life Cycle Assessment 8(6):350-356.
3. Wang M, Lee H, Molburg J. (2004) Allocation of Energy Use in Petroleum Refineries to Petroleum Products: Implications for Life-Cycle Energy Use and Emission Inventory of Petroleum Transportation Fuels. International Journal of Life Cycle Assessment 9(1):34-44.
4. Althaus H-J, Classen M. (2005) Life Cycle Inventories of Metals and Methodological Aspects of Inventorying Material Resources in ecoinvent. International Journal of Life Cycle Assessment 10(1):43-49.
5. Feitz A, Lundie S, Dennien G, Morain M, Jones M. (2007) Generation of an Industry-specific Physico-chemical Allocation Matrix: Application in the Dairy Industry and Implications for Systems Analysis. International Journal of Life Cycle Assessment 12(2):109-117.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. The debate on how the procedure should be interpreted indicates that the current ISO text is too vague to give adequate guidance. At the same time, the criticism against the procedure indicates that it is not flexible enough. The challenge of the development in this area is to develop and agree upon a text that is clear and flexible enough to give adequate guidance on allocation in LCAs with different purposes (1:5).
Main advantages
Clear and adequate guidance on allocation is important because there are many different methods and because the LCA results can depend heavily on the approach to allocation.
Open questions
Researchers disagree on what step in the ISO procedure is the most useful: - Weidema (1:2) argues that system expansion (Step 1b) at joint production and allocation based on physical relationships at combined production (Step 2) are the most adequate approaches for consequential LCA, because they result in the most accurate model of the consequences of decisions. This is supported by Cederberg & Stadig (2:2). - Ekvall & Finnveden (1:3) agree on these conclusions, in principle, but argue that system expansion in practice is often based on inaccurate data. They also add that methods that are easier to apply can be used for allocation problems that are not important for a decision. - Guinée et al. (1:4), on the other hand, argue that economic allocation (Step 3) is the best, generally applicable, and consistent method fitting with their Handbook on LCA. - Frischknecht (2:1) argues that system expansion is similar to Step 3 allocation, and should not be recommended as part of the first step in the ISO procedure. - Curran (1:5) states that that no single method stands out as a general solution to the allocation problem. Specifically, subdivision (Step 1a) can be expected to eliminate the allocation problem on rare occasions only, but that it has frequently been used to reduce an allocation problem (1:3). Researchers disagree on whether this is an appropriate approach: - Ekvall & Finnveden (1:3) state that the approach does not result in accurate information on the consequences of decisions, since the subprocesses are typically not independent from each other. - Wang et al. (2:3), on the other hand, recommend that allocation problems be reduced as much as possible through subdivision. Researchers disagree on whether system expansion (Step 1b) solves allocation problems: Weidema (1:2) argues, based on a large number of

examples, that system exansion is always possible and eliminates the allocation problem in joint production. Other authors argue that system expansion typically adds new allocation problems to the system.

Researchers disagree on how to apply Step 2 allocation:
- Azapagiz & Clift (1:1) recommend to apply a linear programming model of the specific multi-output process.
- Feitz et al. (2:5) recommend instead to compare data from different existing production plants with slight differences in product mixes.

Researchers disagree on the relevance of Step 3 in the ISO procedure:
- Weidema (1:2) argues that system expansion (Step 1b) or allocation based on physical relationships (Step 2) is always possible, which means that Step 3 should never be used.
- Ekvall & Finnveden (1:3) argue that Step 3 is inadequate for important allocation problems in consequential LCA.
- Feitz et al. (2:5) conclude that large errors can be introduced by Step 3 allocation based on economic value.
- Guinée et al. (1:4), on the other hand, recommend economic allocation in Step 3 as the baseline approach for most allocation problems in a detailed LCA. This is also the approach chosen by the ecoinvent team (2:4).
- Frischknecht (2:1) states that Step 3 is adequate for allocation at joint production.

Researchers also disagree on what approaches are part of Step 3 in the ISO procedure.
- ISO/TR 14049 states that Step 3 in the procedure is economic allocation. This statement rules out allocation based on physical parameters such as mass or energy content in cases where it cannot be shown that such allocation reflects underlying physical relationships between the outputs and the environmental burdens.
- Ekvall & Finnveden (1:3) reflect that economic allocation is mentioned as an example only in the standard. They state that Step 3, if generously interpreted, allows also for allocation based on arbitrary physical properties such as mass, volume or energy content.
- Frischknecht (2:1) proposes a further Step 3 approach for joint production where allocation is based on the capacity to carry environmental burdens and still compete with alternative products, arguing that not only economic costs but also environmental burdens affects the competitiveness of products. When the sum of economic costs and environmental burdens of separate production is higher than the sum of costs and burdens for joint production, the costs and burdens are allocated between the joint products in a way that makes them all competitive.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Researchers disagree on the practicability of system expansion:
- Weidema (1:2) concludes that system expansion is seldom difficult.
- Ekvall & Finnveden (1:3), on the other hand, note that system expansion requires collection of additional data, and that the uncertainties regarding what processes should be included in the expanded system can be large.

The different Step 2 approaches have practical advantages and drawbacks:
- The linear programming approach of Azapagiz & Clift (1:1) requires some expertise in linear programming.
- The approach by Feitz et al. (2:5) requires data collection from a large number of production plants in the sector of the multi-output process. On the other hand, when the allocation has been performed, the allocated data are used not only to model a specific plant but all production plants in this sector.

Most authors would probably agree that allocation based on physical measures such as mass, energy, volume, etc. is the easiest approach to apply in most cases.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Several authors (1:2, 1:3, 2:2) argue that system expansion (Step 1b) at joint production and allocation based on physical relationships at combined production (Step 2) are the most adequate approaches for consequential LCA, at least in principle. However, this position is disputed by other authors.

3rd Part: COMMENTS

R&D needs and trends

Ekvall & Finnveden (1:3) states that further research is required to obtain a procedure to investigate how a change in the production of one of the products affects the production of other products from the process. Further research is also required to establish whata data should be used at system expansion.

Curran (1:5) states that the standard "should be expanded to provide more precise guidance in how to approach allocation. The guidance should be goal dependent".

Feitz et al. (2:5) recommend that their approach be applied to develop allocated (Step 2) data for various industrial sectors: agriculture, construction, mining, petrochemical industry etc.

Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. Many scientific papers have been written on multi-output allocation. Only a selection is presented here. In addition, various allocation methods, arguments and analyses have been presented in other formats: PhD theses, conference proceedings, reports, informal discussions, etc. These are not covered by this literature survey. This means the survey presents only part of the diversity in views and perspectives on allocation in the international LCA community. The large diversity in views and the importance of the methodological problem implies that a significant effort is required to reach a general agreement on - what allocation approach is the most appropriate in different cases, or on - how to identify the most appropriate approach to allocation.

[Phase/Topic/Approach]
Inventory analysis/Allocation/Multi-input processes

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

A multi-input process is a waste-management process that simultaneously deals with more than one waste stream. A pure multi-input process is typically not a joint but a combined process, because the input of different waste streams can be independently varied. However, waste-management processes often also has outflows of products, such as electricity, heat, biogas, fertilisers, recycled materials, etc. Such processes are at least partly joint processes, because the maximum volume of products depends on the quantity of waste treated.

The allocation problem here is to decide what share of the environmental burdens of the activity should be allocated to waste stream of the life cycle investigated, i.e., included in the LCA of the product investigated. The international standard ISO 14044 presents no specific guide for allocation at multi-input processes. Essentially, the same procedure as for multi-output processes apply:

1. Allocation should be avoided, wherever possible, either a) through division of the multifunction process into sub-processes, and collection of separate data for each sub-process, or b) through expansion of the system investigated to include the additional functions related to the co-products.
2. Where allocation cannot be avoided, the allocation should reflect the physical relationships between the environmental burdens and the functions, i.e., how the burdens are changed by quantitative changes in the products delivered by the system.
3. Where such physical causal relationships alone cannot be used as the basis for allocation, the allocation should reflect other relationships between the environmental burdens and the functions, for example in proportion to the economic value of the products.

In general terms, this procedure has been criticized because it fails to account for the fact that different approaches to allocation might be adequate in different LCAs, depending on the purpose of the study. For example, it does not account for the distinction between attributional and consequential LCA, despite the fact that this distinction was explicitly agreed upon in order to resolve the debate on allocation and related methodological issues. The ISO procedure has also been criticized because it fails to account for the feasibility of the methods, the amount of work required, and the type of information resulting from the different methods (1:3). It also does not account for fairness or equity (2:1).

The references selected for the discussion on allocation at multi-input processes include all identified, peer reviewed papers on this topic from scientific journals. Two of the papers (2:1, 2:2) have the same corresponding author: Christina Seyler. All specific references discuss waste-management processes with products as well as inflows of multiple waste flows. However, two of the general references (1:1, 1:4) discuss pure multi-input processes.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. General references

1. Azapagic A, Clift R. (1999) Allocation of environmental burdens in multiple-function systems. Journal of Cleaner Production 7:101-119.
2. Weidema B. (2000) Avoiding Co-Product Allocation in Life-Cycle Assessment. Journal of Industrial Ecology 4(3):11-33.
3. Ekvall T, Finnveden G. (2001) Allocation in ISO 14041 – A Critical Review. Journal of Cleaner Production 9(3):197-208.
4. Guinée J, Heijungs R, Huppes G. (2004) Economic Allocation: Examples and Derived Decision Tree. International Journal of Life Cycle Assessment 9(1):23-33.
5. Curran MA. (2007) Co-Product and Input Allocation Approaches for Creating Life Cycle Inventory Data: A Literature Review. International Journal of Life Cycle Assessment 12(Special Issue 1):65-78.

2. Specific references

1. Seyler C, Hellweg S, Monteil M, Hungerbühler K. (2005) Life Cycle Inventory of Use of Waste Solvent as Fuel Substitute in the Cement Industry – a Multi-Input Allocation Model. International Journal of Life Cycle Assessment 10(2):120-130.
2. Seyler C, Hofstetter TB, Hungerbühler K. (2005) Life Cycle Inventory for thermal treatment of waste solvent from chemical industry: a multi-input allocation model. Journal of Cleaner Production 13:1211-1224.
3. Heijungs R, Guinée JB. (2007) Allocation and "what-if" scenarios in life cycle assessment of waste management systems. Waste Management 27:997-1005.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

There is general agreement, in the literature reviewed (1:1, 2:3), that allocation based on physical relationships (Step 2) is the most appropriate for pure multi-input processes, when the input of different waste streams can be independently varied.

Main advantages

Allocation based on physical relationships (Step 2) results in the most accurate model of the consequences of decisions that affects the waste flows.

Open questions

Researchers disagree on how to address allocation when the waste-management process has outflows of products, such as electricity, heat, biogas, fertilisers, etc.:
- Seyler et al. (2:1) allocate the emissions of the waste-management process based on physical relationships between the emissions and the waste flows (Step 2), and applies system expansion (Step 1b) to account for the consequences of the products from the waste-management process.
- Heijungs & Guinée (2:3) denotes this kind of process "open loop recycling" and recommend to allocate the emissions of the waste-management process between the inputs and outputs using a Step 3 approach, despite acknowledging that the choice between different Step 3 approaches is essentially arbitrary. They argue against system expansion (Step 1b) because of the uncertainties it involves, because it might introduce new allocation problems, and because it requires more data.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Researchers disagree on the practicability of system expansion:
- Weidema (1:2) concludes that system expansion is seldom difficult.
- Other researchers (1:3, 2:3) note that system expansion requires collection of additional data, and that the uncertainties regarding what processes should be included in the expanded system can be large.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Several authors (1:2, 1:3) argue that system expansion (Step 1b) at joint production and allocation based on physical relationships at combined production (Step 2) are the most adequate approaches for consequential LCA, at least in principle. However, this position seems to be disputed by, for example, Heijungs & Guinée (2:3).

3rd Part: COMMENTS

R&D needs and trends
Seyler et al. (2:1) state that their model on waste solvent incineration in clinker kilns requires further development to be able to assess also incineration of solid waste in such kilns. Further research is also required to identify the optimal strategy for treatment of waste solvents. Some of the R&D needs identified for multi-output and recycling allocation is relevant also for multi-input processes with products. For example Ekvall & Finnveden (1:3) states that further research is required to establish whata data should be used at system expansion. Specifically, this is needed to specify in what specific cases energy from waste incineration should be assumed to compete with energy from other waste streams and when it should be assumed to compete with other energy sources.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. Only a limited number of scientific papers explicitly address multi-input processes with products. The diversity of views and perspectives in the LCA community can still be expected to be large, because these processes have much in common with multi-output processes and open-loop recycling, where the multitude of opinions is apparent.

[Phase/Topic/Approach]

Inventory analysis/Allocation/Open-loop recycling

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* Open-loop recycling occurs when the material from one product is recycled for use in other products. An allocation problem arises in the LCA because the recycling process provides one function for the product being recycled (waste management) and one function for the product containing recycled material (materials production). The problem is to decide what share of the environmental burdens of the recycling process should be allocated to the life cycle investigated, i.e., included in the LCA of the product investigated. The allocation problem becomes more complex because the material is subsequently used in different products. The raw materials extraction and primary materials production serves all product life cycles where the material is used. The final waste management of the material also serves as final waste management for all product life cycles where the material is used. For this reason, the allocation problem at recycling is often perceived to include the environmental burdens of the primary production, and sometimes also the environmental burdens of the final waste management. Many different solutions to the allocation problems have been suggested (1:5). The choice of solution can have a decisive impact on the results of an LCA. The international standard ISO 14044 recommends to use the same stepwise procedure that is required for dealing with multi-output allocation: 1. Allocation should be avoided, wherever possible, either a) through division of the multifunction process into sub-processes, and collection of separate data for each sub-process, or b) through expansion of the system investigated to include the additional functions related to the co-products. 2. Where allocation cannot be avoided, the allocation should reflect the physical relationships between the environmental burdens and the functions, i.e., how the burdens are changed by quantitative changes in the products delivered by the system. 3. Where such physical causal relationships alone cannot be used as the basis for allocation, the allocation should reflect other relationships between the environmental burdens and the functions, for example in proportion to the economic value of the products. Here, it can be noted that allocation of primary materials production and final waste management cannot be avoided through subdivision (Step 1A) in cases of recycling. On the other hand, ISO 14041 allows a few additional options for allocation at recycling. If the recycling does not cause a change in the inherent properties of the material, the allocation may be avoided through calculating the environmental burdens as if the material was recycled back into the same product. Otherwise, the allocation can be based on physical properties, economic value, or the number of

subsequent uses of the recycled material.

As mentioned above, the ISO procedure has been criticized because it fails to account for the fact that different approaches to allocation might be adequate in different LCAs, depending on the purpose of the study. For example, it does not account for the distinction between attributional and consequential LCA, despite the fact that this distinction was explicitly agreed upon in order to resolve the debate on allocation and related methodological issues. The ISO procedure has also been criticized because it fails to account for the feasibility of the methods, the amount of work required, and the type of information resulting from the different methods (1:3).

The procedure has also been subject to conflicting interpretation. Researchers disagree on what approaches are allowed according to the ISO procedure. They also disagree on what approaches are possible (see Open questions, below).

The references selected for the discussion on allocation at open-loop recycling are a selection of reviewed papers from scientific journals. The selection is based on an assessment of whether the authors are influential in the international debate on allocation and whether the specific papers are relevant examples on the different perspectives on allocation that are highlighted in this document.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. General references

1. Azapagic A, Clift R. (1999) Allocation of environmental burdens in multiple-function systems. Journal of Cleaner Production 7:101-119.
2. Weidema B. (2000) Avoiding Co-Product Allocation in Life-Cycle Assessment. Journal of Industrial Ecology 4(3):11-33.
3. Ekvall T, Finnveden G. (2001) Allocation in ISO 14041 – A Critical Review. Journal of Cleaner Production 9(3):197-208.
4. Guinée J, Heijungs R, Huppes G. (2004) Economic Allocation: Examples and Derived Decision Tree. International Journal of Life Cycle Assessment 9(1):23-33.
5. Curran MA. (2007) Co-Product and Input Allocation Approaches for Creating Life Cycle Inventory Data: A Literature Review. International Journal of Life Cycle Assessment 12(Special Issue 1):65-78.

2. Specific references

1. Ekvall T. (2000) A market-based approach to allocation at open-loop recycling. Resources, Conservation and Recycling 29 (1-2): 93-111.
2. Vogtländer JG, Brezet HC, Hendriks CF. (2001) Allocation in Recycling Systems – An Integrated Model for the Analyses of

Environmental Impact and Market Value. International Journal of Life Cycle Assessment 6(6):344-355.
3. Matsuno Y, Daigo I, Adachi Y. (2007) Application of Markov Chain to Calculate the Average Number of Times of Use of a Material in Society – An Allocation Methodology for Open-Loop Recycling – Part 2: Case Study for Steel. International Journal of Life Cycle Assessment 12(1):34-39.
4. Werner F, Althaus H-J, Richter K, Scholz RW. (2007) Post-Consumer Waste Wood in Attributive Product LCA – Context specific evaluation of allocation procedures in a functionalistic conception of LCA. International Journal of Life Cycle Assessment 12(3):160-172.
5. Heijungs R, Guinée JB. (2007) Allocation and "what-if" scenarios in life cycle assessment of waste management systems. Waste Management 27:997-1005.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

The debate on how the procedure should be interpreted indicates that the current ISO text is too vague to give adequate guidance. At the same time, the criticism against the procedure indicates that it is not flexible enough. The challenge of the development in this area is to develop and agree upon a text that is clear and flexible enough to give adequate guidance on allocation in LCAs with different purposes.

Main advantages

Clear and adequate guidance on allocation is important in the international standard, because there are many different methods and because the LCA results can depend heavily on the approach to allocation.

Open questions

Researchers disagree on what the allocation problem is:
- Guinée et al. (1:4) and Heijungs & Guinée (2:5) propose that the allocation problem arises because the recycling process provides one function for the product being recycled (waste management) and one function for the product containing recycled material (materials production). The problem is to decide what share of the environmental burdens of the *recycling process* should be allocated to the life cycle investigated, i.e., included in the LCA of the product investigated.
- Azapagic & Clift (1:1) and Matsuno et al. (2:3) propose that the allocation problem arises because a specific quantity of material is used in a

cascade of products. The allocation problem then involves the environmental burdens not only of the recycling process but also of the original, *primary production* of the recycled material. The rationale is that primary production of the material is required to provide material also to the other products in the cascade.
- Ekvall & Finnveden (1:3) add that *final waste management* of the recycled material is also necessary for all products in the cascade. The allocation problem then involves the environmental burdens of the primary production, recycling, and final disposal of the recycled material.
- Weidema (1:2) have a similar perception of the problem, but recommend to account for the marginal primary production, recycling, and waste disposal of the *specific type* of material, because these can all be affected by the recycling.

Researchers also disagree on how the environmental burdens should be allocated:
- When the allocation problem only involves the environmental burdens of the recycling process, a *cut-off* approach is applied. The question is to decide if none, all, or part of the recycling process belongs to the life cycle of the investigated product:
    - Vogtländer et al. (2:2) recommend that all the environmental burdens of the recycling process be allocated to the product in which the recycled material is used.
    - Guinée et al. (1:4) propose to allocate the environmental burdens of the recycling process in proportion to the economic revenues from accepting the waste and selling the material.
    - Heijungs & Guinée (2:5) add that the choice of allocation factors is somewhat arbitrary.
- Azapagic & Clift (1:1) suggests to allocate the burdens using a linear-programming model. The application of this model gives the same results as the cut-off method of Vogtländer et al. (2:2). All environmental burdens of primary production will be allocated to the first product in which the material is used, and the environmental burdens of the recycling process be allocated to the product in which the recycled material is used.
- An approach to allocate the environmental burdens *equally* among all the products in the cascade has been presented by, e.g., Matsuno et al. (2:3).
- So called 50/50 allocation means that the environmental burdens of primary production is equally divided between the *first and last* of the products in the cascade. The environmental burdens of recycling is equally divided between the product that delivers scrap to recycling and the product where the recycled material is used (2:1).
- Methods to allocate the environmental burdens among the products in the cascade in proportion to the *loss in quality* or economic value of the material have been presented by, e.g., Werner & Richter (2:4). With this approach most of the environmental burdens of primary production will typically be allocated to the last product in which the material is used.
- Weidema (1:2) and Ekvall (2:1) agree that allocation should be avoided through system expansion, and that the expanded system should include the processes that can be expected to actually be affected by the recycling. However, they disagree on what processes can be expected be affected by the recycling:
    - Weidema (1:2) argue that recycled material from the investigated life cycle typically replaces virgin material. If this is true, the environmental burdens of primary production should be allocated to the last product in which the material is used.
    - Ekvall (2:1) argue that recycled material from the investigated life cycle typically replaces a mix of virgin material and recycled material from other life cycles. If this is true, the environmental burdens of primary production should be divided between the first and the last product in which the material is used. The ratio depends on how sensitive the collection for recycling and the demand for

such material are to changes in the price of the collected material.
- Other approaches have been presented by other authors (1:3, 1:5, 2:4).

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

The linear programming approach of Azapagiz & Clift (1:1) requires some expertise in linear programming.

Vogtländer et al. (2:2) critizise the approach of Guinée et al. (1:4) because it depends on the gate fees and price of recycled materials. These are unstable and highly influenced by govermental policies. For products with a long service life, they are unknown when the product is designed.

Heijungs & Guinée (2:5) point to the fact that system expansion requires more data than a cut-off approach.

Heijungs & Guinée (2:5) and other researchers also argue that system expansion might not eliminate the allocation problem because it often introduces new allocation problems in LCA. To this, it is has been responded that
a) the specific allocation problem at hand is avoided, even if new allocation problems are encountered in the process, and
b) the new allocation problems are often less important than the original allocation problem, which means that it is a fair approximation to neglect the new allocation problems or to solve them with a more simplistic approach.

Other researchers argue that system expansion does not eliminate the allocation problem, because it does not solve the problem regarding how the environmental benefits of recycling should be distributed between the recycled product and the product that contains the recycled material. To this, it is has been responded that there is no important difference between system expansion at recycling and at multi-output processes: it eliminates the allocation problem, but the challenge is to expand the system to include the processes actually affected, as stated in ISO/TR 14049.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Some authors (1:2, 1:3) argue that system expansion is the most adequate approach for consequential LCA,. However, this position seems to be disputed by, for example, Heijungs & Guinée (2:5).

Vogtländer et al. (2:2) state that cut-off using economic allocation is not applicable for products with long service life, notably buildings.

3rd Part: COMMENTS

R&D needs and trends
Ekvall & Finnveden (1:3) states that further research is required to establish whata data should be used at system expansion. Curran (1:5) states that the standard "should be expanded to provide more precise guidance in how to approach allocation. The guidance should be goal dependent". Ekvall (2:1) states that an important research task is to investigate, for the most important materials and markets, how sensitive the collection for recycling and the demand for such material are to changes in the price of the collected material. Matsuno et al. (2:3) argue that further collection of data on steel production, use, and recovery in various countries should contribute to enhancing their model.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. Many scientific papers have been written on allocation at recycling. Only a selection is presented here. In addition, various allocation methods, arguments and analyses have been presented in other formats: PhD theses, conference proceedings, reports, informal discussions, etc. These are not covered by this literature survey. This means the survey presents only part of the diversity in approaches, views and perspectives on allocation in the international LCA community. The large diversity in views and the importance of the methodological problem implies that a significant effort is required to reach a general agreement on - what allocation approach is the most appropriate in different cases, or on - how to identify the most appropriate approach to allocation.

LIFE CYLE INVENTORY

SYSTEM BOUNDARY

[Phase/Topic/Approach]

Inventory analysis/System boundaries

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* ISO 14040 (Section 3.32) defines the concept of system boundary as a set of criteria specifying which unit processes are part of the product system. The product system includes the life cycle from raw material acquisition to final disposal (section 4.3). ISO 14040 states that the system should ideally include all processes that are directly or indirectly connected by physical flows to the product or its function. As observed by, e.g. Raynolds et al. (2:1), this implies that all processes in the global economy should ideally be included in the study. However, according to ISO 14040 (Section 5.2.3) processes that will not significantly change the overall conclusions of the study can be excluded from the system. For this reason, the choice of system boundary depends on the goal and scope of the LCA. To be more specific, it depends on the question to which the LCA should respond. The international standard does not give any specific guidance regarding how the goal of the study affects the system boundary. Here, the distinction between attributional and consequential LCA is a useful example. Attributional LCA aims at describing the environmentally relevant physical flows to and from a life cycle. Consequential LCA aims at describing how the environmentally relevant flows from the technological system as a whole change in response to possible changes in the life cycle (1:3). In an attributional LCA, the system investigated should include all environmentally significant processes in the life cycle from raw material acquisition to final disposal. In a consequential LCA, the system investigated should include processes where the environmental impact is significantly affected, regardless of whether these processes are inside or outside the life cycle of the investigated product (1:1; 1:4). ISO 14044 (Section 4.2.3.3.3) states that the criteria that specifies which unit processes are part of the product system should take into account the mass of the physical flow, the energy demand of the unit processes, and the environmental significance of the unit processes. ISO/TR 14049 says as an example, that the criteria could state that the system boundary should include unit processes responsible for at least 99% of the mass flow, 99% of the total energy demand, and 90% of each environmental impact category. The rest of the processes can be cut off from the system. A problem with such criteria is that it is not possible to know when 90% of the environmental impact or 99% of the energy demand is covered unless data are collected for the full system, i.e. for all processes in the global economy (2:1). Scientific efforts have been directed towards reducing or eliminating the need for cut-off decisions: - The scientifically most significant approach in this effort is probably to apply input-output tables (1:2). This approach potentially eliminates the need for upstreams cut-off, because the input-output table is an aggregated model of all activities in the economy. The approach is further discussed in a separate section.

- Efforts to reduce the need for cut-off include the development of databases and default data aiming to simplify data collection.

Scientific efforts have also been directed towards developing knowledge and methods to improve the basis for cut-off decisions:
- Raynolds et al. (2:1) state that a method to define the system boundary should 1) be quantitative, 2) not require data collection for for all processes in the global economy, 3) be easy to apply and possible to use also in streamlined LCAs, 4) still consider the significance of processes and flows relative to the system as a whole, and 5) facilitate measurements of the system completeness. They propose a method that focus on the mass, energy content and economic value of the flows rather than unit processes. The cut-off criteria is defined as a percentage of the mass, energy content and economic value of the flow that represents the functional unit of the system. As the percentage of the cut-off increases, so does the uncertainty introduced to the overall results (2:2).
- Frischknecht et al. (2:4) investigate the significance of capital goods. They conclude that an LCA typically needs to include the production of capital goods. The only exception is LCAs of metals, where capital goods only have a substantial effect on the land-use impacts.

Some efforts have also been directed towards other types of system boundaries:
- Geographical boundaries: studies have been made by to investigate how different geographical boundaries in the electricity supply system affect LCA results. Koch & Harnisch (2:3) did this in a study on European aluminium production.
- Boundaries in time: this is relevant when emissions occur over a very long time, which can be the case with emissions from landfills or soil. In an environmental product declaration (EPD) of Italian landfills, De Borghi et al. (2:5) defined the system boundary at 30 years after the closure of the landfill. This was in accordance to the product-specific rules defined for such EPDs.
- Boundaries between the technological system and nature: this is relevant to discuss for, e.g., forestry processes, agriculture and landfills. It is related to the boundary in time. If the boundary in time is set to be 30 years after the closure of a landfill, the landfill site is regarded as part of nature after that time.
- Etc.

Finally, scientific efforts have been made to find a more relevant systems perspective than the cradle-to-grave perspective:
- Ekvall & Weidema (1:3) argue that an assessment of environmental consequences should start with the decision at hand, and that it should trace chains of cause and effect originating at this decision. The resulting model does not resemble the cradle-to-grave model in a traditional LCI.
- Ny et al. (1:5) argue that a sustainability assessment should start from the whole biosphere, and that it should focus on activities that contribute significantly to society's violation of the sustainability principles in The Natural Step Framework.

The references selected for the discussion on system boundaries are reviewed papers from scientific journals published the year 2000 or later.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. General references

1. Tillman A-M. (2000) Significance of decision-making for LCA methodology. Environmental Impact Assessment Review 20:113-123.
2. Suh S, Lenzen M, Treloar G, Hondo H, Horvath A, Huppes G, Jolliet O, Klann U, Krewitt W, Moriguchi Y, Munksgaard J, Norris GA. (2004) System boundary selection for life cycle inventories using hybrid approaches. Environmental Science & Technology 38(3):657-664.
3. Ekvall T, Weidema BP. (2004) System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. International Journal of Life Cycle Assessment, 9(3):161-171.
4. Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt W-P, Suh S, Weidema BP, Pennington DW. (2004) Life Cycle Assessment – Part 1: Framework, Goal & Scope Definition, Inventory Analysis, and Applications. Environment International 30(5):701-720.
5. Ny H, MacDonald JP, Broman G, Yamamoto R, Robèrt K-H. (2006) Sustainability Constraints as System Boundaries: An Approach to Making Life-Cycle Management Strategic. Journal of Industrial Ecology 10(1-2):61-77.

2. Specific references

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5. Del Borghi A, Binaghi L, Del Borgi M, Gallo M. (2007) The Application of the Environmental Product Declaration to Waste Disposal in a Sanitary Landfill. International Journal of Life Cycle Assessment 12(1):40-49.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. Data collection is responsible for a large share of the cost and effort in an LCA. The results of an LCA also depends heavily on the completeness and quality of the collected data. For this reason, it is important that the data collection focus on data that are relevant and important for the conclusions of the study. Good cut-off criteria is a valuable tool in this respect. In a comparative LCA, the system boundaries should be equivalent in the compared alternatives. To ensure this, the cut-off criteria should be well defined.
Main advantages
The different approaches presented above have different advantages: - The input-output tables are a powerful tool that potentially allows for including all upstreams activities in the investigated system (1:2). - The approach suggested by Raynolds et al. (2:1) result in well-defined cut-off criteria and also meet other relevant requirements. - The approaches of Ekvall & Weidema (1:3) and Ny et al. (1:5) aims at increasing the relevance of the data and, hence, of the LCA results.
Open questions
Ny et al. (1:5) give little guidance to how to identify the activities that contribute significantly to society's violation of the sustainability principles. Koch & Harnisch (2:3) conclude that it is difficult to identify fully appropriate geographical boundaries for the electricity supply, at least in their study on European aluminum production. There is also no single correct way to decide on - the percentages used as cut-off criteria in the approach of Raynolds et al. (2:2), - the boundary in time, or - the boundary between the technological system and nature.
Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Ekvall & Weidema (1:3) suggests that, for example, partial equlibrium models could be integrated into the assessment to make it possible to trace more chains of cause and effect. It is not clear if this is feasible in practice, as discussed in the section on consequential LCI.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Raynolds et al. (2:1) state that their approach is applicable to LCAs where the focus is on combustion emissions such as CO_2, NO_X, SO_X and hydrocarbons.

The approach of Ekvall & Weidema (1:3) is applicable in consequential LCA.

The approach of Ny et al. (1:5) is applicable in sustainability assessments, when sustainability is defined according to the principles of The Natural Step.

3rd Part: COMMENTS

R&D needs and trends

Suh et al. (1:2) state that further research is required on the integration of input-output tables in LCA. Methods and tools to define the boundary where the input-output tables are applied, to avoid double counting, to make allocation compatible, etc. need further development.

Koch & Harnisch (2:3), who investigated CO_2 emissions of European aluminium production, recommend further research on CO_2 emissions associated with aluminium smelters in other parts of the world.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

The open questions also mentioned above also indicate areas where further research can be justified.

LIFE CYCLE INVENTORY

MODELLING CHANGES OVER TIME

- Scenario analysis
- Dynamic modelling

[Phase/Topic/Approach]
Life Cycle Inventory/Modelling changes over time/Scenario Analysis

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

Scenarios are in one way or another an integral part of any LCA. However, they are not always dealt with explicitly and there has so far been no general LCA framework or procedure available on the systematic development of scenarios.
To deal with these issues, the Working Group 'Scenario Development' in LCA of SETAC-Europe was founded. In the first phase the Working Group has examined how and for what reasons different scenarios are developed for an LCA study.

The term "scenario" is used in a broad sense in various areas, in particular is used to refer to the setting of frame conditions or a description of the system to be modelled. The working group on "Scenario Development in LCA" adopted a more precise definition "*a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future*", but for this review we selected the papers according to the more general one defined above, since the definition itself of scenario is not agreed (in LCA, different choices of the model, of the input parameters, or of the surrounding conditions have often been referred to as a scenario).
The frames of the scenarios are defined in the first phase of LCA, the goal and scope definition. but the details of these scenarios are worked out in the subsequent phases [1].

Dimension of LCA scenario development	Direct influence on inventory analysis	Direct influence on impact assessment
System boundaries	X	
Allocation methods	X	
Technology	X	
Time	X	X
Space	X	X
Characterisation methods		X
Weighting methods		X

An LCA can include a hierarchy of scenarios within scenarios that concerns different parts of the Technosphere, ecosphere, or valuesphere. E.g. the choice of a specific weighting method can be considered as a choice of one specific valuation scenario. The weighting factors themselves can be based on environmental or technology scenarios about future damages.

The LCA framework defined in ISO 14040 does not explicitly include scenario development in its covered usage.
Since scenarios inherently deal with the past, present and future situations, including the paths among them, time-dependent conditions and effects should be taken into account in scenario development [3].

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. **General references**

- [1]. G. Huppes et al., **The nature of modelling in LCI**", UNEP-SETAC WG Inventory Analysis TF3 Methodological Consistency, Draft version 2006
- [2] B.P. Weidema et al., **Scenarios in Life-Cycle Assessment**, SETAC-Europe LCA Working Group *Scenario Development in LCA*; SETAC publication, 2004.

2. **Specific references**

- [3] Y. Fukushima, M. Hirao, **A structured framework and language for scenario-based life cycle assessment**, Int J LCA 7 (6) 317-329, 2002.
- [4] M. Shimada, K. Miyamoto, Y. Fukushima, M. Hirao, **A new methodology for time-dependent scenario-based analysis**, abstract presented at Setac Europe 11th Annual Meeting, 2001. No full paper available.
- [5] M. Spielmann, R. W. Scholz, O. Tietje, P. de Haan, **Scenario modelling in prospective LCA of transport systems. Application of Formative Scenario Analysis**, Int J LCA 10 (5) 325-335, 2005.
- [6] H.L. Pesonen, T. Ekvall, G. Fleischer, G. Huppes, C. Jahn, Z.S. Klos, G. Rebitzer, H. Wenzel, **Framework for scenario development in LCA**. International Journal of Life Cycle Assessment 5 (1), pp. 21-30 (2000).
- [7] M. H□jer et al., **Scenarios in selected tools for environmental system analysis**. Journal of Cleaner Production xx (2008) 1-13, article in press.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Scenarios in LCA cover all the procedure's steps: in "Goal and scope definition" the elements relevant for the scenario analysis are defined, while the modelling of scenarios is done in LCI and LCIA and, finally, in the Interpretation conclusions and results are discussed. Despite scenarios in LCA are very relevant, because the inherent decision-support nature of LCA (and decisions relate to future), the literature analysed does not show such evidence.

Indeed, the issue of scenarios is a complicated matter for two main reasons:

i) they deal with the future, that is uncertain by definition, and

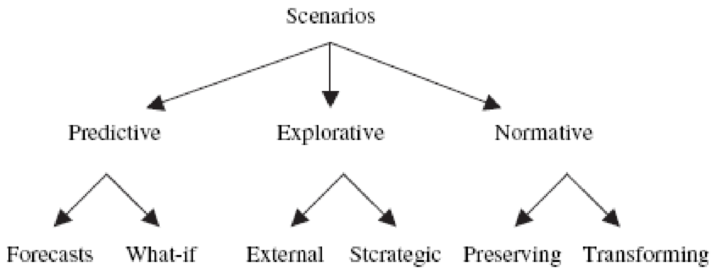
ii) they involve expertise in different disciplines.

When translated into the LCA field, these principal features, pose several questions:

- Scenario definition and scenario categories.
- Techniques for scenario development.
- Data availability.
- Relevance: when the use of scenarios is relevant in LCA?
- Uncertainty: how to evaluate the inherent uncertainty of future evaluations?
- Expertise: the use of scenarios requires to go beyond the LCA domain, and to involve expertise belonging to the field of economy, planning, etc.

The paper presented by H□jer et al. (2008), addresses these questions: its main purpose is to analyse how different types of scenarios can be used in connection with different environmental systems analysis tools, among which LCA. This paper was very useful for this review, as it is an analysis of the state-of-the-art of the applications and role of scenarios into LCA. For this reason, this paragraph is mainly based on that paper. The authors refer to the work of B□rjeson et al. (2006) that presented a guide to help users in selecting the appropriate scenario types for a specific situation and in understanding which specific category of scenario can be used for. A general framework for scenario development in LCA can be found in Pesonen et al. (2000) and Weidema et al. (2003a), but a first structured framework for scenario-based LCA was proposed by Fukushima (2002). Pesonen et al. (2000) introduced two basic approaches: what-if-scenarios and cornerstone-scenarios, also in relation to the time frame of the analysis. What-if-scenarios are used in situation with a short time horizon when the researcher is familiar with the decision problem and can set defined hypothesis on the basis of existing data; cornerstone scenarios are more suited to long term planning and give potential direction of future developments.

B□rjeson et al. (2006) further detailed this classification by proposing the scheme showed below, in which three main categories of scenarios are distinguished, namely predictive (what will happen?), explorative (what can happen?) and normative (how can a specific target be reached?), each of them containing two scenarios types, respectively: Forecast and What-if, External and Strategic, Preserving and Transforming. What-if and cornerstone, in this scheme, belong respectively to predictive and explorative scenarios.



Scenario typology. Source: B□rjeson et al. (2006)

The paper by H□jer et al. (2008), highlights other main aspects:

- **Data**.

Data availability and reliability represent a hot spot that hampers the application of scenarios to LCA. Indeed, the data uncertainty can be very large in scenarios that refer to technologies not yet in use and, furthermore, most LCAs are based on input data that refer to several years ago, an element that makes their representativeness questionable in prospective studies.

- **Uncertainty**

Uncertainty is inherent to future evaluations and reduces the value of long-term forecasts. Despite the authors state that there is no exact time frame when forecasts are considered too uncertain, because it depends on the aim of the study as well as on worldviews and perceptions, the knowledge generated by scenarios should be evaluated together with the associated uncertainty. Indeed, scenarios' user should be aware of the uncertainty related to the scenario, in order to make the most suitable choice, clearly also in accordance with other boundary conditions. Thus, dealing with scenario increases the need for methods for uncertainties treatment.

- **Relevance**, i.e. in which situation one approach is more suited than others, in terms of its ability to make the knowledge required available.

The authors showed that predictive and explorative scenarios could be useful in analytical tools like LCA to describe future situations; on the other hand, transformative scenarios, in which large changes in the overall structure are involved, seem to be of little use in LCA due to the difficulty in making available reliable input data for LCA.

The work performed by H□jer et al. (2008) represents a good starting point in order to improve the use of scenarios in LCA, but further research is needed in this area, both at methodological and practical level, trying to find a balance between the feasibility and the uncertainty related to scenario development. One research line could be devoted to develop a set of forecasts, with a number of different parameters, which could be used as general input for many LCA studies (H□jer et al., 2008). Indeed, this contradict, as pointed out by H□jer et al. (2008), what the scenario literature often recommend, that scenarios should be tailor-made to the specific question. However, the limited resources available would suggest the development of consistent and generic scenarios of different types that could be used by different practitioners. Maybe, since the necessary expertise is not always available when scenarios are developed, the availability of pre-defined scenarios, with a defined resolution at different level, would increase their use in analytical tools such as LCA and the final results would benefit from it in terms of consistency and transparency.

Further elements on how to analyse scenarios in LCA will be brought into the debate by the upcoming "guidance document for future scenario LCA studies and data", within the ILCD Handbook of the European Platform on LCA (2nd half of 2008)

[3] Fukushima et al.
The authors propose a general framework for scenario-based LCA (based on the definition of scenario given in [2]), a framework that provides retrospective and prospective studies with a clear structure. The most important characteristic of the structure is the recognition and separation of three modelling processes, lifecycle modelling, scenario modelling and valuation modelling. Next, they introduced a tool, termed lifecycle modelling language (LCML), developed for modelling lifecycle systems and valuation procedures with its relevant scenarios within the proposed framework. LCML facilitates accumulating knowledge obtained from scenario-based LCA studies, by reusing the constructed models, or by applying the same patterns identified from the LCML description, and contributes to reducing the time and efforts needed for an investigation.

[4] M. Shimada et al.
The authors developed a new methodology to model time dependent lifecycle and extended their LCML tool presented in [3] and developed a new methodology which enables to perform a time-dependent scenario-based analysis. In a lifecycle model constructed using extended LCML, a) all parameters such as relations between input and output of a process, flow rates and constraint parameters can be treated as time-dependent functions; b) social stocks such as the amount of products in use can be taken into consideration.

[5] M. Spielmann et al.
The authors considered a set of cornerstone scenarios representing future developments of an entire Life Cycle Inventory (LCI) product system. They illustrated the method using a comparison of future transport systems.
Scenario modelling is organized by means of Formative Scenario Analysis (FSA), which provides a set of possible and consistent cornerstone scenarios. Unit processes scenarios are generated for those unit processes of an LCI product system which are time dependent and of environmental importance. Unit process scenarios are combinations of levels of socio-economic and technological impact variables. Two core elements of FSA are applied in LCI scenario modelling. So-called impact matrix analysis is applied to determine the relationship between unit process specific socio-economic variables and technology variables. Consistency Analysis is employed to integrate various unit process scenarios into the overall cornerstone scenarios, based on pair-wise ratings of the consistency of the levels of socio-economic impact variables of all unit processes. Two software applications are employed which are available from the authors.

Open questions

[1] ▪ When presenting the results of a multiple scenario study, the issue of uncertainties included in each of the scenarios becomes extremely important. The decision-maker has to be fully aware of the uncertainties underlying each scenario in order to be able to make comparisons between them. See rationale fur further information.
Practicability aspects
Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. [4] The approach is applied in a case study on comparison of polyvinylchloride and polyethylene water pipe.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. [1] ▪ Scenario development will therefore increase the need for methods how to treat uncertainties in the data as well as the need for a procedure for estimating input data [3] ▪ Even if the methodology of the scenario development is established and even if it is integrated with LCA, it must be noted that extended use of LCA for scenario development is a costly activity. Since there is little accumulated knowledge about the scenario development and a scenario always includes non existent processes, the model to be evaluated must be constructed from the very beginning and the data collection may be more difficult than in the conventional LCA studies. Therefore, accumulation of knowledge about the scenario development must increase reusability of models and data. ▪ More efforts to assure transparency are needed in the novel applications of LCA to scenario development, because of the increased complexity and uncertainty in models and data.

See rationale for further information.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

Life Cycle Inventory/Modelling changes over time/Dynamic modelling

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* The treatment of time turns out to be an important task of modelling in the inventory phase. Historically, time has been ignored or assumed to be infinite. LCI is based on a steady state linear equilibrium model, i.e. a model that indicates a hypothetical equilibrium situation with *ceteris paribus* assumptions. This means that no technology will change; no adaptations other that supply-demand matching will take place; and equilibrium will be reached (Huppes et al., 2006 draft). Changes in time are ignored because time is outside the model: this could be an acceptable simplification if the situation develops gradually without interruptions and quick changes are not foreseen. Looking at the future is the main task of policy makers, thus the analysis should allow considering the future boundary conditions like legal regulations, changes in technology, i.e. it should allow considering the time dimension in a proper way. In the last years, several attempts to introduce time dimension in the LCA modelling have been proposed as a reply to the apparent limitation of ISO LCA structure, but the applications are still controversial.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- [4] G. Huppes et al., **The nature of modelling in LCI**", UNEP-SETAC WG Inventory Analysis TF3 Methodological Consistency, Draft version 2006.
2. Specific references
- [1] Hiroki Hondo, Yue Moriizumi, Tomohiko Sakao, **A method for Technology Selection Considering Environmental and Socio-Economic Impact. Input-Output optmization model and its application to housing policy**, Int J LCA 11 (6) 383-393, 2006.
- [2] Thomas Gloria, **An approach to Dynamic Environmental Life Cycle Assessment by evaluating Structural Economic Sequences**, PhD thesis Tuft University, May 2000. - [3] Alissa Kendall **A dynamic life cycle assessment tool for comparing bridge deck design**, Centre for Sustainable Systems – University of Michigan (2004).

- [5] K. Yokota, Y. Matsuno, M. Yamashita, Y. Adachi, **Integration of life cycle assessment and population balance model for assessing environmental impacts of product population in a social scale**, Int J LCA 8 (3) 129-136, 2003.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

The term "dynamic LCA" in this review refers to the inclusion of time dimension in LCI, both in terms of continuous mathematical function ("true" dynamic) and discrete intervals ("quasi" dynamic). Indeed, the terminology used in LCA literature is sometime confusing and misleading as some authors use the word "dynamic" as synonym of dependence on chosen parameters rather than of "changes over time".

This is, for example, the approach presented by Kendall (2004), in which the proposed LCA model is considered dynamic due to the dependence on the chosen design parameters. The model allows comparing the sustainability of alternative concrete bridge deck designs, and broadens the scope of bridge LCA studies by accounting for the dynamic nature of the interlinked bridge and traffic system. The timeline can be changed to reflect changes in assumptions regarding the life of the bridge deck, the durability of repairs and for sensitivity analysis. The idea is that an optimal formulation of materials can be developed through iterations in material formulations and their associated LCA. The LCA computer model developed is tailored to a specific bridge deck application, but its dynamic nature makes it applicable also to other infrastructure systems such as roadways and concrete pipe.

The other approaches selected for the review share the definition of "dynamic LCA" chosen for this review. In particular Pehnt (2006) developed a dynamic LCA in which the future state of the system is modelled extrapolating into the future those parameters that are environmentally relevant and at the same time show a significant time-dependency.

Yokota et al. (2003) presented an approach in which LCA and Population Balance Model (PBM) were integrated to quantitatively assess the total environmental impacts induced by the product population in a society over time. They introduced time as a critical parameter and employed all the products in a society as a proper unit of analysis to assess the environmental impacts of a technology/product, while not explicitly dealing with socio-economic aspects.

Fischer & Pflieger (2007) have presented the inclusion of time as a continuous mathematical function by developing a time-dynamic parameterized LCI-model, i.e. the modelling of time-related aspects by considering dynamic changes in physical/technical system. The model comprises three steps:

i) the parameterized modelling, i.e. the identification of relevant parameters in LCI: these are parameters with a high environmental relevance and important technological changes within short time periods.
ii) The development of time series for parameters processes and systems to be used in parameterized models.
iii) The development of prognosis functions for the parameters. This means that for each point of time, the inventory quantities can be calculated as a function of time dependent parameter: thus, each parameter is described by a continuous mathematical function.

Various statistics and existing databases provide a good basis to implement key categories like energy production, material production or transportation for a broad period, nevertheless the major limitation is the lack of data. LCI(t) is possible but challenging and existing tools have to be adjusted. Further research should be directed towards the identification of industry sectors where time-related issues are relevant to LCA results and the realization of data preparation for relevant processes there.

"True" (i.e. in terms of continuous mathematical function) dynamic approaches are still pioneering, and several efforts are still necessary both at methodological and practical level: indeed, the available software tools do not reflect advances in modelling because they are based on static relations, and are not supported by databases that could be representative of the future situation.
Research lines should consider what knowledge is added to LCA from dynamic models: maybe spending resources on developing models in which time is modelled as a continuous mathematical function could be unfruitful, since the use of recursive analysis in different time frames with data representing future technological relations could give a valid answer as well. On the other hand, the issue of distribution of impact over time would represent a more interesting field of analysis, at present not covered by the literature analysed in this review.
Then, an accurate balance should be found between the need of having an optimum representation of the reality and the complexity/feasibility of the modelling itself. For decisions related to the long period, the use of scenarios could be more relevant and feasible: on this aspect, efforts should be spent developing technological scenarios related to the main processes.

Some approaches more in detail:
<u>[1] H. Hondo et al.</u>
The authors developed a new methodology, considering the context of a society where technologies are introduced, in order to determine **the optimal configuration of technologies to minimize the cumulative environmental burden over time on a social scale.** An <u>inter-temporal linear programming model using an input-output table was formulated</u> to make the methodology operational. Using the new model, the optimal use of long-life and thermal insulating technologies for houses is examined to minimize CO2 emissions across the entire life cycle of all the houses in Japan. First, the causal relationships between different times were modeled. An inter-temporal model is useful to analyze the step-by-step consequences by a decision with regard to technology/product selection in the future. Second, a basic scenario in the future (e.g. population, technological structure, households' disposal incomes) was adopted to simulate the state of technology selection using the model.
The results show that it is not always feasible or not necessarily an optimal solution on a social scale to introduce only a technology that is best evaluated by using the conventional LCA. Inferior technologies can also play a significant role because of various socio-economic conditions and requirements, e.g. population decline, limited housing budgets, and employment stability.
The question addressed by the present study, i.e. the choice of house-related technologies in the future, is considered to be the consequential approach-type (an approach designed to describe the consequences of a decision)

<u>[2] T. Gloria</u>
The author wants to demonstrate the steps necessary to conduct a dynamic LCA study by embracing the construct of structural economics with emphasis on utilizing a dynamic input-output framework. The method approach incorporates endogenous as well as exogenous changes such as technological changes and changes in consumer demand as they affect environmental impacts in a dynamic framework. Specifically, it will focus on

the key elements of structural economics using a Sequential Interindustry Model (SIM), that creates a temporal framework by distributing the static I-O modelling activities over time. SIM is based on the Leontif static model where interdependencies and the specifics of production technology are captured. The model generates a simulation of emissions to the environment based on scenarios of economic activity. This is accomplished by creating a projection in time of a sequence of production activities and consumption activities based on present and future consumer demand activities.

Main advantages

[1] H. Hondo et al.
The new methodology proposed can provide valuable information to support policy-making toward a sustainable society.
Furthermore, the methodology succeeds in revealing the process of changes by explicitly introducing the notion of time.
The present methodology allows for exploring the factors/mechanisms that strongly affect the environmental consequences, by adopting an optimization model that represents various socio-economic factors as constraints.

[2] T. Gloria
The approach considers how to deal with the dynamics of technological changes and changes in final demand.
The dynamic simulation gives insight to the dynamics of a new technology and its diffusion into a dynamic economy and its ultimate change in resources used and emissions to the environment: this means that the effects of the dynamics of the economic system and the relevance to the introduction of the new technology can be examined.

[3] Kendall

- An expanded scope over previous LCA studies. The model broadens the scope of bridge LCA studies by accounting for the dynamic nature of the interlinked bridge and traffic system. This new scope is an important development in LCA applications to bridges and similar infrastructure systems.
- LCA model flexibility: users can explore the impacts of changes in material formulation and properties as well as test the sensitivity of the model with regard to key assumptions.
- The model proposed can manage a long-lived system and respond to changes in many system parameters and provide sensitivity analysis to uses uncertainty.

Open questions

[1] H. Hondo et al.
The operational model proposed still has scope for improvement, and the validity of assumptions in the future should be discussed. The present results also imply that the stability of employment would influence the technology selection and environmental consequences, which has received little attention so far. Thus, it may be worthwhile to explore the interaction between employment stability and technology selection more.
This study deals with only the labour market for the house construction sector, although a macro-level unemployment rate may be more suitable as an indicator of social acceptability. Treating the unemployment rate in a society as a constraint requires consideration of labour movement between different industries, employment adjustment time for each industry, etc.
Since there are unavoidable uncertainties in the future, the simulation results in the present study also have various uncertainties.

See rationale for further information.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

[1] H. Hondo et al.
The inter-temporal linear programming (LP) model was execute with the GAMS (General Algebraic Modelling System) code.

For the other approaches, no problems related to practicability aspects have been underlined.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

[1] H. Hondo et al.
The new approach has been applied to technology selection for housing policy toward the long term reduction of CO_2 emissions in Japan.

[3] Kendall
The LCA computer model is tailored to a specific bridge deck application, but its dynamic nature and the larger integrated framework of macroscale modelling and microscale tailoring can be applied to other infrastructure systems such as roadways and concrete pipe.

[5] Matsuno et al.
The method has been applied to assess the GWP for air conditioner but it is applicable also to assess other environmental impacts caused by a variety of product population.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. <u>[1] H. Hondo et al.</u> It may be worthwhile to explore the interaction between employment stability and technology selection more. The combination of inter-temporal modeling and scenario development in the future contributes to a prospective analysis on technology/product selection based on the consequential approach. <u>[2] T. Gloria</u> There is a need for discussion and consensus in the open literature regarding the philosophy and construct of dynamic LCA. <u>[3] Kendall</u> ▪ Fully integrated the LCA model with a life cycle cost (LCC) model ▪ Model additional concrete infrastructure systems such as roadways and concrete pipe. ▪ Considering changes over time in material production energy intensities and emissions factors in future modeling ▪ Expand the scope of the LCA model to include other advanced materials.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. The majority of the approaches analysed do not consider the time modelling in a proper way: often the terminology used is quite misleading. This means that many authors with the term "dynamic" do not intend the change over time but the dependence of chosen parameters. See rationale for further information.

LIFE CYCLE IMPACT ASSESSMENT

NEW IMPACTS CATEGORIES + METHODS

- GMO
- Radiation
- Indoor
- Water
- Salinity
- Fire

[Phase/Topic/Approach]
LCIA/new impact categories + methods/GMO

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- Jank, Bernhard; Berthold, Aline; Alber, Sebastian; Doblhoff-Dier, Otto (1999). Assessing the Impacts of Genetically Modified Microorganisms. International Journal of Life Cycle Assessment, 4,5, 251-252.
2. Specific references
-

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. Biotechnology could play an important role in reducing the relative consumption of energy and raw materials, in recycling and the elimination of wastes. The risk assessment of microorganisms used in biotechnology is an important prerequisite for introducing new production strains. Risks in respect to human health may be due to pathogenicity, allergenicity or the production of toxic metabolites. Pathogenic microorganisms may enter the human body and initiate an infection, depending on their transmissibility, infectivity and virulence. LCIA methods today are not capable yet of including and assessing such risks. Jank et al. (1) tried to integrate the concept of risk assessment of microorganisms into the impact assessment of LCA in the following way: According to their hazardous characteristics, microorganisms, and genetically modified microorganims in particular, were assigned to more or less homogeneous impact categories, called risk classes, see Table).

Table: Risk classes of microorganisms based on the classification by the European Federation of Biotechnology (EFB).

1	Microorganisms that have never been identified as causative agents of disease in man and that offer no threat to the environment.
2	Microorganisms that may cause disease in man and which might, therefore, offer a hazard to laboratory workers. They are unlikely to spread in the environment. Prophylactics are available and treatment is effective.
3	Microorganisms that offer a severe threat to the health of laboratory workers, but a comparatively small risk to the population at large. Prophylactics are available and treatment is effective.
4	Microorganisms that cause severe illness in man and offer a serious hazard to laboratory workers and to people at large. In general, effective prophylactics are not available and no effective treatment is known.
E	Microorganisms that offer a more severe threat to the environment than to man. They may be responsible for heavy economic losses. This group includes several classes, Ep1, Ep2, Ep3 to accommodate plant pathogens.

The classification of microorganisms was qualitative and did not take into account the actual concentrations and volumes.
The probability of infection also depends on the amount and concentration of viable agents to which a person is exposed. LCA offered the opportunity for quantitative risk assessment taking into account volumes and concentrations. This approach requires quantitative factors for hazardous characteristics of individual microorganisms. Hazardous characteristics such as pathogenicity, allergenicity and toxicity appeared, however, difficult to get.

Main advantages

Main advantage of the approach of Jank et al. (1) is that a first attempt has been undertaken to also include impacts of GMOs into LCA.

Open questions

	Jank et al. (1)
Impact category	Risk classes (see table above)
intervention	releases of GMOs (??)
Indicator	pathogenicity, allergenicity, toxicity
Characterisation model	n.a.
Characterisation factor	n.a.

The table above illustrates the compliance of the Jank et al. (1) method with the general structure of LCIA (see Annex X). Main gaps for this impact category and method include the unambiguous definition of the interventions, the indicator, the characterisation models, its data needs and related characterisation factors. All of these need further elaboration.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach. GMO aspects can currently not yet be included quantitatively into LCA. The practical use of the current approach is very limited as it requires significant efforts from the practitioner.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. All sectors and applications involving GMOs.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/new impact categories + methods/radiation

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. The impact category 'impacts of ionising radiation' covers the impacts arising from releases of radioactive substances as well as direct exposure to radiation, in building materials for example. Exposure to ionising radiation is harmful to both human beings and animals. The areas of protection are therefore human health, the natural environment and natural resources.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Frischknecht, R.; Braunschweig, A.; Hofstetter, P.; Suter, P. (2000). Human health damages due to ionising radiation in life cycle impact assessment. Environmental Impact Assessment Review, 20, 159-189.
- (2) Meijer, Arjen; Huijbregts, Mark; Reijnders, Lucas (2005). Human Health Damages due to Indoor Sources of Organic Compounds and Radioactivity in Life Cycle Impact Assessment of Dwellings - Part 2: Damage Scores. International Journal of Life Cycle Assessment, 10, 6, 383-392.
2. Specific references
-

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Most LCIA approaches today neglect effects due to ionising radiation. Frischknecht et al. (1) describe the assessment of the human health damages related to the man-made routine releases of radioactive material to the environment as reported in LCA. The fate and exposure analyses are based on site-specific modelling of the French nuclear fuel cycle, from which generic exposure factors are derived. The effect analysis is based largely on epidemiological studies. The damage analysis relies on the concept of disability adjusted life years (DALY). Cultural theory is used in the damage assessment to create two value-compatible assessment scenarios. Two sets of damage factors for damage-oriented and two sets of equivalency factors for effect-oriented impact assessment methods are presented.

Building on Frischknecht et al. (1), Meijer et al. (2) determined characterisation factors for radon and 3 gamma-radiating elements that are released from building materials inside dwellings.

Main advantages

A comprehensive tool such as LCA should not neglect potentially relevant effects to human health. This becomes more evident as an assessment of human health damages of different electricity supply systems showed that low-dose ionising radiation contributes to 13% and 80–99% of total human health damages of nuclear power production, applying an individualist and an egalitarian perspective, respectively (1).

Open questions

	Frischknecht et al. (1)	Meijer et al. (2)
Impact category	radiaton	human health
intervention	release of radioactive isotopes	release of radioactive isotopes
Indicator	damage to human health (DALY)	damage to human health (DALY)

The table above illustrates the compliance of the Frischknecht et al. (1) and Meijer et al. (2) with the general structure of LCIA (see Annex X). Main gap for this impact category and method is the expansion of the list of characterisation factors to include more than the current 31 radionucleides (1) and 3 gamma radiating elements and radon (2).

The impact pathway and damage factors assigned to the 31 radionucleides considered by Frischknecht et al. (1) correspond to the typical situation for Western European nuclear power supply. It must be emphasised that this assessment does not include human health damages due to ionising radiation released by severe accidents, nor by long-term underground waste storage facilities. Emissions stemming from other sources (e.g., coal power plants) can be evaluated with the same coefficients if the typical situation (population density, meteorology, etc.) is analogous. For other radionucleides, new calculations according to the prevalent pathways need to be done. Furthermore, the damage factors given by (1) are expected to change due to future improvements of the models (although we expect the main structure of the proposed approach to be maintainable).

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach. Lists of characterisation factors help increase practicability. Main problem is getting the relevant emission data as far as these are not provided by e.g. the ecoinvent database for the energy sector; for instance for building materials this my be a serious problem
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. Western European nuclear power supply and in terms of population density, meteorology, etc. analogous situations (1); indoor, Dutch reference an analogous dwellings (2)

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/new impact categories + methods/indoor & occupational exposure

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Bruzzi, R.; E. Demou, P. Droz, S. Hellweg, M. Huijbregts, O. Jolliet, A. Langenegger, D. Vernez, A. Meijer and M. Huijbregts (2006). Indoor Exposure Models and their Applicability to LCA. Part A: Occupational Exposure; Part B: Household Exposure. Draft 30-10-2006.
2. Specific references
- (2) Meijer, Arjen; Huijbregts, Mark; Reijnders, Lucas (2005). Human Health Damages due to Indoor Sources of Organic Compounds and Radioactivity in Life Cycle Impact Assessment of Dwellings - Part 2: Damage Scores. International Journal of Life Cycle Assessment, 10, 6, 383-392.
- (3) Hofstetter, P.; Norris, G.A. (2003). Why and how should we assess occupational health impacts in integrated product policy? Environmental Science & Technology, 37:10, 2025-2035.
- (4) Meijer, Arjen; Mark Huijbregts; Edgar G. Hertwich; Lucas Reijnders (2006). Including Human Health Damages due to Road Traffic in Life Cycle Assessment of Dwellings. International Journal of Life Cycle Assessment, 11, Special Issue 1, 64-71.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. Most LCIA approaches today neglect occupational health effects. Except for the Nordic countries, where some efforts have been made to address occupational exposure, models to assess occupational health effects in LCA are scarce. Recently, attempts have been made to integrate indoor exposure models with environmental models commonly applied within LCA. The conclusion from these studies is that indoor airflow and exposure models are in principle compatible with environmental models, and that the importance of occupational health effects in comparison to the total human toxicity effects may be significant (3). Meijer et al. (2,4) determined characterisation factors for 36 volatile organic compounds, radon and 3 gamma radiation for a Dutch reference dwelling, and calculated damage score for a range of building materials applying these factors.
Main advantages
A comprehensive tool such as LCA should not neglect potentially relevant effects to human health – moreover as human exposure in indoor environments is generally significantly higher and longer than in ambient (outdoor) environments - and by including methods considering indoor exposure to chemicals within LCA, problem shifting to indoor environment is mapped and can in principle be avoided. Main advantage of (2,4) compared to (3) is the fact that (2,4) provided quantitative CFs comparable to CFs of other impact categories, whereas (3) is a qualitative method.
Open questions
Main gaps for this impact category and the methods of Hofstetter & Norris (3) and Meijer et al. (2,4) are the lack of emission data (2,3,4), qualitative character of the characterisation method (3) or the expansion of the list of characterisation factors to include more than the current 36 organic volatile, 3 gamma radiating elements and radon (2,4). Data is still a problem on both impact assessment level as on the inventory level. Emissions to the workplace are often unknown. Thus, in order to consider workplace emissions within LCA, emission factors need to be made available. Furthermore, exposure determinants vary among workplaces. For instance, room dimensions and ventilation rates may differ among workplace settings. Therefore, it is unlikely that a single standard model for indoor exposure with fixed parameter values can be used.
Practicability aspects
Practicability aspects refer to the availability of tool and data in order to implement the analysed approach. Except for the method of Meijer et al. (2,4) – who have determined emission rates for 38 volatile organic compounds, radon and gamma radiation emitted by 17 building material categories – other practical lists of emissions and associated characterisation factors are lacking hindering full application of these methods/models.

Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. Indoor dwellings (2,4). Workplace (3).

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. The trend foreseen is that indoor (fate & exposure) will become a compartment in the UNEP-SETAC model for life cycle impact assessment of toxic releases: USE-tox. It will then not be a separate impact category anymore.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/new impact categories + methods/other new impact categories

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es.
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. **General references**

- (1) Pelletier, N.L.; Ayer, N.W.; Kruse, S.A.; Flysjo, A.; Robillard, G.; Scholz, A.J.; Ziegler, F.; Tyedmers, P.H.; Sonesson, U. (2007). Impact categories for life cycle assessment research of seafood production systems: review and prospectus. International Journal of Life Cycle Assessment, 12, 6, 414 – 421

2. **Specific references**

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Life Cycle Assessment (LCA) offers a convenient means of quantifying the impacts associated with many of the energetic and material inputs and outputs in seafood production industries. However, the relevant but limited suite of impact categories currently used in most LCA research fails to capture a number of important environmental and social burdens unique to fisheries and aquaculture. Notable examples include the modeling of benthic impacts, by-catch, emissions from anti-fouling paints, and the use of Net Primary Productivity appropriation to characterize biotic resource use. Socio-economic impacts have not been quantified, nor does a generally accepted methodology for their consideration exist. Pelletier et al. (1) have reviewed a number of developments and proposals for operationalising such seafood production related impact categories in LCA, and conclude a.o. that “while these impacts are, indeed, highly relevant, convincing methods for relating them to a functional unit must be developed before they can be incorporated in standard LCA research.”

Main advantages
Main advantage of the review by Pelletier et al. (1) is that a number of impacts are identified that need to be worked out further if LCAs of seafood production systems would have to become more reliable and more in line with the range of environmental and socio-economic impacts associated with fisheries production. Or as Pelletier et al. (1) state: “it is apparent that the development of appropriate impact categories will be essential to arriving at more comprehensive evaluations of the environmental and social interactions of seafood production.”
Open questions
Some impact categories have been identified but elaborated methods fitting in the general structure of LCIA are still missing and should be developed.
Practicability aspects
Practicability aspects refer to the availability of tool and data in order to implement the analysed approach. Methods and factors are still lacking.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. Seafood production systems.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.
Comments
Comments of the person who fill in the scheme in order to understand the “importance” of the approach analysed.

[Phase/Topic/Approach]
LCIA/new impact categories + methods/water

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. This impact category deals with water quantity aspects, or in other words the resource availability of the resource water. Water quality aspects are assumed to be covered by other impact categories including the toxicity impact categories, eutrophication and acidification. Water is a fund resource, i.e. resources that can be used or depleted since they possess the capability of regeneration. Depletion of water is by definition a local or regional problem. As far as water use is included in LCA, the LCIA indicator often used for water use is the total input of water used (kg or m^3). This indicator is, however, not adequate to assess water resources from a sustainability perspective.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- UNEP-SETAC Life Cycle Initiative WG LCIA TF2 on resources: Pro Memori.
2. Specific references
- (1) Owens J. W. (2002). Water Resources in Life-Cycle Impact Assessment: Considerations in Choosing Category Indicators. Journal of Industrial Ecology, 5, 2, 37-54.
- (2) Heuvelmans, G.; Garcia-Qujano, J.F.; Muys, B.; Feyen, J.; Coppin, P. (2005). Modelling the water balance with SWAT as part of the land use impact evaluation in a life cycle study of CO2 emission reduction scenarios. Hydrological Processes, 19, 729-748.
- (3) Pfister, S. (2007). Assessment methodology for water consumption in the context of LCA. http://www.ifu.ethz.ch/ESD/research/water_use/index_EN

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Owens (1) proposes new indicators including in-stream water *use* indicator; in-stream water *consumption* indicator; off-stream water use indicator; off-stream water consumption indicator; and of-stream water *depletion* indicator.
Heuvelmans et al. (2) proposes an indicator of the depletion of water due to water use (water as a resource). The proposed characterisation model is the dynamic water reserve life (DWRL = R/(U-P)). The dynamic water reserve life is a function of regional reserves of water (R) and current regional consumption (U) and precipitation (P). The necessary inventory data to calculate the impact score is the consumption of water (kg).
Stefan Pfister (3) at ETH Zürich just started a project developing an assessment methodology for water consumption in the context of LCA including following Sub-goals:

- Analysis of water consumption patterns in industry and other economic sectors
- Qualitative vulnerability analyses of the changing availability of water resources, identifying stress factors on diverse ecosystems and human groups in different regions
- Description and quantification of the cause-effect chains (integration of vulnerability-assessment results and potential environmental effects)
- Development and application of a generic assessment method to quantify the impact of water use on humans and the natural environment
- Adaptation of the proposed assessment method to the most important LCA methodologies and existing life cycle inventories (LCI)

GIS-based data evaluation, correlation analyses and case studies in cooperation with industrial partners are among the methods applied.

Main advantages

Main advantage is that first suggestions are done how to improve and elaborate the impact assessment of water use (water as a resource).

Open questions

	Owens (1)	Heuvelmans et al. (2)	Pfister (3)
Impact category	n.a.	depletion (water)	n.a. yet
intervention	water use (kg)	water use (kg)	n.a. yet
Indicator	in-stream water *use*; in-stream water *consumption*; off-stream water use; off-stream water consumption; off-stream water *depletion*	dynamic water reserve life (DWRL)	n.a. yet
Characterisation model	n.a.	DWRL = R/(U-P)	n.a. yet

Characterisation factor	n.a.	n.a.	n.a. yet

The Table above illustrates the compliance of the methods discussed above with the general structure of LCIA. Pfister (3) has just started his research and therefore has no results yet. Main gaps for the other two methods are methods operationalisation of indicators, characterisation model and related characterisation factors (1) or the operationalisation of the characterisation models and related characterisation factors (2).
The objective of Owens' (2) contribution to this impact category was merely to enhance the further development of LCIA water indicators, but his contribution stopped at proposing the indicators listed above without further elaboration inot characterisation models and factors.
For the water depletion indicator proposed by Heuvelmans et al. (2), no operational factors are available as yet. To derive such a set, information on the reserve fresh water is necessary. Furthermore, also worldwide evapotranspiration and precipitation data should be available. Finally, because water is not globally available (i.e. not shipped all over the world like ores and fossil fuels) a differentiation of the factors for different regions is recommendable, using regional reserves, regional evapotranspiration and precipitation rates.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Practical value of the methods discussed is currently very limited, unless practitioner is willing to put significant efforts into operationalisation of the methods proposed.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

No limitations.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/new impact categories + methods/salinity

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. Current LCIA methods do not adequately characterize the effects of common ions associated with salinity impacts. Salinisation of water resources and of agricultural plots is of strategic concern in countries as South Africa and Australia, and the need for life-cycle assessments to be able to incorporate salinity effects is apparent. There are sufficiently clear cause-effect relationships between the sources and impacts of salinity, and impacts are claimed to be sufficiently different in nature from existing categories to warrant a separate salinity impact category. The references include only specific methods as developed for soil salinisation in Australia (1) and water and soil salinisation in South Africa (2)-(4).
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
2. Specific references
- (1) Feitz, Andrew; Lundie, Sven (2002). Soil Salinisation: A Local Life Cycle Assessment Impact Category. International Journal of Life Cycle Assessment, 7, 4, 244-249.
- (2) Leske, T.; Buckley, C. (2003). Towards the development of a salinity impact category for South African environmental life-cycle assessments: Part 1 - A new impact category. Water SA, 29, 3, 289-296.
- (3) Leske, T.; Buckley, C. (2004). Towards the development of a salinity impact category for South African life cycle assessments: Part 2 - A conceptual multimedia environmental fate and effect model. Water SA, 30, 2, 241-251.
- (4) Leske, T.; Buckley, C. (2004). Towards the development of a salinity impact category for South African life cycle assessments: Part 3 – Salinity potentials. Water SA, 30, 2, 253-265.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Feitz and Lundie (1) propose a soil salinisation potential (SP) as an indicator for irrigated salinity and potential soil degradation from poor irrigation practices. The indicator uses the threshold electrolyte concentration concept that predicts the adjusted sodium adsorption ratio (SAR)/Electrical conductivity (EC) ratio that soil will no longer flocculate, but potentially disperse. The SAR is converted to a threshold EC and compared to the measured EC in order to develop a site-specific irrigation equivalence factor (EF). This site/region/process specific EF is then used to weight the sodium load to soil and repeated for each stage throughout the entire life cycle to determine the overall Salinisation Potential (SP). The data required for calculating the SP is generally readily available either on site or from the water chemistry of the local watercourses. Preliminary calculations require the volume, pH, electrical conductivity (EC), alkalinity and the concentrations of Na, Ca, and Mg of the irrigation water.

Leske and Buckley (2)-(4) have developed a salinity potentials approach applying a multi-media model comparable to the USES-LCA model of Huijbregts, adapted for specific salinity requirements and elaborated for South-African conditions. In terms of the potential salinity, various effects potentials are defined for a release of salt into an initial release compartment (irc) including aquatic ecotoxicity, aesthetic, materials damage, natural wildlife, livestock, natural vegetation and agricultural crop effects. These are weighted and then aggregated into the total salinity potential (TSP; or equivalency factor) for the release of salts into an initial release compartment (irc). For salinity, common ions comprise sodium, calcium, magnesium, chloride sulphate and bicarbonate. Collectively, these components are defined (in the context of the study of Leske and Buckley) as total dissolved salts (TDS). An equivalency factor has only been calculated for TDS as a lumped parameter, mainly because salinity effects data and surface and groundwater quality data are rather available expressed as (a function of) TDS, than expressed as (a function) of individual ions.

Main advantages

Main advantage of the approaches proposed is they offer the possibility to include salinisation impacts into LCIA.

Open questions

	Feitz and Lundie (1)	Leske and Buckley (2)-(4)
Impact category	Soil salinisation	Salinity
intervention	Irrigation water (Liter)	TDS (kg)
Indicator	Sodium Adsorption Ratio (SAR)	aquatic ecotoxicity; aesthetic; materials damage; natural wildlife; livestock; natural vegetation; and agricultural crop effects
Characterisation model	US 1954 salination model, with a threshold salination level added	non-steady state multi-media model providing the fate factor combined with effect factor for each indicator listed above

Characterisation factor	Salinisation Potential (Kg Na^{+}-eq./Liter irrigation water)	Salinity Potential$_{infinite}$ (SP; kg TDS eq./kg TDS)

The table above illustrates the compliance of the Feitz and Lundie (1) and Leske and Buckley (2)-(4) approaches with the general structure of LCIA (see Annex X). Feitz and Lundie explain that their approach cannot match with this general structure "as it is not the ions specifically that cause damage to the soil, but the ratio between them. This is unlike impact categories such as the Global Warming Potential where particular greenhouse gases may be assigned a given equivalence factor."

Main limitations of the indicator proposed by Feitz and Lundie (1) include: it only assesses the potential for soil salinisation from irrigation practices; individual equivalence factors must be calculated for each relevant life cycle step; the required information may not also be available; and the electrolyte threshold curve may not be appropriate for some soils. Nevertheless, the soil salinisation potential is envisaged to be appropriate for most irrigation situations.

Main limitations regarding the indicator proposed by Leske and Buckley (2)-(4) include: the salinity potentials are only relevant to South African conditions, and their use in LCA in other countries may not be applicable; the LCA practitioner should take care when applying the salinity potentials to prevent double accounting for certain impacts (currently, this is simple because no equivalency factors exist for common ions, or for total dissolved salts as a lumped parameter); the LCA practitioner is also required to have some knowledge about the nature of salts emitted into the atmosphere when generating the life cycle inventory and applying the salinity potentials (not all matter emitted into the atmosphere will be deposited as salt); the various salinity potentials that make up the total salinity potential have, in the absence of better information, all been given equal weight and it is recommended that a method be developed to weight the salinity potentials.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

The Feitz and Lundie (1) approach is not using a readily available list of equivalency factors. For each relevant life cycle step a site specific equivalence factor has to be calculated and data on irrigation volume, EC, Na, Ca, Mg, $CaCO_3$ and pH have to be collected.

The Leske and Buckley (2)-(4) approach is only applicable for South African conditions and needs some specific knowledge for the collection of the correct inventory data.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

The Feitz and Lundie (1) approach is only applicable for irrigation practices.
The Leske and Buckley (2)-(4) approach is only applicable for South African conditions.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. In order to increase the applicability of the Feitz and Lundie (1) approach, it will be necessary to develop more easily accessible data sets needed for the calculations, or even better, to develop a list of equivalence factors for a set of archetype environments. The Leske and Buckley (2)-(4) approach needs to be elaborated for other regions than South Africa and should be elaborated to include associated inventory data collection guidelines.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/new impact categories + methods/fire

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* In a conventional LCA the risk factors for accidental spills are generally excluded. In the LCA data for the production of a chemical, for example, only factors during normal operation are considered. However, there can also be, for example, emissions during a catastrophic event such as a fire accident in the factory. One specific reference on fire accidents is included and analysed below.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Andersson P., M. Simonson, C. Tullin, H. Stripple, J.-O. Sundqvist & T. Paloposki (2004). Fire-LCA Guidelines, Nordtest Technical Report TR 583, ISSN 0283-7234.
2. Specific references

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. Fires occur often enough for statistics to be developed providing necessary information on material flows in the model. A model has been specifically developed by Andersson et al. (1) to allow for this inclusion and will be referred to as the Fire-LCA model. The model itself is generally applicable, provided that appropriate additions and changes are made whenever a new case is studied. Andersson et al. write: "The fundamental function of a better fire performance is to prevent a fire from occurring or to slow down the fire development. Improving a products fire performance will thus change the occurrence of fires and the fire behaviour. By evaluating the fire statistics available with and without different types of fire performance improvements the environmental effects can be calculated. The benefits of a higher fire performance must be weighed against the "price" society has to pay for the production and handling of possible additives and/or other ways of production. The LCA methodology will be used to evaluate the application of higher fire performance in society. In this way a system perspective is applied. A Life Cycle Assessment model should be able to describe the LCA system as defined in the Goal and Scope of the study. In this case it should be able to describe the entire life cycle of a product with different fire performance. [...] The model is essentially equivalent to a traditional LCA approach with the inclusion of emissions from fires being the only real modification. In this model a functional unit is characterised from the cradle to the grave with an effort made to incorporate the emissions associated with all phases in the unit's life-cycle. Thus, the model includes production of material for the product to be analysed, as well as the production of the additives if applicable e.g. different flame retardants. If possible the model should be designed in such a way that the fire performance can be varied. Furthermore, the model should include production, use and waste handling of the product during its lifetime. During the lifetime of the products to be analysed, some products will be involved in different types of fires. The Fire-LCA model will therefore include modules to describe the fire behaviour for the different types of fires. Fire statistics are used to quantify the amount of material involved in the different types of fires. [...]"
Main advantages
Open questions
The method proposed by Andersson et al. (1) is no LCIA method but actually a modification of an LCA-study to include and compare product systems with and without fire-prevention measures on the basis of the "convential" impact categories. Therefore this method is not further included as part of the WP5 LCIA analysis, and should be part of the WP5 LCI analysis.
Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

LIFE CYCLE IMPACT ASSESSMENT

NEW CHARACTERISATION METHODS FOR CATEGORIES THAT HAVE NOT YET BEEN ELABORATED IN THE Jolliet et al: LIST FROM 2004.

- Casualties
- Noise
- Exergy
- Risk-based
- Land use

[Phase/Topic/Approach]

LCIA/new characterisation method for ICs not yet elaborated in list Jolliet et al. 2004/casualties

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* This impact category refers to casualties resulting from accidents. The area of protection is human health. Most LCIA-methodologies do not include an impact category ‘casualties’. Schmidt & Brunn Rasmussen (1999) describe a very useful method for including the working environment in LCA which encompasses casualties. It is based on a database developed by EDIP in which the working environment impacts per kilo of produced goods are listed for a number of economic activities.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Hofstetter, P.; Norris, G.A. (2003). Why and how should we assess occupational health impacts in integrated product policy? Environmental Science & Technology, 37:10, 2025-2035.
2. Specific references

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. Hofstetter & Norris (1) discuss injuries (casualties) related to working environment accidents and these are part of the analysis of “indoor & occupational exposure”. Thus, no relevant literature is available for this impact category and the analysis is thus further skipped here.
Main advantages

Open questions
Practicability aspects
Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/new characterisation method for ICs not yet elaborated in list Jolliet et al. 2004/noise

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. Noise, or noise nuisance, refers to the environmental impacts of sound. In principle, these impacts could cover at least human health and ecosystem health, but the environmental mechanisms are complex, non-linear and highly dependent upon local circumstances. Moreover, noise is similar to odour in that a given level of exposure is experienced differently by different individuals. Something considered a nuisance by one person might be appreciated by another, as exemplified by the case of loud music. Hence, whether or not sound waves will lead to 'nuisance' depends partly on the actual situation and partly on the person interviewed. Most LCIA methodologies do not have an impact category 'noise'. This runs counter to the observed fact that most people deem noise to be a major environmental problem, but is probably due to the unavailability of an appropriate and practically feasible impact assessment method for noise.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. **General references**
2. **Specific references**
- (1) Müller-Wenk, Ruedi (2004). A Method to Include in LCA Road Traffic Noise and its Health Effects. International Journal of Life Cycle Assessment, 9, 2, 76-85.
- (2) Meijer, Arjen; Mark Huijbregts; Edgar G. Hertwich; Lucas Reijnders (2006). Including Human Health Damages due to Road Traffic in Life Cycle Assessment of Dwellings. International Journal of Life Cycle Assessment, 11, Special Issue 1, 64-71.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

(1) Müller-Wenk

This article describes a method for a quantitative assessment in LCA of noise impacts on human health originating from road vehicle noise. An adaptation to rail noise is planned. The method starts out from the following data: transport distance in km, quantity transported, category of vehicle, time (day/night) and country of transport.

The magnitude of health impairment due to noise is determined separately for each vehicle class (cars, trucks,..) and is calculated per vehicle-kilometre driven during the day or at nighttime on the Swiss road network. This health impairment is expressed in cases of sleep disturbance or communication disturbance, and furthermore aggregated in DALY (Disability Adjusted Life Years) units representing the number, duration and severity of the health cases. The method is modelling the full cause-effect chain from the noise emissions of a single vehicle up to the health damage. As in some other modern concepts of environmental damage assessment, the analysis is subdivided into the four modules of fate analysis, exposure analysis, effect analysis and damage analysis. The fate analysis yielding the noise level increment due to an additional road transport over a given distance is conducted for transports with known or with unknown routing, the latter case being more important in LCA practice. The current number of persons subject to specific background levels of noise is determined on the basis of the road traffic noise model, LUK, developed by the Swiss canton of Zurich. The number of additional cases of health impairment due to incremental noise is calculated with data out of the Swiss Noise Study 90. An assessment of the severity of sleep disturbance and communication disturbance, in comparison to other types of health impairment, was performed by a panel consisting of physicians experienced in the field of severity weighting of disabilities.

(2) Meijer et al.

Meijer et al. build on Müller-Wenk (1) and elaborate this for indoor exposure to noise by outdoor road transport. They have developed a methodology to calculate damages to human health of occupants due to *indoor* exposure to noise emitted by neighbourhood car traffic. The goal of the study was to assess the influence of the location of the dwelling on the health of the occupants, compared to the damage to human health associated with the rest of the life cycle of that dwelling. Fate, exposure and human health effects were addressed in the calculation procedure. Fate factors for noise were based on noise levels generated by traffic. Effect factors for noise were based on linear relationships between noise level changes and health effects, while taking into account threshold values for noise levels for negative impacts. Damage factors were calculated on the basis of disability adjusted life years (DALYs). A default noise reduction due to the dwelling itself is included in the calculations. The indoor exposure models used to calculate health damages are based on the work of Müller-Wenk (1) for noise.

In the fate calculations, noise levels are calculated for a scenario rather than on a per-vehicle base because of the non-linear relationship between traffic density and noise level, and because there are threshold values for the noise levels above or under which a change in noise level has no effect on the human health.

For the calculation of the effect factors for traffic noise, data from epidemiological researches – as obtained by Müller-Wenk -was used. In these works, a linear dose-response relationship between average noise levels and negative impacts was adopted.

Main advantages

(1) Müller-Wenk

Müller-Wenk has provided a method enabling practitioners to take into account noise impacts, and that is its main advantage.

(2) Meijer et al.

The advantage of the work of Meijer et al. compared to Müller-Wenk (1) is that it adds the indoor compartment to the work of Müller-Wenk. Meijer et al. also have developed different traffic scenarios with different car/truck speeds etc. whereas Müller-Wenk works with one average vehicle and one average truck scenario. This is however also possible in the work of Müller-Wenk but needs to be elaborated.

Open questions

(1) Müller-Wenk

A question is to which extent the traffic noise can be aggregated in a life cycle perspective to noise from other phases of the life cycle.

(2) Meijer et al.

Calculations made by Meijer et al. are subject to uncertainties. The first type of uncertainty is attached to the assumed traffic scenarios. These are defined assuming typical conditions for traffic densities, speed and distance between road axis and the façades. When the actual traffic situation differs too much from the situation defined in the traffic scenarios, a new scenario can be defined and the corresponding differences in damage score can be calculated using the method described in this study.

The second type of uncertainty is attached to the fate factor calculations and lie in the average noise levels caused by road traffic and in the noise characteristics of the dwelling. When the actual parameters differ considerably from the parameters used in this study, new fate factors can be calculated in order to decrease the uncertainties.

Another type of uncertainty is in the dose-response relationships, and those related to the determination of DALY's.

A quite other type of question is whether the noise impacts of road transport should be attributed to the LCA of a house.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

(1) Müller-Wenk

See above.

(2) Meijer et al.

See above.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. (1) Müller-Wenk Outdoor noise exposure from *road transport*. (2) Meijer et al. Indoor noise exposure from *road transport* related to the LCA of a house.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. (1) Müller-Wenk Elaboration to other sources of noise than road transport. (2) Meijer et al. Elaboration to other sources of noise than road transport. How can noise impacts of road transport be attributed to the LCA of a house?
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/new characterisation method for ICs not yet elaborated in list Jolliet et al. 2004/exergy

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. (1) argues that "Too much of environmental work is dedicated to greenwash and massive propaganda to give people a false sense that the situation (of the state of the environment; JG) is improving. This only makes the situation worse. By adopting exergy based tools and methods we will initiate "an exacting and demanding process [...]. [...]Every real process is irreversible, i.e., it always implies exergy destruction and usually also exergy losses as waste flows to the environment. Exergy loss is defined as the exergy input minus the exergy output, i.e., exergy destruction and exergy waste. Exergy is an extensive quantity, with the same unit as energy. All materials have a definable and calculable exergy-content, with respect to any defined external environment. [...] Today, methods like Life Cycle Analysis or Life Cycle Assessment (LCA) have become popular since they indicate the sources of the environmental problems in the production processes. Unfortunately, these are also methods that allow a high level of manipulation when it comes to evaluating the total assessment by using different weight factors." Exergy analysis in (1) is considered as a possible option to replace current characterisation methods by one overall exergy weighting: • "The exergy content of a natural resource input to the economy can be interpreted as one general measure of its potential usefulness" • "[...] exergy embodied in wastes would be one measure of the potential for causing harm to the environment." "[...] exergy can be regarded as a potential for causing environmental harm." The authors of the other approaches use similar – although less strong and explicit – words on the value of exergy-based indicators for LCIA. Actually, the subject of exergy is part of "improvement of existing methods – resources" when exergy is proposed as indicator for depletion of resources, and part of "new impact categories + methods" when exergy is proposed as overall method for the impact assessment of resources and emissions. As quite a few proposals have been published on this subject, exergy is nevertheless treated as a separate subject here.
Relevant references
The relevant references should be organised along two lines: - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references

2. Specific references
- (1) Gong, M.; Wall, G. (2001). On exergy and sustainable development - part II: indicators and methods. Exergy, an International Journal, 1:4, 217-233
- (2) Cornelissen, R.L.; Hirs, G.G. (2002). The value of exergetic life cycle assessment besides the LCA. Energy Conversion and Management, 43, 1417-1424.
- (3) Bösch, M., S. Hellweg, M.A.J. Huijbregts and R. Frischknecht (2007). Applying Cumulative Exergy Demand (CExD) Indicators to the ecoinvent Database. International Journal of Life Cycle Assessment, 12, 3, 181-190.
- (4) Daniel, J.J.; Rosen, M.A. (2002). Exergetic environmental assessment of life cycle emissions for various automobiles and fuels. Exergy, an International Journal, 2, 283-294.
- (5) Bakshi, B.R. (2000). A thermodynamic framework for ecologically conscious process systems engineering. Computers and Chemical Engineering, 24, 1767-1773.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.   There are several authors (1-5) that consider exergy as a possible indicator for depletion of resources, or even as a possible overall method for the impact assessment of resources and emissions. Gong & Wall (1), Cornelissen & Hirs and Bösch et al. (3) advocate applying exergy for assessing the depletion of natural resources. Physical resources are classified into natural exergy flows, exergy funds and exergy deposits. Natural exergy flows and sustainable use of exergy funds establish the renewable resources. Unsustainable use of exergy funds, e.g., careless clearing of forests, and exergy deposits make up for the non-renewable resources. The total exergy use over the life cycle is considered. Bösch et al. explain that exergy "can be utilised as an indicator of resource quality demand when considering the specific resources that contain the exergy. Such an exergy measure indicates the required resources and assesses the total exergy removal from nature in order to provide a product, process or service." Also this approach thus focuses on exergy as indicator for the depletion of resources. Daniel & Rosen (4) and Bakshi (5) do – in contrast to (1), (2) and (3) – include emissions as well as resources. Daniel & Rosen (4) discuss a case study examining emissions produced during 13 fuel life cycles for automobiles, on mass and exergy bases. The masses of fuel life cycle emissions are compared with the chemical exergies of these emissions. Bakshi (5) advocates applying the concept of emergy, being "the embodied energy or energy memory in any product or service. It is defined as the total amount of energy needed directly or indirectly to make any product or service. Since the ability to do work can be different for different kinds of energy, it is essential to convert all types of energies into a common unit before combining them. For convenience, units of solar energy are usually selected as the common unit." Bakshi (5) argues that "although exergy is a more useful concept than energy, it only provides information about the current state of the system, and its future ability to do work. It does not provide any information about the quality of the available energy. Thus, the concept of exergy does not highlight the fact that electrical exergy can do more

types of work than the same amount of solar exergy. Furthermore, exergy provides no information about the thermodynamic or energy history of the product or service at a global scale. These shortcomings are overcome by the concept of emergy."

Main advantages

All approaches distinguished advocate the use of the exergy concept and their proposal on exergy are basically the same with some differences on a detailed level. Main advantage of (4) and (5) compared to (1), (2) and (3) is that (4) and (5) also takes emissions into account in addition to resources. Depending on how one judges the environmental relevance of this approach, the advantage may as well turn into a disadvantage.
Whether the emergy concept of (5) has added advantages over the proposed exergy concepts of by others is difficult to grasp. One advantage might be that the emergy approach "includes the contribution of ecological products and services along with economic inputs in process analysis. Examples of ecological products and services include, sunlight, rain, and soil formation. These inputs are at least as important as the economic inputs, but are usually not measured by money, and are ignored by most existing environmentally conscious engineering methods."

Open questions

The main open questions include:

- What is the precise added value of emergy over exergy?
- Can exergy/emergy also be a environmentally) relevant indicator for emission related impacts?
- How can gaps in the availability of exergy data be filled and characterisation factors be made available for all approaches?

To what extent the R&D topics listed by Gong & Wall (1) also count for the other approaches and how the exact exergy methods adopted and elaborated by the different authors match or differ, remains unclear as yet.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

<u>Gong & Wall (1)</u>
No list of characterisation factors.
According to Gong & Wall (1), the result of an LCEA and exergy flow diagrams are easy to understand, however, the exact calculations are too complicated for common use. Exergy has been applied to a number of different areas with different methods. The results from these methods are not immediately comparable. A final common problem in most of the referred studies is the lack of data.

<u>Cornelissen & Hirs (2)</u>
No list of characterisation factors.

<u>Bösch et al. (3)</u>
Very important aspect of this approach is that the authors provide exergy-based characterisation factors for 112 different resources.

Daniel & Rosen (4)
No list of characterisation factors.

Bakshi (5)
No list of characterisation factors.
"Information about the materials used and emissions in each process may be obtained from the existing databases use in LCA. Emergy analysis requires additional information about the transformities of ecosystem services and products. Such information has been tabulated by Odum (1996). If the transformity of a resource is available, Eq. (2) can be used to determine its total emergy. The emergy breakdown into renewable, non-renewable and economic sources requires separate transformities for each category of input, or a more detailed analysis.
Most of the previous work on emergy analysis has ignored the impact of emissions. This is in contrast to the approach for LCA, which focuses primarily on the analysis of emissions, and ignores contributions from the ecosystem. This complementary nature of emergy analysis and LCA is exploited in the proposed approach. [...] To determine the emergy flows, R, and F2 the emissions are characterized and classified according to the method of LCIA. The emergy of the emissions in each category may then be determined based on knowledge about the emergy of impact per unit of emission [...]."
Concluding: also this approach requires more data than conventional LCA and a lot of these data still need to be collected and/or calculated.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

No specific limitations.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. <u>Gong & Wall (1)</u> According to Gong & Wall (1), exergy evaluations of emissions should be standardized, and user-friendly computer programs should be developed; methods to add the environmental impact to the exergy of emissions must be further elaborated; general methodological guidelines should be developed in order to increase comparability between different exergy studies; and, data suitable for exergy studies should be made available. <u>(3) Bösch et al.</u> "A differentiation between the exergy of fossil, nuclear, hydro-potential, biomass, other renewables, water and mineral/metal resources is recommended in order to obtain a more detailed picture of resource quality demand and to recognise trade-offs between resource use, for instance energetic and non-energetic raw materials, or nonrenewable and renewable energies." <u>Bakshi (5)</u> Data should be made available.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. Not all of the authors go into R&D needs and trends but basically these needs and trends are quite similar for all of the approaches.

[Phase/Topic/Approach]

LCIA/new characterisation method for ICs not yet elaborated in list Jolliet et al. 2004/risk-based

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. Discussions on the delimitation between Life Cycle Assessment (LCA) and Risk Assessment (RA) go back at least two decades. LCA is mostly based on the general prevention principle, whereas RA is based on the risk minimization principle. The two approaches merely replenish each other, and even after two decades of discussion, ways are still being sought to combine or even integrate the two. This topic doesn't concern a specific impact category, but rather focuses on a discussion of approaches to risk assessment in conjunction with LCA.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
2. Specific references
- (1) Khan, F.I.; Sadiq, R.; Husain, T. (2002). GreenPro-I: a risk-based life cycle assessment and decision-making methodology for process plant design. Environmental Modelling & Software, 17, 669-692.
- (2) Nishioka, Y.; Levy, J.I.; Norris, G.A.; Wilson, A.; Hofstetter, P.; Spengler, J.D. (2002). Integrating Risk Assessment and Life Cycle Assessment: A Cases Study of Insulation. Risk Analysis, 22, 5, 1003-1017. - Nishioka, Y.; Levy, J.I.; Norris, G.A.; Bennet, D.H.; Spengler, J.D. (2002). A risk-based approach to health impact assessment for input-output analysis. Int. J LCA, 10, 3, 193-199. - Nishioka, Y.; Levy, J.I.; Norris, G.A. (2006). Integrating air pollution, climate change, and economics in a risk-based life-cycle analysis: a case study of residential insulation. Human and Ecological Risk Assessment, 12, 552-571.
- (3) Sweet, L.; Strohm, B. (2006). Nanotechnology - life-cycle risk management. Human and Ecological Risk Assessment, 12, 528-551.
- (4) Wegener Sleeswijk, A. (2003). General prevention and risk minimization in LCA. A combined approach. Environmental Science & Pollution Research, 10:1, 69-77.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. (1) Khan et al. Khan et al. propose a methodology called “GreenPro-I” which comprises of a risk-based life cycle assessment (RBLCA) and a risk-based Multi-Criteria Decision Making (MCDM) approach. We here focus at the first. The major objective of RBLCA is to help in decision-making and selecting the best management alternative available for a specific process/product design, which can reduce the risk and other environmental burdens at the optimal cost. The authors propose a Impact and Risk Assessment (IRA) phase which basically is similar to the ISO-LCA LCIA phase. It remains unclear what the term “risk-based” actually stands for in this method. When characterisation methods are discussed, emissions of pollutants are given in rates (kg/h) but it is not explained where these rate data stem from, if they are possibly used in a RA besides an LCA and – if not – how rates match with the fact that (page 671 below) the RBLCA for process design has the objective “quantifying and evaluating the environmental performance of a process from *cradle to grave*” which can never be done on a rate (kg/h)-basis. (2) Nishioka et al. Nishioka et al. propose to *combine* Input-Output LCA with risk concepts illustrated by a case-study on insulation. Increasing residential insulation can decrease energy consumption and provide public health benefits, given changes in emissions from fuel combustion, but also has cost implications and ancillary risks and benefits. RA or LCA can be used to calculate the net impacts and determine whether more stringent energy codes or other conservation policies would be warranted, but few analyses have combined the critical elements of both methodologies. Nishioka et al. therefore propose a combined analysis modelling (US) state-by-state residential energy savings and evaluating PM, NO_x and SO_2 emission reductions. They apply dispersion modelling results to estimate reductions in exposure, and apply concentration-response functions for premature mortality and selected morbidity outcomes. This risk-based results are then combined with life-cycle based information, considering three pathways: a) Population and occupational exposure to air pollutants associated with the *upstream process chains for fossil-fuel cycles*. b) Population and occupational exposure to air pollutants associated with the *upstream process chains for insulation manufacturing*. c) Changes in indoor air quality associated with increased residential insulation, leading to changes in exposure of occupants to indoor pollutants. For the analysis of population risks associated with upstream impact pathways, economic input/output LCA is combined with intake fraction concepts and concentration-response functions. (3) Sweet & Strohm Application of a proactive risk-based approach that considers the life cycle of the product, rather than a precautionary principle approach that would likely restrict the progress and advance of nanoscience, will be useful in helping to assess the unknown and unpredictable risks associated with nano-products, nanotoxicity, and nanopollution. This article summarizes what is currently known regarding the potential toxicity and hazards of nanomaterials. A life-cycle perspective is used to identiS important areas for further consideration and research. A conceptual framework is

proposed for linking the strategies of life cycle and risk analysis within the same toolbox. This approach allows for prevention and treatment of a material's life-cycle risks, which can be considered in an integrated manner, thereby promoting continuous improvement, proactive risk reduction, and a flexible and adaptive approach to evaluating nanotechnology without stifling innovation.
The authors propose - instead of advocating a precautionary principle approach that would likely restrict the progress and advance of nanoscience application - a proactive risk-based approach that considers the life cycle of the product, will be useful in helping to asses the unknown and unpredictable risks associated with nanoproducts, nanotoxicity and nanopollution. LCA should identify hotspots and recommend improvements whereas RA should consider environmental, health and safety impacts.
Further methodological elaborations are not provided by the authors!

(4) Wegener Sleeswijk
"Methods for life cycle assessment of products (LCA) are most often based on the general prevention principle, as opposed to the risk minimization principle. Here, the desirability and feasibility of a combined approach are discussed, along with the conditions for elaboration in the framework of LCA methodology, and the consequences for LCA practice. A *combined* approach provides a separate assessment of above and below threshold pollution, offering the possibility to combat above threshold impacts with priority. Spatial differentiation in fate, exposure, and effect modelling is identified to play a central role in the implementation. The collection of region-specific data turns out to be the most elaborate requirement for the implementation in both methodology and practice. A methodological framework for the construction of characterization factors is provided. Along with spatial differentiation of existing parameters, two newly introduced spatial parameters play a key role: the sensitivity factor (distinguishing between sensitive and insensitive areas) and the threshold factor (distinguish between above and below threshold areas). The practicability of the proposed procedure is illustrated by an example of its application. Providing a reasonable data availability, the development of separate LCA characterization factors for the respective assessment of pollution levels above and below environmental threshold values seems to be a feasible task that may add to LCA credibility."

Main advantages

(1) Khan et al.
It is unclear what the term "risk-based" actually stands for in this method.

(2) Nishioka et al.
This method of combining LCA and RA is – compared to (1) and (3) - well described and elaborated. This method clearly distinguishes between the role of RA and the role of LCA.

(3) Sweet & Strohm
Sweet & Strohm present no more than a first conceptual framework without any further elaboration.

(4) Wegener Sleeswijk
As (2), this method of combining LCA and RA is – compared to (1) and (3) - well described and elaborated.

This way of combining LCA and RA is different from (1) – (3) in that it tries to fit some key characteristics from RA (threshold and sensitive areas) into LCA methodology itself, and not separate from LCA. Besides taking over elements from RA into LCA, the added value of RA to LCA as a tool in itself is still acknowledged.

Open questions

(1) Khan et al.
Needs further elaboration/explanation and cannot be further evaluated before that.

(2) Nishioka et al.

(3) Sweet & Strohm
Needs further elaboration and cannot be further evaluated before that.

(4) Wegener Sleeswijk
Needs further elaboration and cannot be further evaluated before that.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

(1) Khan et al.
Probably easy to apply.

(2) Nishioka et al.
Requires quite some efforts by a practitioner.

(3) Sweet & Strohm
Not practical at all.

(4) Wegener Sleeswijk
Requires extra data to be supplied by a practitioner.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose. No specific limitations as far as known.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. There are many points of uncertainty and further work that are listed in Nishioka et al. (2006, 564-568) and in the paper of Wegener-Sleeswijk (4). In general, however, one can say that further clarification of the added role of RA and LCA to each other is needed and that further elaborations are required what specific methods (or only elements of methods) are useful to combine for which decision-situations. Another issue is how elements of RA can be included in refined new-LCA, as has been done for example by Wegener-Sleeswijk (4). Key needs here are improvement of availability of regional emission and environmental data.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. With respect to the Nishioka et al. (2) proposals, I remain confused as to what the added value of this approach actually is. If I understand the Nishioka et al. proposal correctly, they propose impact pathway (RA) modelling for foreground processes and LCA modelling for the background supply processes. For the impact pathway modelling, residential fuel and power sector analyses are made determining regional specific emissions rates and then intake fractions are applied linking site-specific emissions to population exposure as a function of population patterns and meteorology etc. (Nishioka et al. 2006, p.558). The emissions are no total yearly emissions, but emissions related to the insulation case. This is no full RA, and the authors also acknowledge that, and it is also no complete LCA but then the question remains: what is it and what exactly is the added value, particularly if non-site-specific and non-industry specific (without specific information on background environments) IO-LCA plays such a key role in getting emission information?

[Phase/Topic/Approach]

LCIA/new characterisation method for ICs not yet elaborated in list Jolliet et al. 2004/land-use impacts

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. Specific methods – and thus specific references – have been left out on purpose, since this impact category and the range of (developing) methods are too broad and too complicated to allow for a more detailed discussion of individual methods. The category 'land use impacts' covers a range of consequences of human land use. It is a relatively new topic in LCIA and still being debated and developed. A distinction is often made between use of land with impacts on the resource aspect and use of land with impacts on biodiversity, life support functions, etc. The resource aspect is not part of this analysis but captured separately under the heading of "resource depletion". On the intervention side a distinction is often made between land occupation (i.e. occupancy and use) and land transformation (i.e. changing its quality).
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Milà i Canals, Llorenç; Christian Bauer; Jochen Depestele; Alain Dubreuil; Ruth Freiermuth Knuchel; Gérard Gaillard; Ottar Michelsen; Ruedi Müller-Wenk; Bernt Rydgren (2007). Key Elements in a Framework for Land Use Impact Assessment Within LCA. International Journal of Life Cycle Assessment, 12, 1, 5-15.
- (2) Udo de Haes Helias (2006). How to approach land use in LCIA or, how to avoid the Cinderella effect? International Journal of Life Cycle Assessment, 11, 4, 219-221.
- (3) Milà i Canals Llorenç; Müller-Wenk Ruedi; Bauer Christian; Depestele Jochen; Dubreuil Alain; Freiermuth Knuchel Ruth; Gaillard Gérard; Michelsen Ottar; Rydgren Bernt (2007). Key Elements in a Framework for Land Use Impact Assessment in LCA. International Journal of Life Cycle Assessment, 12, 1, 2-4.
- (4) Guinée, Jeroen, Lauran van Oers, Arjan de Koning and Wil Tamis, 2006. Life cycle approaches for Conservation Agriculture - Part I: A definition study for data analysis; Part II: Report of the Special Symposium on Life Cycle Approaches for Conservation Agriculture on 8 May 2006 at the SETAC-Europe 16th Annual Meeting at The Hague. Research commissioned by Syngenta Crop Protection AG, Basel. CML report 171, CML, Leiden.
2. Specific references

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. “Land use by agriculture, forestry, mining, house-building or industry leads to substantial impacts, particularly on biodiversity and on soil quality as a supplier of life support functions. Unfortunately there is no widely accepted assessment method so far for land use impacts. The UNEP-SETAC Life Cycle Initiative Working Group on LCIA Task Force 2 (TF2) on Resources and Land Use has developed a framework for the Life Cycle Impact Assessment (LCIA) of land use. This framework builds from previous documents, particularly the SETAC book on LCIA, developing essential issues such as the reference for occupation impacts; the impact pathways to be included in the analysis; the units of measure in the impact mechanism (land use interventions to impacts); the ways to deal with impacts in the future; and bio-geographical differentiation.” TF2 describe in their paper Milà i Canals et al. (1) “the selected impact pathways, linking the land use elementary flows (occupation; transformation) and parameters (intensity) registered in the inventory (LCI) to the midpoint impact indicators and to the relevant damage categories (natural environment and natural resources). An impact occurs when the land properties are modified (transformation) and also when the current man-made properties are maintained (occupation). The size of impact is the difference between the effect on land quality from the studied case of land use and a suitable reference land use on the same area (dynamic reference situation). The impact depends not only on the type of land use (including coverage and intensity) but is also heavily influenced by the bio-geographical conditions of the area. The time lag between the land use intervention and the impact may be large; thus land use impacts should be calculated over a reasonable time period after the actual land use finishes, at least until a new steady state in land quality is reached. Guidance is provided on the definition of the dynamic reference situation and on methods and time frame to assess the impacts occurring after the actual land use. Including the occupation impacts acknowledges that humans are not the sole users of land. The main damages affected by land use that should be considered by any method to assess land use impacts in LCIA are (according to TF2; JG): 1) biodiversity (existence value); 2) biotic production potential (including soil fertility and use value of biodiversity); 3) ecological soil quality (including life support functions of soil other than biotic production potential). Biogeographical differentiation is required for land use impacts, because the same intervention may have different consequences depending on the sensitivity and inherent land quality of the environment where it occurs. Preliminary suggestions are provided for this. The recommendation of indicators for the suggested impact categories is a matter of future research.” (1) The above is the opinion of the UNEP-SETAC LCI WG LCIA TF2 group. There are, however, strong opposite opinions like expressed by Udo de Haes (2), who commented upon Milà i Canals et al. (1) on two main points. The first one concerns the narrowing down to just three main types of impact related to land use: to biodiversity (existence value), to biotic production (including soil fertility and the use value of biodiversity), and to ecological soil quality (including other life support functions). The second concerns the lack of a critical analysis whether the selected impacts do fit in the methodological structure of LCA. He suggest to approach the subject of 'Land use and LCA' as follows: • identification of (possibly) all relevant aspects connected with land use • identification of conditions for a good fit of aspects in LCA

- identification of those aspects of land use which do fit well in LCA, in combination with suggestion how to cover these in LCI and LCIA categories
- identification of those aspects of land use which are problematic to include in LCA
- survey of other possibilities to include the latter aspects in environmental analysis.

Udo de Haes then provides a long list aspects connected with land use and then elaborates the analysis of which aspects fit in the LCA structure, largely building on the analyses made by Guinée et al. (4). Udo de Haes concludes suggesting that alternative options are developed to address impacts that do not fit in the LCA structure. Examples concern local ecological or ecotoxicological modelling, with its results communicated along the value chain; and sustainability certification of resource extraction, connected with labelling of the forthcoming products, as procedural tool. An open point is then how the results of an LCA study and the additional information should best be combined.

Without going into further detailed discussions, it is clear that "Land use impacts have received increasing attention in LCA studies in the last years, but an agreed assessment framework and methods are still lacking. The debate on this issue needs to continue, bearing in mind that LCA results will be incomplete and less credible as long as land use impacts are not being incorporated, particularly for such hot topics as the comparison of products and services based on biotic system vs. those based on abiotic ones." (3)

Main advantages

Not applicable.

Open questions

The open questions for this impact category are still very basic:

- What are the main impact categories under the heading "land-use impact"?
- How can these impacts be best assessed in LCIA? Which indicators, which interventions, which characterisation models and factors?

What should be done with impacts/aspects of land use that do not fit in the general LCIA structure?

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

With respect to the UNEP-SETAC TF2 recommendations, not practical methods have been recommended yet and are thus not yet available
Many existing (older; pre-UNEP-SETAC ones) methods lack practical elaboration or require substantial efforts from practitioners to be applied in case-studies.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose. Not applicable.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. The main R&D needed is the building of consensus on what needs to be assessed (impact categories) and then the elaboration of indicators, characterisation methods and factors for these impact categories. The work of the UNEP-SETAC WG TF2 group should preferably be the starting point for this. Important in the elaboration of indicators etc. is to preferably develop and elaborate methods with readily-available lists of intervention-characterisation factor combinations, so that it is clear to the practitioner which intervention data should be collected with respect to land-use and that these can be practically and easily handled in the impact assessment phase. "One of the goals of a Symposium reported on by Guinée et al. (4) was to initiate a broad discussion on the topic of Conservation Agriculture, its principles and indicators and how it can be addressed in LCA. From the presentations it became clear that Task Force 2 of the UNEP-SETAC LC-Initiative would be the most appropriate forum for this discussion. However, it also appeared that the discussions in this forum progress very slowly and that they get stuck at a conceptual and theoretical level. Support from agro-industry (like Syngenta) could certainly help to enhance the work of the Task Force 2 of the UNEP-SETAC LC-Initiative by e.g. financing the application in a case-study of operative land-use related impact assessment methods to lift of the discussion over the level of concepts and methodological debates and to enable finding out what the key differences between methods in practice are. This could then be the starting point of a debate and consensus process on most representative indicators and related operative methods for impact assessment of land use related impacts in LCA. One of the conclusions from the definition study (Part I) may well be that certain impacts do not fit in the LCIA structure or cannot satisfactorily be addressed by LCIA (similar to acute toxic impacts). For these impacts then recommendations should be formulated as to how these could additionally be addressed by other (analytical) tools, in a similar way as it is recommended to apply RA in addition to LCA, particularly for local threshold passing assessments. For impacts that do fit in the LCIA structure, there is a discussion on the most relevant and operative indicators for Life Cycle Impact Assessment (LCIA) of land use related interventions. We observe an analogy between the treatment of toxicity impact in LCIA and the treatment of land use related impacts. Also with respect toxicity, there has been an intensive debate on the usefulness of including toxic impact in LCIA. The debate was initiated from scientists and stakeholders that were particularly active in the field of Risk Assessment. They argued that as they 1) performed RA-studies already, 2) complied with chemical legislation, 3) did not surpass any thresholds locally; and 4) LCA could not deal with thresholds and

acute effects, it made no sense to include toxicity into LCIA. Many discussions followed focusing on the added value of LCIA to RA and vice versa and in the end there was quite broad consensus that it was useful to also look at toxicity from an LCA perspective. The way toxic impact were assessed in LCA at that time was, however, very simplistic. Toxic emissions were divided by a standard and then aggregated ("critical volumes approach"). After that, the multi-media modelling based approaches have been introduced, better reflecting the behaviour of chemicals through the environment but at the same time initiating long and as yet unresolved scientific debates on best multi-media modelling and effect assessment practices. It is just this Spring, that within TaskForce 3 (TF3) of the UNEP-SETAC LC-Initiative, it has been decided to built a much simpler multi-media *consensus* model – independent of any of the existing models. This consensus model will be used as best practice for given periods of time and at the same time it will be the starting point for further model improvements. New developments from existing (scientific, non-consensus based) multi-media models will be submitted for discussion and brought into the consensus model when consensus is reached on these developments. This foreseen future for the TF3 work resembles much of the way the IPCC works and how their (consensus / policy) GWPs are accomplished. We suggest that land-use impact assessment modellers could learn from this. They could even try to skip the part during which intense debates were held while little progress was made by starting with a simple m^2.yr and simultaneously start working on a better and more sophisticated but operative approach (without bothering the average LCA practitioner too much with these difficult discussion as we don't bother them either with difficult GWP-model inner side discussions).

In summary the recommendations are:

- Apply operative land-use related impact assessment methods in a case-study in order to initiate a constructive debate on the level of concepts and methodology. This will enable us to identify the key differences between a variety of methods which are currently being practised;
- Develop a scientific framework for Conservation Agriculture defining what it means and how it can best be measured (indicators);
- Learn from the LCIA experiences with the toxicity categories in defining best practice for LCIA of land use related impacts." (4)

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

I have analysed this topic on a general level, since this impact category and the range of (developing) methods are too broad and too complicated to allow for a more detailed discussion of individual methods.

LIFE CYCLE IMPACT ASSESSMENT

NEW LCIA DAMAGE/ENDPOINT METHODS

NORMALISATION

WEIGHTING

SPATIAL DIFFERENTIATION

SIMPLIFIED METHODS AND PROXIES

MONETARIZATION OF EFFECTS

TIME DEPENDENCE&DISCOUNTING

[Phase/Topic/Approach]

LCIA/ new LCIA damage_endpoint methods

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* A major defining aspect of Impact assessment methods is the point in the environmental mechanism at which the category indicators are defined. They may be defined close to the intervention (the midpoint, or problem-oriented approach). Alternatively, they may be defined at the level of category endpoints (the endpoint, or damage approach). A cluster of category endpoints of recognisable value to society is referred to as an "area of protection", for example human health, natural resources, the natural environment and the man-made environment. Some of the endpoint/damage methods include a weighting scheme and that one may be a deviation from the ISO 14040 standards when a study concerns a comparative assertion intended to be disclosed to the public. The references include only specific methods (1)-(5) like: ReCiPe (1), (4); LInX (2);ExternE (3); and LIME (5).
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
2. Specific references
- (1) Heijungs, Reinout; Mark Goedkoop; Jaap Struijs; Suzanne Effting; Maartje Sevenster and Gjalt Huppes (2003). Towards a life cycle impact assessment method which comprises category indicators at the midpoint and the endpoint level. Report of the first project phase: Design of the new method.
- (2) Khan, F.I.; Sadiq, R.; Veitch, B. (2004). Life cycle index (LInX): a new indexing procedure for process and product design and decision-making. Journal of Cleaner Production, 12, 59-67.
- (3) Rabl, A., A. Markandya, A. Hunt, P. Bickel & R. Friedrich (2004). ExternE-Pol. Externalities of Energy: Extension of accounting framework and Policy Applications. Final Report contract N° ENG1-CT2002-00609.
- (4) Goedkoop et al. (in prep.). ReCiPe.
- (5) Itsubo, Norihiro & Atsushi Inaba (2007). LIME2 – Development of the updtaed Japanese damage oriented LCIA methodology. Abstract book (LC02-3) of the SETAC Europe 17th annual meeting, 20-24 May 2007, Porto, Portugal.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. <u>Heijungs et al. (1)</u> "[...] there is no single method that is to be preferred in all circumstances. LCA has been stated to be goal and scope dependent, and this indeed applies to the method for LCA as well. But at the same time, the autonomous developments in LCA have sometimes lead to discrepancies between methods that cannot be explained by necessity alone, and for which historical reasons are an important factor. One such instance is the development of midpoint-oriented and endpoint-oriented methods for life cycle impact assessment (LCIA). There are methods for LCIA that convert emissions of hazardous substances and extractions of natural resources into impact category indicators at the midpoint level (like acidification, climate change and ecotoxicity), and there are methods for LCIA with impact category indicators at the endpoint level (like damage to human health and damage to ecosytem quality). Given the specific types of use, the existence of methods for addressing midpoints next to methods for addressing endpoint is legitimate. A series of interviews of users of LCA in the Netherlands confirms this. But there are differences between the underlying models that are at least confusing, and that may be unnecessary. For instance, there is no reason to assume that windspeed and temperature that are entered as environmental properties in the fate model could be different. It is therefore desirable that methods for LCA should be harmonised at the level of detail, while allowing a certain degree in freedom as to the main principles, in the current case their orientation towards midpoint or endpoint indicators. This report describes a study for the design of an LCIA method that is harmonised as to modelling principles and choices, but that offers results at midpoint and endpoint level. The report provides a basis for the factual construction of these harmonised models, after which they can be run to produce characterisation factors at both levels. The report should be seen in a context of the availability of two major Dutch systems of LCIA, the midpoint-oriented Handbook LCA by Guineé and co-workers (CML, Leiden University) and the endpoint-oriented Eco-indicator 99 by Goedkoop and co-workers (Pré Consultants, Amersfoort). Extensive co-operation with the RIVM ensures in a possible second phase access to the knowledge and the models of a whole range of environmental issues, from acidification to climate change." <u>Khan et al. (2)</u> "Life cycle assessment (LCA) is an important technique in the successful implementation of a process or product development in the context of environmental sustainability. Attempts have been made to incorporate LCA in public and corporate processes and product related decision-making. The European Union's eco-labeling schemes and the United Kingdom's Integrated Pollution Prevention and Control Directive have tried to integrate life cycle thinking with policy making. However, these efforts still have not made LCA an integral part of process and product selection and design. The absence of an easy to use tool for rapid reconnaissance is a basic limitation of the LCA application. A new life cycle indexing system — LInX — is proposed, which will facilitate the LCA application in process and product evaluation and decision-making. The LInX is comprised of four important sub-indices or attributes — environment, health and safety (EHS), cost, technical feasibility, and socio-political factors. Further, each attribute contains a number of basic parameters, e.g. EHS consists of 11 parameters. Quantification of each basic parameter is

performed for the complete life cycle of a proposed process or product. An analytical hierarchy process is used to compute the weights for each basic parameter and sub-indices. A composite process is used to determine the final overall index. This paper explains the methodology for computation of the new indexing system and demonstrates it with an application."

Rabl et al. (3)
"This project is the continuation of the ExternE project series for the analysis of the external costs of energy. Its objectives are:

- Improving, validating and extending the methodology of ExternE;
- Providing an assessment of new technologies for energy systems;
- Implementing the methodology in the accession countries of Eastern Europe;
- Creating a permanent internet site for ExternE.

Several significant improvements of the ExternE methodology have been achieved. They concern:

- Dose-response functions for health impacts and for crops;
- Monetary valuation of chronic bronchitis, visibility, damage to cultural monuments, and energy supply security;
- Choice of background emissions for the atmospheric modeling;
- Inclusion or exclusion of impacts upstream or downstream of the power plant, depending on whether and how they have already been internalized.

Most of these improvements have not yet been implemented in the current version of ExternE because they are arriving too late for inclusion in the final report for the NewExt project. In choosing the optimal moment for the publication of new results one has to weigh the risk of being out of data with the risk of confusion by too many different numbers. A framework has been developed for using multicriteria analysis to quantify impacts whose monetization has remained problematic. It involves stakeholders or environmental experts, asking them for their ranking of different impacts. A preliminary test has been carried out to estimate monetary values for acidification and eutrophication. The results are promising but not yet sufficiently reliable for use. The LCA inventory for the emission of pollutants has been updated to correspond to the energy technologies in use in 2000, and external costs have been calculated for a wide variety of advanced energy technologies, including advanced photovoltaics. The ExternE methodology has been implemented in the new EU countries of Central and Eastern Europe, and external costs have been calculated for power production in the Czech Republic, Hungary and Poland and for transport in the Czech Republic."

Goedkoop et al. (4)
Following the principles that were set in (1), consistent midpoint and endpoint models were developed and used for specific impact categories. The results will be available soon.

Itsubo et al. (5)
"LIME(Life-cycle Impact assessment Method based on Endpoint modeling) was developed under the discussion in LCA 1st National Project of Japan. This method is based on the environmental conditions in Japan and the state-of the art in natural science and social science. After the publication of this method, more than 50 Japanese companies have already applied this method and published their results to appeal their

environmental performance. While this was spread to the society of Japan, the developers could receive various requirements from practitioners.
In order to fulfil these requirements, the following studies were conducted under the LCA second National Project of Japan.
1.Improvement of the reliability of damage factors and integration factors based on uncertainty analysis and sensitivity analysis
2.Development of weighting factors which improve the representativeness of environmental thoughts of Japanese population
3.Development of the methodologies for noise and indoor pollution
Through these researches, new lists of LIME2 factors were established. This presentation summarizes what we obtained in this project."
Further information has not been published yet.

Main advantages

Heijungs et al. (1)
The design of a consistent method with both midpoints and endpoints leaves the practitioner room to be more flexible in the choice of the impact assessment method.

Khan et al. (2)
An indexing tool is easy and fast to use. However, in using such an index, compromises with respect to comprehensiveness and quality must be made.

Rabl et al. (3)
The determination of external costs of environmental impacts is important for an integration of LCC within a cost-benefit analysis framework.

Goedkoop et al. (4)
See (1).

Itsubo et al. (5)
Pro memori : sufficient information has not published yet in English in order to assess this issue.

Open questions

Heijungs et al. (1)
The preference for a midpoint or an endpoint (or perhaps both) is a thing that will have to be considered.

Khan et al. (2)
The field of application for a full method and an easy and fast index will have to be considered.

Rabl et al. (3)

The degree to which environmental information is properly and acceptably reflected using monetary metrics will have to be considered.

Goedkoop et al. (4)
See (1).

Itsubo et al. (5)
Pro memori : sufficient information has not published yet in English in order to assess this issue.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Heijungs et al. (1)
Not a practical method.

Khan et al. (2)
An important problem in practice is that an index system needs a weighting of different types of environmental impacts.

Rabl et al. (3)
Montetarization values are only available for a limited number of impacts and pollutants.

Goedkoop et al. (4)
Not yet available, so not yet known.

Itsubo et al. (5)
Pro memori : sufficient information has not published yet in English in order to assess this issue.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

The sector of application is not relevant.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. Heijungs et al. (1) See (4). Khan et al. (2) Not known. Rabl et al. (3) Monetarization is an important topic, both in terms of application and in terms of research. Goedkoop et al. (4) The integration of midpoints and endpoints is a recent development, and we can expect that additional research will (have to) be carried out the coming decade. Itsubo et al. (5) Pro memori : sufficient information has not published yet in English in order to assess this issue.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]
LCIA/normalisation

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. ISO 14042 (2000E) defines normalisation as "calculation of the magnitude of indicator results relative to reference information". The reference information may relate to a given community (e.g. The Netherlands, Europe or the world), person (e.g. a Danish citizen) or other system, over a given period of time. Other reference information may also be adopted, of course, such as a future target situation. Normalisation is considered an optional element of LCIA in ISO 14042 (2000E). The main aim of normalising the (category) indicator results is to better understand the relative importance and magnitude of these results for each product system under study. Normalisation can also be used to check for inconsistencies, to provide and communicate information on the relative significance of the (category) indicator results and to prepare for additional procedures such as weighting or Interpretation (ISO 14042, 2000E). There exist other definitions of 'normalisation', as is the case in multicriteria analysis (where it if often understood as division of the various values in a data set by a single reference value from that set, to express all the values in terms of that reference value). In contrast to the normalisation mentioned above, one could call this "internal normalisation". Internal normalisation is not usually applied in LCA and also not in line with the ISO definition of (external) normalisation given above.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Norris, Gregory A. (2001). The Requirement for Congruence in Normalization. International Journal of Life Cycle Assessment, 6, 2, 85-88.
- (2) Heijungs, R., J.B. Guinée, R. Kleijn & V. Rovers (2007). Bias in Normalization: Causes, Consequences, Detection and Remedies.

Int. J. LCA(12), 4, 211-216.
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2. Specific references
- (3) Bare, J.C.; Gloria, T.P.; Norris, G. (2006). Development of the method and U.S. normalization database for life cycle impact assessment and sustainability metrics. Environmental Science & Technology, 40:16, 5108-5115.
- (4) Wegener Sleeswijk, Anneke; Lauran van Oers; Jeroen Guinée; Jaap Struijs and Mark Huijbregts (in prep.). Normalisation in product life cycle assessment: An LCA of the Global and European Economic Systems in the year 2007.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Norris (1)

"Two purposes for normalization in LCA are presented: resolving non-commensurate units, and assessing significance. Two families of approach for normalization in LCA are described: internal and external. The need for congruence between the normalization and valuation is illustrated by showing the nonsensical conclusions which can result from an approach that is common in North American LCA applications: internal normalization with external valuation. In order to achieve congruence with internal normalization methods, valuation in such instances must be case-specific. External normalization methods bring an added benefit not provided by internal normalization methods: an assessment of relative significance. [...] The absurd results illustrated in the previous section occur because internal normalization and external valuation are not congruent. Congruence requires a common basis for normalization and valuation. In the examples above, very common in North American LCA, the weights reflect the importance of each impact category *in general,* while the normalization results reflect the relative performance of the alternatives *with respect to each other.* Congruence will always be absent when internal or case-specific normalization is used in conjunction with weights that are case-independent. [...] Note that congruence is not guaranteed but must be carefully pursued in the second solution as well. Specifically, spatial and temporal scope of the emissions inventory used in normalization must be precisely those emissions which are causally-related to the damages considered during valuation, for each impact category. [...] In summary, the requirements for congruence between normalization and valuation within each impact category appear to warrant more careful attention than they have received to date, in both internal as well as external normalization applications."

Heijungs et al. (2)

Usually, "a normalized score for a certain impact category is obtained by determining the ratio of the category indicator result of the product and that of a reference system, such as the world in a certain year or the population of a specific area in a certain year. In determining these two quantities, the numerator, the denominator, or both can suffer from incompleteness due to a lack of emission data and/or characterisation factors. This leads to what we call a biased normalization. As a consequence. the normalized category indicator result can be too low or too high. Some examples from hypothetical and real case studies demonstrate this. Especially when for some impact categories the normalized category indicator result is right, for others too low, and for others too high, severe problems in using normalized scores can show up. It is shown how this may affect the three types of usage of normalized results: error checking, weighting and standalone presentation. Some easy checks [applying contribution analyses] are proposed that at least alert the LCA practitioner of the possibility of a biased result. These checks are illustrated for an example system on hydrogen production. A number of remedies of this problem is possible. These are discussed. In particular, case-dependent normalization is shown to solve some problems, but on the expense of creating other problems. It appears that there is only one good solution: databases and tables of characterisation factors must be made more completely, so that the risk of detrimental bias is reduced. On the other hand, the use of the previously introduced checks should become a standard element in LCA practice, and should be facilitated with LCA software."

Bare et al. (3)
"[...] The U. S. Environmental Protection Agency (EPA) has developed a normalization database based on the spatial scale of the 48 continental U.S. states, Hawaii, Alaska, the District of Columbia, and Puerto Rico with a one-year reference time frame. Data within the normalization database were compiled based on the impact methodologies and lists of stressors used in TRACIs - the EPA's Tool for the Reduction and Assessment of Chemical and other environmental Impacts. The new normalization database published within this article may be used for LCIA case studies within the United States, and can be used to assist in the further development of a global normalization database. The underlying data analyzed for the development of this database are included to allow the development of normalization data consistent with other impact assessment methodologies as well.

Wegener Sleeswijk et al. (4)
"In the methodological context of the interpretation of environmental life cycle assessment (LCA) results, a normalisation study was performed. 15 impact categories were accounted for, including climate change, acidification, human toxicity, ecotoxicity, depletion of abiotic resources, and land occupation. The year 2000 was chosen as a reference year, and information was gathered on two spatial levels: the global and the European level. From the 1036 environmental interventions collected, 56 interventions turned out to account for at least 75 percent of the impact scores of all impact categories. All non-toxicity related, emission dependent impacts are fully dominated by the bulk emissions of only 12 substances or substance groups: CO_2, CH_4, SO_2, NO_x, NH_3, N_2O, CO, PM_{10}, NMVOC, and (H)CFCs emissions to air and emissions of N- and P-compounds to fresh water. For the toxicity-related emissions (pesticides, organics, metal compounds and some specific inorganics), the availability of information was still very limited, leading to large uncertainty in the corresponding normalisation factors. Apart from their usefulness as a reference for LCA studies, the results of this study stress the importance of efficient measures to combat bulk emissions and to promote the registration of potentially toxic emissions on a more comprehensive scale."

Main advantages

Bare et al. (3)
US.

Wegener Sleeswijk et al. (4)
Europe and Globe.

Open questions

Is it possible to merge the work of Bare et al. (US) and Wegener Sleeswijk (Europe and Globe) into one encompassing global normalisation data set with regional (US, Europe, Australia,...) differentiations?

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Bare et al. (3)
Normalisation factors and nackground data all available.

Wegener Sleeswijk et al. (4)
Normalisation factors and nackground data all available.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Bare et al. (3)
US data only.

Wegener Sleeswijk et al. (4)
Global and European data.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. <u>Heijungs et al. (2)</u> More evidence on the correctness of the following hypotheses: 1. The bias may be large for impact categories that are not so often included in LCA, or that are not well established and not widely recognized. This includes land use, noise, radiation, marine and sediment toxicity, etc. 2. The bias may be large for impact categories that are connected to many substances. This includes different forms of toxicity and radiation. 3. The bias may be small for impact categories that are dominated by just a few substances. This includes climate change and acidification. <u>General</u> (In)Congruence and bias issues may play an important role in normalisation, and should therefore receive further attention resulting into clear guidelines how to deal with these issues. The methodological and data choices – forming the background of incongruence and bias issues - made in drafting normalisation data must be made consistently with the same choices in drafting valuation/weighting data and in performing LCA case-studies. It would be useful to draft a list of these issues as checklist for practitioners and normalisation data/method developers. Merging of the work of Bare et al. (US), Wegener Sleeswijk (Europe and Globe) and Lundie et al. 2007 (Australia) into one encompassing global normalisation data set with regional (US, Europe, Australia,...) differentiations.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/weighting

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* Weighting is an optional step of Impact assessment in which the (normalised) indicator results for each impact category assessed are assigned numerical factors according to their relative importance, multiplied by these factors and possibly aggregated. Weighting is based on value-choices (e.g. monetary values, standards, expert panel). A convenient name for the result of the weighting step is 'weighting result', of which there is generally one for each alternative product system analysed. As a variation, though, weighting may also yield several weighting results per product system, for instance for human health, ecosystem health and resources. Before weighting can be performed, the various indicator results must first be converted into the same units, one possible method for which is normalisation.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Bengtsson, M.; Steen, B. (2000). Weighting in LCA - approaches and applications. Environmental Progress, 19:2, 101-109.
- (2) Schmidt, Wulf-Peter; Sullivan, John (2002). Weighting in Life Cycle Assessments in a Global Context. International Journal of Life Cycle Assessment, 7, 1, 5-10.
- (3) Eshet, T, O. Ayalon & M. Shechter (2006). An inclusive comparative review of valuation methods for assessing environmental goods and externalities. International Journal of Business Environment, 1, 2, 190-210.
2. Specific references
- (4) Itsubo, Norihiro; Sakagami, Masaji; Washida, Toyoaki; Kokubu, Katsuhiko; Inaba, Atsushi (2004). Weighting Across Safeguard Subjects for LCIA through the Application of Conjoint Analysis. International Journal of Life Cycle Assessment, 9, 3, 196-205.
- (5) Finnveden, G., P. Eldh & J. Johansson (2006). Weighting in LCA based on ecotaxes – development of a mid-point method and experiences from case studies. International Journal of Life Cycle Assessment, 11, Special Issue 1, 81-88.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. <u>Bengtsson & Steen (1)</u> "The article deals with the weighting step in Life Cycle Assessment (LCA) . Different weighting method are briefly described, and four operational such method (Ecoscarcity 97, EDIE Ecoindicator 99, and EPS 2OOOd) are applied to a simplified case to illustrate how they can contribute with additional information to the environmental assessment and decision making process. It is argued that the use of weighting can contribute to the relevance and acceptability of LCA results, but that the weighting step should be seen as a test of the compatibility between environmental impact profiles and different value profiles rather than as an impact. The authors also discuss some issues of controversy connected to weighting, as well as the practical implications procedure leading to a true measure of the aggregated impact. The authors also discuss some issues of controversy connected with weighting, as well as the practical implications of the ISO standard for weighting in LCA." <u>Schmidt & Sullivan (2)</u> "The option of weighting impact categories according to ISO 14042 on Life Cycle Impact Assessment (LCIA) is particularly difficult for global organizations, as they have to consider a wide range of values. The motivation for employing weighting is usually based on the desire to simplify LCIA output, especially in circumstances where product system tradeoffs occur. Looking globally at regional variations in legislation, consumer values, monetary valuation, existing weighting sets and expert opinions, no globally agreed upon weighting set is likely to be derived. This is due to both the inherent subjectivity of weighting and local variations in environmental imperatives. Hence, the authors recommend that LCIA quantitative weighting, especially those provided in pre-packaged software instruments, should not be employed. Admittedly, to use a spectrum of LCIA results for internal design decisions, some kind of tradeoff analysis has to be performed, especially if comparing competing design alternatives. However, this trade-off analysis should be done separately from the technical LCA study and should reflect values and visions of the global organization, as well as the circumstances of the targeted market, in a qualitative way. For any external communication, none of the quantitative weighting sets can be used." <u>Eshet et al. (3)</u> "Economists have developed various concepts aimed at proposing monetary values for environmental non-marketed goods. This review analyses the different approaches and reveals most of the methods rely on economic welfare theory, based on the values that individuals ascribe, directly or indirectly, to their preferences regarding an environmental good with no observable price in the market. However, in practice, approximate methods, based on expert judgement and assessment, dominate mostly because they are easier to attain." <u>Itsubo et al. (4)</u> "Many types of weighting methods, which have integrated the various environmental impacts that are used for life-cycle impact assessment (LCIA),

were proposed with the aim of developing the methodology as a useful information resource for decision making, such as in the selection of products. *Economic valuation indexes*, in particular, have attracted attention, as their assessment results are easy to understand and can be applied in conjunction with other assessment tools, including life-cycle costing (LCC) and environmental accounting. *Conjoint analysis* has been widely used in market research, and has recently been applied to research in environmental economics. The method enables us to provide two types of assessment results; an economic valuation and a dimensionless index. This method is therefore expected to contribute greatly to increasing the level of research into weighting methodology, in which an international consensus has yet to be established. Conjoint analysis, however, has not previously been applied to LCIA. LCA National Project (METI/NEDO/JEMAI) has conducted a study aimed at the development of a Japanese version of the damage-oriented impact assessment method called LIME (Lifecycle Impact assessment Method based on Endpoint modeling), in order to enhance its reliability and transparency. This study aimed at the application of conjoint analysis to the step of weighting in LIME. An ultimate goal of the research is to determine an amount of willingness to pay (WTP) for avoiding a unit quantity of damage of every safeguard subject (endpoint). Potential annual damages of four safeguard subjects (human health, biodiversity, social assets, and primary production), known as normalization values in LCIA, were used as fundamental information in this study. These data can be obtained through damage assessment. Taking this background into account, we performed a comparison of importance among the four safeguard subjects defined in LIME by applying conjoint analysis. A choice-based type of questionnaire was prepared for the interview with the respondents selected by random sampling. Pre-tests were conducted for 108 respondents in advance of the main survey. After we confirmed that the analyzed results of the pre-test were revealed to be statistically significant, the main surveys were conducted for 400 respondents by interviewing. WTP per quota can be determined by statistical simulation based on the random utility theory reflecting the responses to the questionnaires by random sampling. The values of one unit (standard) of attributes were significant statistically at the 1% level (all of the p value for coefficients of safeguard subjects were less than 0.0001). Based on the calculated results, two types of weighting factors, an economic valuation and a dimensionless index were obtained. The capability of generating two kinds of weighting factors is unique to conjoint analysis. A relative comparison of importance among the four categories indicates that human health gains the highest recognition, biodiversity gains the second highest recognition, and the weight of primary production and social assets have been estimated to be relatively smaller than the other two safeguard subjects. It is desirable to prepare a small number of attributes when conducting a conjoint analysis, because the efforts of respondents have to be reduced as far as possible. We confirmed that the damage-oriented method, which minimizes the number of attributes, is suitable to the requirement of conjoint analysis, because the results of comparisons among safeguard subjects were statistically significant, and showed that the contents of the questionnaires were well understood among the respondents. Judging from the results of this study, where statistical significance has not even been fully verified in the conventional research on the development of weighting coefficients for LCIA, it can be concluded that the weighting factors derived from this study based on the economic theory have a possibility to reveal the impact of environment on society."

Finnveden et al. (5)

"The weighting phase in Life Cycle Assessment (LCA) is and has always been a controversial issue, partly because this element requires the incorporation of social, political and ethical values. Despite the controversies, weighting is widely used in practise. In this paper we will present an approach for monetisation of environmental impacts which is based on the consistent use of ecotaxes and fees in Sweden as a basis for the economic values. The idea behind this approach is that taxes and fees are expressions of the values society places on resource uses and emissions. An underlying assumption for this is that the decisions taken by policy-makers are reflecting societal values thus reflecting a positive view of representative democracy. In the method a number of different ecotaxes are used. In many cases they can directly be used as valuation weighting factors, an example is the CO2-tax that can be used as a valuation of CO2-emissions. In some cases, a calculation has to be made in order to derive a weighting factor. An example of this is the tax on nitrogen fertilisers which can be recalculated to an emission of nitrogen which can be used as a weighting factor for nitrogen emissions. The valuation weighting factors can be connected to characterisation methods in the normal LCA practise. We have often used the Ecotax method in parallel to other weighting methods such as the Ecoindicator and EPS methods and the results are compared. A new set of weighting factors has been developed which has been used in case studies. It is interesting to note that the Ecotax method is able to identify different environmental problems as the most important ones in different case studies. In some cases, the Ecotax method has identified some interventions as the most important ones which lack weighting factors in other weighting methods. The midpoint-endpoint debate in the LCA literature has often centred on different types of uncertainties. Sometimes it is claimed that an advantage with having an endpoint approach is that the weighting would be easier and less uncertain. Here we are however suggesting a mid-point weighting method that we claim are no less uncertain than other often used weighting methods based on a damage assessment. This paper can therefore be seen as a discussion paper also in the midpoint-endpoint debate. The Ecotax method is ready to use. It should be further updated and developed as taxes are changed and new characterisation methods are developed. The method is not only relevant for LCA but also for other environmental systems analysis. The Ecotax method has also been used as a valuation method for Cost-Benefit Analysis (CBA), Life Cycle Costing (LCC) and within the context of a Strategic Environmental Assessment (SEA)."

Main advantages

Itsubo et al. (4)
Weighting at endpoint level.
Based on economic valuation: conjoint analysis.

Finnveden et al. (5)
Weighting at midpoint level.
Based on economic valuation or monetisation of environmental impacts, which is based on the consistent use of ecotaxes and fees in Sweden as a basis for the economic values.

Open questions

Bengtsson & Steen (1)
"It is argued that the use of weighting can contribute to the relevance and acceptability of LCA results [...]." It is a question whether this view is indeed shared widely or not, particularly with respect to the second point of acceptability?

Schmidt & Sullivan (2)
"Existing LCA weighting schemes are highly variable and are unlikely to yield a universal weighting set for the world, especially for global

organizations and companies." Is there a need for a universal weighting set for the world, and if so, are there other ways to yield such a set?

Eshet et al. (3)
This paper reviews economic valuation methods independent from LCA. For the latter reason, it has not been included any further in this analysis, moreover as economic valuation methods are already included under (1), (4) and (5) of this analysis.

Itsubo et al. (4)
Itsubo et al. (4) have developed one specific economic valuation index, whereas there are many different methods to develop similar indices. These are discussed e.g. in Eshet et al. (3). It would therefore be a question how the one selected by Istubo compares to the other options discussed by Eshet et al.

Finnveden et al. (5)
"An obvious problem with the Ecotax method is that monetary measures which are decided for one purpose (taxation) are assumed to be valid for another purpose, in this case as a measure of the environmental importance. We don't know if this assumption is correct. It depends on what the basis for the decision on the tax levels was."

"A key aspect when evaluating the Ecotax method is whether it can be assumed that the taxes correspond to the external costs, or at least reasonable approximations of them. Unfortunately we do not know the answer to this question, partly because we do not know which are the 'right' external costs."

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Bengtsson & Steen (1)
n.a.

Schmidt & Sullivan (2)
n.a.

Eshet et al. (3)
n.a.

Itsubo et al. (4)
Weighting factors have been derived.

Finnveden et al. (5)
"The Ecotax method is ready to use."

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Bengtsson & Steen (1)
n.a.

Schmidt & Sullivan (2)
n.a.

Eshet et al. (3)
n.a.

Itsubo et al. (4)
Japan.

Finnveden et al. (5)
Sweden.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

Bengtsson & Steen (1)
Can the use of weighting contribute to the relevance and acceptability of LCA results?

Schmidt & Sullivan (2)
Is there a need for a universal weighting set for the world, and if so, are there other ways to yield such a set?

Itsubo et al. (4) (and Eshet et al. (3))

- How does the conjoint analysis – choice base questionnaire compare to the other options discussed by Eshet et al.?
- Weighting factors for other countries and regions should be developed as the current ones are based on Japanese values.

Finnveden et al. (5)

- Are monetary measures which are decided for one purpose (taxation) valid for use as a measure of the environmental importance?
- Do taxes correspond to external costs, or they at least reasonable approximations of them?
- The method "should be further updated and developed as taxes are changed and new characterisation methods are developed."
- Furthermore, weighting factors for other countries and regions should be developed as the current ones are based on Swedish ecotaxes and thus reflect Swedish values.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/spatial differentiation

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. The reliability and validity of LCA results can be substantially improved by introducing spatial differentiation. Although location-specific data will rarely be available for all processes within a product life cycle, spatially differentiated assessment may be preferable for those processes for which the required information is available. Especially for processes that appear to predominate in the overall impact of a product life cycle, additional effort to gather location-specific information is advisable. To render spatial differentiation generally applicable to any process in any product life cycle, spatially specific characterisation factors are needed.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
2. Specific references
- (1) Nigge, Karl-Michael (2001). Generic Spatial Classes for Human Health Impacts, Part I: Methodology. International Journal of Life Cycle Assessment, 6, 5, 257-264.
- (2) Wegener Sleeswijk, A. (2003). General prevention and risk minimization in LCA. A combined approach. Environmental Science & Pollution Research, 10:1, 69-77.
- (3) Nansai, K.; Moriguchi, Y.; Suzuki, N. (2005). Site-dependent life-cycle analysis by the SAME approach: Its concept, usefulness, and application to the calculation of embodied impact intensity by means of an input-output analysis. Environmental Science & Technology, 39, 7318-7328.
- (4) Finnveden, Göran; Nilsson, Måns (2005). Site-dependent Life-Cycle Impact Assessment in Sweden. International Journal of Life Cycle Assessment, 10, 4, 235-239.
- (5) Sandra Bellekom; José Potting; René Benders (2006). Feasibility of Applying Site-dependent Impact Assessment of Acidification in LCA. International Journal of Life Cycle Assessment, 11, 6, 417-424.
- (6) Jyri Seppälä; Maximilian Posch; Matti Johansson; Jean-Paul Hettelingh (2006). Country-dependent Characterisation Factors for

	Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. International Journal of Life Cycle Assessment, 11, 6, 403-416.
-	(7) Hauschild Michael Z.; Potting José; Hertel Ole; Schöpp Wolfgang; Bastrup-Birk Annemarie (2006). Spatial Differentiation in the Characterisation of Photochemical Ozone Formation: The EDIP2003 Methodology. International Journal of Life Cycle Assessment, 11, Special Issue 1, 72-80.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Nigge (1)

"A new method for the spatially differentiated assessment of impacts of airborne pollutants on human health is presented. It is applicable to primary pollutants with linear exposure response functions. This includes the most important primary air pollutants from transportation and energy generation. The article looks at the spatial differentiation of impacts due to emission height and the local population density distribution around the emission site, as has been predicted using a Gaussian plume model. The differentiation due to population density is captured by way of five generic spatial classes: large cities in agglomerations, highly densified districts in agglomerations, cities in urbanized regions, country average districts, and low density rural districts in rural regions. Average impacts are calculated for each class. The method is simple enough to be applied to a large number of emissions within Life Cycle Assessments. It was used to calculate site-dependent exposure efficiencies for a variety of primary pollutants emitted at different heights. For traffic emissions of pollutants with short atmospheric residence times, the exposure efficiencies vary by a factor of 5 across Germany and by a factor of 75 across Europe. This differentiation due to population density decreases significantly with an increasing atmospheric residence time of the pollutants and with an increasing emission height."

Wegener Sleeswijk (2)

"Methods for life cycle assessment of products (LCA) are most often based on the general prevention principle, as opposed to the risk minimization principle. Here, the desirability and feasibility of a combined approach are discussed, along with the conditions for elaboration in the framework of LCA methodology, and the consequences for LCA practice. A *combined* approach provides a separate assessment of above and below threshold pollution, offering the possibility to combat above threshold impacts with priority. Spatial differentiation in fate, exposure, and effect modelling is identified to play a central role in the implementation. The collection of region-specific data turns out to be the most elaborate requirement for the implementation in both methodology and practice. A methodological framework for the construction of characterization factors is provided. Along with spatial differentiation of existing parameters, two newly introduced spatial parameters play a key role: the sensitivity factor (distinguishing between sensitive and insensitive areas) and the threshold factor (distinguish between above and below threshold areas). The practicability of the proposed procedure is illustrated by an example of its application. Providing a reasonable data availability, the development of separate LCA characterization factors for the respective assessment of pollution levels above and below environmental threshold values seems to be a feasible task that may add to LCA credibility."

Nansai et al. (3)
"This paper describes a practical approach to site-dependent life-cycle analysis (SDLCA) that differentiates site-dependent environmental impacts from a system's processes by considering the geographical conditions of each process. This approach converts an environmental output into its impacts by using site-dependent characterization factors (SDCFs). This approach defines an areas – the Spatial Area of iMpact Equivalency (SAME)s - within the boundaries of the geographical system during site-dependent life-cycle inventory (SDLCI) analysis and calculates an environmental output from a process for the SAMEs. Each
SAME represents a collection of geographical areas with internally homogeneous environmental impacts and can be mapped using a geographic information system. Preparing a SDLCI and SDCFs based on SAMEs facilitates the implementation of SDLCA by permitting the use of fewer regions during SDLCI. To demonstrate application of the SAME approach, an embodied impact intensity was formulated; it quantifies the impact directly and indirectly on the basis of the unit activity of a sector by means of input-output analysis with SDCFs. The validity of using SAMEs for SDLCA is demonstrated through two case studies: one studying suspended particulate matter, and one studying benzene. In both cases, the impact intensities are calculated using the SAME approach and the results are compared with those of site-generic LCI. [...]Here, it is important that the regions defined for the collected SDCFs conceptually cover the actual geographical boundaries of the product system being analyzed (see Figure S-1 in the Supporting Information (SI)). [...]In terms of the practical approach, our concerns are how to avoid generating an impractically large number of regions while still effectively reflecting regional differences in the impacts generated by each process during SDLCIA. In the present study, a geographical information system (GIS) was used to display the extents of SAMEs in the form of a map."

Finnveden & Nilsson (4)
"Although LCA is traditionally a site-independent tool, there is currently a trend towards making LCA more site-dependent if not site-specific. For Europe, site-dependent impact factors have been calculated on a country basis for acidification, terrestrial eutrophication and toxicological impacts. It is, however, an open question whether this is the optimum level for site-dependent factors. T*he aim of this paper is to develop site-dependent characterisation factors for different parts of Sweden for air emissions of NOx, SOx and particulates regarding ecosystem and human health impacts*. Based on experiences from a case-study, the usability of the site-dependent factors for LCA are discussed, as well as the appropriate level of site-dependency for ecosystem and human health impacts. The *Ecosense model* is used for calculating sitedependent factors for some atmospheric pollutants. Characterisation factors are calculated for four different places in Sweden with two different stack heights. The characterisation factors for ecosystem impacts show fairly small differences between different parts of Sweden (within a factor of two). For health impacts, the differences between different parts of the country were larger and more significant (up to one order of magnitude). Also the difference between low and high stack heights may be relevant, especially in densely populated areas. These results suggest that for ecosystems, site-dependent characterisation factors for the considered atmospheric pollutants on a country level may be sufficient for most applications. However, for health impacts, site-dependent factors on a country level may be inappropriate. Beside LCA, the calculated factors and the methodology used should also be useful for other environmental system analysis tools, such as Strategic Environmental Assessment, Cost-Benefit Analysis and Environmental

Management Systems."

Bellekom et al. (5)

"Taking into account the location of emissions and its subsequent, site-dependent impacts improves the accuracy of LCIA. Opponents of site-dependent impact assessment argue that it is too time-consuming to collect the required additional inventory data. In this paper we quantify this time and look into the added value of site-dependent LCIA results. We recalculated the acidifying impact for three existing LCA studies: linoleum, stone wool, and water piping systems. The amount of time needed to collect the required additional data is reported. The EDIP2003 methodology provides site-generic and site-dependent acidification factors. We used these factors to recalculate acidification for the case studies. We analyzed differences between site-generic and site-dependent acidification and reported problems experienced. Finding the location of processes and emissions was easy. The reports of the three case studies contained most of this information. Far more time was needed to disaggregate processes to the level where emissions can be localized. Although the overall conclusions with regard to acidification did not change in the case studies, the relative importance of processes shifted when considering sub-levels. This is especially important for improvement analysis. Site-dependent acidification assessment was hampered in the linoleum case study where about 40% of the acidification originates from non-European emissions. However, EDIP2003 provides no site-dependent factors for these countries and site-generic factors had to be used instead. Thus, calculating site-dependent acidification is only feasible for LCA studies in which the majority of the emissions originate in Europe. We could not reproduce all parts of the three case studies using the report and additional public resources. This hindered our recalculation. In fact, any additional analysis will be hampered by this lack of reproducibility. ISO recommends such reproducibility for comparative assertion disclosed to the public. Spatially differentiated acidification is feasible for each of the three case studies. Finding the location of processes and emissions was easy, but quite some time was needed to disaggregate processes and emissions to the appropriate level. Overall conclusions on acidification remained the same for the case studies, but the relative contribution of basic processes changed when applying site-dependent impact assessment. Though the three case studies were all rather detailed and complete, none of them was fully reproducible. This complicated recalculation of acidification, and will in fact make any additional analysis difficult."

Seppälä et al. (6)

Several authors have shown that spatially derived characterisation factors used in life cycle impact assessment (LCIA) can differ widely between different countries in the context of regional impact categories such as acidification or terrestrial eutrophication. Previous methodology studies in Europe have produced country-dependent characterisation factors for acidification and terrestrial eutrophication by using the results of the EMEP and RAINS models and critical loads for Europe. The unprotected ecosystem area (UA) is commonly used as a category indicator in the determination of characterisation factors in those studies. However, the UA indicator is only suitable for large emission changes and it does not result in environmental benefits in terms of characterisation factors if deposition after the emission reduction is still higher than the critical load. For this reason, there is a need to search for a new category indicator type for acidification and terrestrial eutrophying in order to calculate site-dependent characterisation factors. The aim of this study is to explore new site-dependent characterisation factors for European acidifying and eutrophying emissions based on accumulated exceedance (AE) as the category indicator, which integrates both the exceeded area and amount of exceedance. In addition, the results obtained for the AE and UA indicators are compared with each other. The chosen category indicator, accumulated exceedance (AE), was computed according to the calculation methods developed in the work under the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (LRTAP). Sulphur and nitrogen depositions to 150x150 km2 grid cells over Europe were calculated by source-receptor matrices derived from the EMEP Lagrangian model of long-range transport of air pollution in Europe. Using the latest critical load data of Europe, the sitedependent characterisation factors for acidification and terrestrial eutrophication were calculated for 35 European countries and 5 sea areas for 2002 emissions and emissions predicted for 2010. In the determination of characterisation factors, the emissions of each country/area were reduced by various amounts in order to find stable characterisation factors. In addition, characterisation errors were calculated for the AE-based characterisation factors. For the comparison, the results based on the use of UA indicator were calculated by 10% and 50% reductions of emissions that corresponded to the common practice used in the previous studies. The characterisation factors based on the AE indicator were shown to be largely independent of the reduction percentage used to calculate them. Small changes in emissions (≤100 t) produced the most stable characterisation factors in the case of the AE indicator. The characterisation errors of those characterisation factors were practically zero. This means that the characterisation factors can describe the effects of small changes in national emissions that are mostly looked at in LCAs. The comparison between country-dependent characterisation factors calculated by the AE and UA indicators showed that these two approaches produce differences between characterisation factors for many countries/areas in Europe. The differences were mostly related to the Central and Northern European countries. They were greater for terrestrial eutrophication because the contribution of ammonia emission differ remarkably between the two approaches. The characterisation factors of the AE indicator calculated by the emissions of 2002 were greater than the factors calculated by the predicted emissions for 2010 in almost all countries/sea areas, due to the presumed decrease of acidifying and eutrophying emissions in Europe. [...] It would also be useful to compare the approach based on the AE indicator with the method of the hazard index, as recommended in the latest CML guidebook."

Hauschild et al. (7)

"In the life cycle of a product, emissions take place at many different locations. The location of the source and its surrounding conditions influence the fate of the emitted pollutant and the subsequent exposure it causes. This source of variation is normally neglected in Life Cycle Impact Assessment (LCIA), although it is well known that the impacts predicted by site-generic LCIA in some cases differ significantly from the actual impacts. Environmental impacts of photochemical ozone (ground-level ozone) depend on parameters with a considerable geographical variability (like emission patterns and population densities). A spatially differentiated characterisation model thus seems relevant. The European RAINS model is applied for calculation of site-dependent characterisation factors for Non-Methane Volatile Organic Compounds (NMVOCs) and nitrogen oxides (NOx) for 41 countries or regions within Europe, and compatible characterisation factors for carbon monoxide (CO) are developed based on expert judgement. These factors are presented for three emission years (1990, 1995 and 2010), and they address human health impacts and vegetation impacts in two separate impacts categories, derived from AOT40 and AOT60 values respectively. Compatible site-generic characterisation factors for NMVOC, NOx, CO and methane (CH4) are calculated as emission-weighted European averages to be applied on emissions for which the location is unknown. The site-generic and site-dependent characterisation factors are part of the EDIP2003 LCIA methodology. The factors are applied in a specific case study, and it is demonstrated how the inclusion of spatial differentiation may alter the results of the photochemical ozone characterisation of life cycle impact assessment. Compared to traditional midpoint characterisation modelling, this novel approach is spatially resolved and comprises a larger part of the cause-effect chain including exposure assessment and exceeding of threshold values. This positions it closer to endpoint modelling and makes the results easier to interpret. In addition, the developed model allows inclusion of the contributions from NOx, which are neglected when applying the traditional approaches based on Photochemical Ozone Creation Potentials (POCPs). The variation in site-dependent characterisation factors is far larger than the variation in POCP factors. It thus seems more important to represent the spatially determined variation in exposure than the difference in POCP among the substances."

Main advantages

Nigge (1)

This method applies generic spatial classes that can thus be applied for all regions/countries, applying a Gaussian Plume model.

Wegener Sleeswijk (2)

The spatial differentiation proposed is on a region-basis and has been elaborated (not yet published) on a country basis:
see
http://www.leidenuniv.nl/cml/ssp/software/globox/globack1.zip
and
http://www.leidenuniv.nl/cml/ssp/software/globox/globack2.zip.

Nansai et al. (3)

This approach is not limited to chemicals and impact categories and may thus serve a basic approach for spatial differentiation of all impact categories. For this it needs, however, further practical elaboration (see R&D needs below).

Finnveden & Nilsson (4)

Site-dependent characterisation factors for different parts of Sweden for air emissions of NOx, SOx and particulates regarding ecosystem and human health impacts, applying the Ecosense model.

Bellekom et al. (5)

This paper has checked the practical applicability of various site-dependent methods by quantify the time needed to collect the required additional inventory data and by looking into the added value of site-dependent LCIA results. The acidifying impact for three existing LCA studies was re-calculated with the (site-generic and site-dependent) EDIP2003 methodology.

Seppälä et al. (6)

Advantage: regionalised factors.
Disadvantage: only Europe with the EMEP Lagrangian model of long-range transport of air pollution in Europe; method (4) lacks characterisation factors for direct emissions to water and soil.

Hauschild et al. (7)
Regionalised factors for NMVOC, CO and NOx for 41 European states and Europe generic. RAINS-based model.
Compared to the other approaches, this approach comprises a larger part of the cause-effect chain including exposure assessment and exceeding of threshold values. This positions it closer to endpoint modelling and makes the results easier to interpret.

Open questions

Nigge (1)
Are Nigge's Gaussian plume model-based generic spatial classes applicable to other impact categories than for impacts of airborne pollutants on human health? How does this approach compare to the approach of Finnveden & Nilsson (4) elaborated for largely the same priority substances but applying the Ecosense model?

Wegener Sleeswijk (2)
To what extent is the current country-based spatial differentiation also relevant and feasible for other impact categories than toxicity?

Nansai et al. (3)
Elaboration of the SAMEs approach for different impact categories and substances.

Finnveden & Nilsson (4)
Validation for other countries if suggest that for ecosystems, site-dependent characterisation factors for ecosystems for the considered atmospheric pollutants on a country level may indeed be sufficient for most applications, whereas for health impacts, site-dependent factors on a country level may be inappropriate.
How does this approach compare to the approach of Nigge (1) elaborated for largely the same priority substances but applying a Gaussian plume model?

Bellekom et al. (5)
Are the application test-results found for the EDIP 2003 methodology also valid for other spatial differentiation approaches in LCA?

Seppälä et al. (6)
Main open question is a comparison of this approach (4) with the proposal by Huijbregts (1999; 2001), which has (surprisingly) not been done as part of this paper. "In the LCA terminology, the method based on AE indicator represents the 'only above' approach. The same concerns one version of the hazard index (HI) method developed by Huijbregts and his colleagues (2001). The main difference between these two approaches seems to be that the hazard index method uses a ratio scale in the calculation of exceedance, whereas the AE approach uses the absolute difference. [...] In both cases, the values of exceedance are weighted by the areas of ecosystems. In order to clarify the meaning of ratio scale of the HI method in terms of characterisation factors, there is a need to calculate the corresponding characterisation factors with the same input data and an integrated assessment

model. In addition, there is a need to discuss the philosophical/conceptual aspects related to the calculation rules of both methods. The discussion should also include the hazard index approach in which all deposition situations above and below critical loads in Europe were taken into account. It should be noted that both HI approaches were only applied in the marginal way, i.e. country-dependent characterisation factors for acidification and terrestrial eutrophication were calculated by the derivation in the deposition situation. In this work, the AE approach was studied from the point of view of various emission reductions. Are the conclusions made for the AE indicator also suitable for the HI indicator? This is a question to be explored in depth in future studies."

Hauschild et al. (7)
What the added value of a RAINS-based model compared to the Eulerian model applied by Labouze et al. (2) is, remains unclear in Hauschild et al. as they don't discuss the paper by Labouze et al.
Hauschild et al. claim that "the variation in site-dependent characterisation factors is far larger than the variation in POCP factors. It thus seems more important to represent the spatially determined variation in exposure than the difference in POCP among the substances." This should be checked with the other models that are also regionalised. It would means that no CFs for individual VOCs would be necessary to derive.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Nigge (1)
The generic spatial classes have currently been elaborated for Germany and for Western and Central Europe for PM 2.5, PM 10, SO2, NOx, benzene, formaldehyde, acetaldehyde, benzo[a]pyrene, 1,3-butadiene.

Wegener Sleeswijk (2)
List of characterisation factors for different countries, for the toxicity impact categories for a wide range of chemicals is in preparation and will be published soon.

Nansai et al. (3)
Because of present limitations in the available data on SDCFs for Japanese pollutant emissions, the SAME approach has up till now only been applied to the human health impact evaluation of benzene emissions.

Finnveden & Nilsson (4)
Site-dependent characterisation factors for different parts of Sweden for air emissions of NOx, SOx and particulates regarding ecosystem and human health impacts.

Bellekom et al. (5)

Focus of this study was on practicability aspects.

Seppälä et al. (6)
List of characterisation factors for emissions of SO_2, NO_2 and NH_3 to air is supplied for different European countries.

Hauschild et al. (7)
Site-dependent and site-generic characterisation factors for exposure of vegetation to photochemical ozone (in m^2.ppm.hours/g emission) and for exposure of humans to photochemical ozone, emissions of NMVOC, CO and NOx to air (in pers.ppm.hours/g emission).

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Nigge (1)
Germany and Western/Central Europe

Wegener Sleeswijk (2)
Global.

Nansai et al. (3)
Japan.

Finnveden & Nilsson (4)
Different parts of Sweden.

Bellekom et al. (5)
Depending on method applied: EDIP 2003 for Europe etc etc. Focus of this study was on practicability aspects.

Seppälä et al. (6)
Europe.

Hauschild et al. (7)
Europe.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

Main challenge is to develop spatial differentiation over the different impact categories in such a consistent way that clear and unambiguous guidelines can be developed how to collect which geographic data in the inventory analysis. One impact assessment method may need more detailed (at the level of locations or in terms of the value of a certain parameter, e.g. pH value) geographic data than another (e.g., country or continent). The data needed for each of these different characterisation methods need to relate in such a way that the practitioner is requested to collect data at a certain geographic level (e.g. country) and that all other geographic data needed for other characterisation methods can be derived from this entry. Maybe GIS could offer the data hierarchy framework for this. The SAME approach - and possibly also GLOBOX - offers the greatest potential with respect to this challenge.

Key issue is the availability of regional emission and environmental data in order to calculate regional characterization factors and to combine these with the appropriate regional emission data.

Nigge (1)
"The extension of the generic spatial classes to other countries is a topic of further research."

"Three main limitations apply to the method of generic spatial classes presented here: It is based on the assumption of a linear exposure response function, which is valid for the major pollutants from energy generation and transportation. For other pollutants, further research needs to clarify to what extent spatial differentiation of impacts also arises from variations in their background concentration. Further research is also required regarding the extent to which population exposures are sensitive to built-up structures, topographical features and local climates. The Gaussian plume model used here does not consider such effects."

Comparison of this approach to the approach of Finnveden & Nilsson (4).

Wegener Sleeswijk (2)
Coverage of more chemicals and checking the feasibility and relevance of the country-based spatial differentiation approach for other impact categories.

Nansai et al. (3)
"[...] it is essential to prepare sufficient available SDCFs for the practical approach to be feasible in SDLCA. Developing databases of SDCF values will facilitate future environmental analyses based on SDLCA. [...]If SDCFs based on the SAMEs and the corresponding SAME geometries are also well prepared in available databases, the SAME approach can become a practical and useful method for performing SDLCA without

increasing to impractical levels the numberof regions required to cover the geographical system boundary for SDLCI. [...]Finding effective, high-quality SAME definitions for use in SDLCIA would become an important research challenge for SDLCA in the future. The data used to define SAMEs, such as population distributions, meteorological data, and vegetation data, could be obtained from both existing statistics and from new satellite data. Such research would significantly support the original purpose of SDLCA, which is to differentiate site-dependent impacts based on the geographical properties that affect a process. For compilation of SDLCI information based on the SAME approach, it is also necessary to obtain locational" emission data.

Finnveden & Nilsson (4)
Validation for other countries if suggest that for ecosystems, site-dependent characterisation factors for ecosystems for the considered atmospheric pollutants on a country level may indeed be sufficient for most applications, whereas for health impacts, site-dependent factors on a country level may be inappropriate.
Comparison of this approach to the approach of Nigge (1).

Bellekom et al. (5)
Validation of the application test-results found for the EDIP 2003 methodology other spatial differentiation approaches.

Seppälä et al. (6)
It should be investigated how this method (4) compares to the method of Huijbregts (1999; 2001) and it should be investigated how the current model can include impact outside Europe and/or how the model can be extended to other continents besides Europe.

Hauschild et al. (7)
Hauschild et al. claim that "the variation in site-dependent characterisation factors is far larger than the variation in POCP factors. It thus seems more important to represent the spatially determined variation in exposure than the difference in POCP among the substances." This should be checked with the other models that are also regionalised. It would means that no CFs for individual VOCs would be necessary to derive.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/simplified methods & proxies

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. LCA is often considered to be too complex, time-consuming and too costly. Therefore, as long as LCA exists method developers have tried to derive and develop simplified LCA methods, particularly for applications as DfE when lots of data are not known (yet). Although the LCIA phase is straight on and not that time-consuming, also simplified methods for this phase have been proposed. These methods are the subject of this analysis.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
2. Specific references
- (1) Fleischer, Günter; Gerner, Karin; Kunst, Heiko; Lichtenvort, Kerstin; Rebitzer, Gerald (2001). A Semi-Quantitative Method for the Impact Assessment of Emissions Within a Simplified Life Cycle Assessment. International Journal of Life Cycle Assessment, 6, 3, 149-156.
- (2) Ritthof, M.; Rohn, H.; Liedtke, C. (2002). Calculating MIPS. Resource productivity of products and services. Wuppertal Institute for Climate, Environment and Energy Wuppertal.
- (3) Kleijn, R. (2001). Adding it all up. The sense and non-sense of bulk-MFA Journal of Industrial Ecology, 4:2, 7-8.
- (4) Voet, Ester van der; van Oers, Lauran; Nikolic, Igor (2004). Dematerialization: Not Just a Matter of Weight. Journal of Industrial Ecology, 8, 4, 121-138.
- (5) Huijbregts, M.A.J.; Rombouts, L.J.A.; Hellweg, S.; Frischknecht, R.; Hendriks, J.; Meent, D. van de; Ragas, A.M.J.; Reijnders, L.; Struijs, J. (2006). Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environmental Science & Technology, 40:3, 641-648.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. <u>Fleischer et al. (1)</u> “Dealing with data gaps, data asymmetries, and inconsistencies in life cycle inventories (LCI) is a general problem in Life Cycle Assessment (LCA) studies. An approach to deal with these difficulties is the simplification of” the LCIA method in such a way that it can deal with incomplete knowledge on LCI emissions with respect to their quality (what is emitted) and/or with respect to their quantity (how much is emitted). “Simplification is essential for applying LCA in the context of design for environment (DfE). The tool **euroMat** is a comprehensive DfE software tool that is based on a specific, simplified LCA approach, the Iterative Screening LCA (IS-LCA). Within the scope of the IS-LCA, there is a quantitative assessment of energy-related processes, as well as a semi-quantitative assessment of non-energy related emissions which supplement each other. The semi-quantitative assessment, which is in the focus of this article, aims at lowering the requirements for the quality of non-energy related emissions data through combined use of qualitative and quantitative inventory data. Potential environmental impacts are assessed based on ABC-categories for qualities (harmfulness) of emissions and XYZ-categories for quantities of emitted substances. Employing statistical methods assignment rules for the ABC/XYZ-categories were derived from literature data and databases on emissions to air, water, and soil. Statistical tests as well as a DfE case study (comparing the materials aluminum and carbon fiber reinforced epoxy for a lightweight container to be used in an aerospace application) were conducted in order to evaluate the level of confidence and practicality of the proposed, simplified impact assessment. Statistical and technical consistency checks show that the method bears a high level of confidence. Results obtained by the simplified assessment correlate to those of a detailed quantitative LCA.” [...] “The semi-quantitative impact assessment method is a combination of an ABC-assessment for the identification of hot-spots (quality of emissions) and an XYZ-assessment, which is a measure for the quantity of a material flow between the observed product system and the environment (the natural environment as well as processes outside the system boundaries). In this terminology, an 'A' denotes serious environmental problems associated with an emission, whereas a 'C' indicates that a substance does not cause any significant problems. In the XYZ-assessment 'X' denotes a great, 'Y' a medium, and 'Z' an insignificant quantity. For each environmental medium (air, water, soil), an ABC/XYZ-categorization of an emission is performed. This semi-quantitative approach makes it possible to use both the available, detailed quantitative LCI data and qualitative information in the assessment, since both can be categorized in the ABC and XYZ-system. This eliminates data asymmetries and inconsistencies.” [...] “XYZ-categories are used to indicate the quantitative relevance of an emission. Within the second step of the ISLCA, quantitative inventory data are not available for all processes and product systems. Available data are widely based on literature and significant differences in data quality exist. Experiences based on 15 DfE case studies conducted with euroMat show that only incomplete quantitative or semi-quantitative data on masses of emissions (great amount, medium amount, small amount, according to expert judgment) are available in most cases. Therefore, on the one hand, a systematic and consistent measure is necessary that defines the terms as being a great (X), medium (Y), or small (Z) amount. On the other hand,

existing quantitative data have to be assigned to the XYZ-intervals in order to ensure data symmetry. The question becomes, "How does one classify an amount of an emission as great, medium, or small?".”

MIPS (2,3)

“MIPS means Material Input Per Service unit. In order to estimate the input orientated impact on the environment caused by the manufacture or services of a product, MIPS indicates the quantity of resources (known as “material” in the MIPS concept) used for this product or service. Once one has the reciprocal, a statement can be made about resource productivity, i.e. it can be calculated how much use can be obtained form a certain amount of “nature”.

Material extractions and *emissions* cause changes in natural *material flows* and *cycles*. Previously stable cycle systems become unstable (see greenhouse effect). This drastically and/or permanently alters conditions in the environment. [...] MIPS calculates the use of resources from the point of their extraction from nature: all data corresponds to the amount of moved tons in nature, thus to the categories of biotic or renewable raw material, abiotic or non-renewable raw material, water, air and *earth movement* in agriculture and silviculture (incl. erosion). All material consumption during manufacture, use and recycling or disposal is calculated back to resource consumption. this is done by simple calculation factors for energy consumption or also for transport, which are expressed in t/MWh or t/tkm. Complex system analyses are concealed there, which, for example, indicate resource consumption per *energy carrier* and type of power plant.

[...] the calculation of the MIPS value of the result of Step 5 [...]:

- abiotic raw material 1.2 kg
- biotic raw material 0.01 kg
- water 42 kg
- air 0.04 kg
- erosion 2.2 kg

[...] it is permissible and often makes sense to compile the following categories equally: “abiotic raw materials”, “biotic raw materials”, as well as “earth movement” (but here, only “erosion”). The sum of these categories can be understood as a main indicator of these observations and is called “Total Material Requirement” (TMR). [...] The category “water” should likewise be examined separately, as interference with water can have very different effects and consequences regionally. Differentiating between processing and colling water helps to avoid making the specific significance of this value unnecessarily difficult, because of the vast amounts of water necessary for cooling. When considering the category “air”, the various uses of particles are to be comprehensively summed up (combustion, chemical transformation and physical transformation). CO_2 emissions are dealt with in the section “combustion air”. The category “air” should also not be summed up with others”

Voet et al. (4)

“This article contains the results of a study performed to support the Dutch environmental policy of dematerialization. The aim of the study was to develop and apply a methodology to identify the materials that contribute most to the environmental problems in the Netherlands. The developed methodology combines aspects of material flow accounting (MFA) and life-cycle assessment (LCA) and aims at adding a set of environmental weights to the flows of the materials. The methodology was applied to a number of materials. For these materials, impacts per kilogram were extracted from a standard LCA database in combination with standard LCA software. These impacts per kilogram are then multiplied with the yearly throughput of each material in the Netherlands to obtain an indication of the environmental impacts associated with each material. [...] Materials vary many orders of magnitude in their impacts per unit mass. In general, the impact per unit of mass of bulk materials is lower than that of materials used in small quantities. This implies that the variation in orders of magnitude of impact multiplied by mass is much less than either mass or impact per kilogram separately. High-priority materials based on impact multiplied by mass are either small-quantity materials with very high impacts per kilogram (such as heavy metals) or large-quantity materials with not-so-low impacts per kilogram (such as materials from agriculture and plastics). [...]"

This paper is particularly interesting with respect on their observation on the role of MIPS versus LCA. The following observations are made by the authors: "On a detailed level, weight as an indicator for environmental pressure is clearly misleading. The impact of sand, despite its large flows, is indeed orders of magnitude less than the impact related to the small-scale heavy metals. Comparing with DMC on a more aggregated level, some of the results presented above suggest that the outcomes might not be too different. The fact that metals have to be extracted from their ores leads to a high impact, but also to a high weight in DMC, because DMC includes not only finished materials but also raw materials like ores. The results are obtained just for one country and might not be representative. It would be interesting to compare other countries as well and/or developments over time. It would also help to look into the database more closely and find the reasons for high scores. This could contribute also to the debate on the value of mass-based indicators. It remains without doubt, however, that for a policy on materials more detailed information is needed on the impacts of specific materials. Otherwise it would not be possible to prioritize among materials. [...]

- The mass flows of an individual material are not indicative of its environmental pressure, either absolute or compared with other materials.
- On a more aggregate level of groups of materials, mass-based and impact-based indicators appear to point in the same direction. At the least, therefore, the relevancy of the mass-based indicators cannot be dismissed easily."

Huijbregts et al. (5)
"The appropriateness of the fossil Cumulative Energy Demand (CED) as an indicator for the environmental performance of products and processes is explored with a regression analysis between the environmental life-cycle impacts and fossil CEDs of 1218 products, divided into the product categories "energy production", "material production", "transport", and "waste treatment". Our results show that, for all product groups but waste treatment, the fossil CED correlates well with most impact categories, such as global warming, resource depletion, acidification, eutrophication, tropospheric ozone formation, ozone depletion, and human toxicity (explained variance between 46% and 100%). We conclude that the use of fossil fuels is an important driver of several environmental impacts and thereby indicative for many environmental problems. It may therefore serve as a screening indicator for environmental performance. However, the usefulness of fossil CED as a stand-alone indicator for environmental impact is limited by the large uncertainty in the product-specific fossil CED-based impact scores (larger than a factor of 10 for the majority of the impact categories; 95% confidence interval). A major reason for this high uncertainty is non-fossil energy related emissions and land use, such as landfill leachates, radionuclide emissions, and land use in agriculture and forestry."

Main advantages

Advantage of Fleischer et al. (1) and Huijbregts et al. (5) compared to MIPS (2,3) is that Fleischer et al. and Huijbregts et al. test their simplified indicators to the "normal" LCIA method, and draw conclusion on how good their indicators are compared to "normal" LCIA. MIPS doesn't make such a comparison.

Open questions

Fleischer et al. (1)

1. The XYZ determination of the quantity of an emission remains debatable. Whether an emission quantity is great, medium or insignificant depends on a specific chemical, as the authors also note. XYZ classification of what is great is now related to the ABC classification, and it remains an open question whether this is correct and defendable. For example, 2,3,7,8-TCDD is carcinogenic (A.1.1) but emitted in quantities of pico-grams (<<Z) only (and more examples can be given here, like CO2 on the other side of the spectrum: B.2.2 chemical which is emitted in more than great amounts).
2. What does the system do if quality and quantity of an emission are unknown?
3. How do the efforts needed to apply the IS-LCA system compare to the efforts needed to quantify LCI-data gaps as yet and apply "normal" LCIA methods?

MIPS (2,3)

Kleijn (3): "When used for MIPS, bulk-MFA can be regarded as a simplified LCA in which the mass flows (including hidden flows) are used as an indicator of the environmental impact of the product or service."

General observations:

- It seems that MIPS has developed without reference to international developments and standardisation of LCA.
- MIPS accounts for material inputs only, as an indicator for further environmental impacts. LCA accounts for both such material inputs from the environment, as related to depletion, and also includes outputs to the environment as related to all relevant environmental problems, including global warming, acidification, eutrophication, toxicity, etc. Furthermore, LCA can also cover other types of interventions to the environment, like radiation, land use shifts, noise, etc.
- Conclusion: MIPS is one form of simplified LCA, that can be improved by explicitly using the ISO-LCA framework.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

All methods are operational but the degree of operability significantly differs.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Fleischer et al. (1)
DfE.
"The application of the developed method does not have to be limited to DfE. Most LCA studies have to deal with data gaps, data asymmetries, and inconsistencies [...]. In these cases, this semi-quantitative method may facilitate the impact assessment as well." This implies, however, that the A/B/C X/Y/Z method is applied as basis of such a case-study and that the "normal" LCIA methods are not applied.

MIPS (2,3)
Materials and products.

Voet et al. (4)
Materials.

Huijbregts et al. (5)
Products and processes.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

Fleischer et al. (1)
"The statistical base of the method is expanded continuously since it is an integral part of the DfE software tool euroMat, which is currently being further developed. That should foster the application of the method. Outside DfE, the method should also be capable of facilitating simplified LCAs in general."
"[...] the assignment rules have to be reviewed and adapted in the future in order to update the values for the XYZ-intervals used in the method. This should be done continuously as new LCI data are to be integrated."

MIPS (2,3)
- Explicit methods choices e.g. functional unit specification, allocation, evaluation frameworks
- Explicit link to data bases LCA Forum, Eco-Invent etc.
- Explicit analysis of where the mass simplification makes sense and where not.

Voet et al. (4)

"The comparison of impact indicators and mass-based indicators needs to be elaborated further. Comparisons should be made for other countries as well, over time, for the total, as well as broken down into categories, and on the level of the individual materials. If the use of mass headline indicators is to be adopted by national governments as indicators for environmental pressure, the relation of these indicators to environmental impacts, however remote, should be clarified further."

Huijbregts et al. (5)

"[...] in the current study we evaluated the fossil CED with the environmental impacts assessed according to the LCA methodology, but not with observed environmental impact. This implies that in the current work, impacts missing in LCA have not been tested with regard to the CED either. For instance, some environmental problems such as scarcity of clean drinking water, salination, endocrine disruption, and indoor exposure to chemicals are usually neglected in LCA (and in the present paper). We do not expect that these impacts will have a good correlation with the fossil CED.

It should also be noted that the correlation analysis is based on cradle-to-gate and waste treatment data only. For a complete cradle-to-grave assessment, we would additionally need data on intermediate steps, such as product manufacturing and use. This information is for most products not readily available. Further research is required to unravel the correlation between fossil CED and environmental impacts on a cradle-to-grave basis."

Comments

[Phase/Topic/Approach]
LCIA/monetarization of effects

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* Monetarization refers to the use of financial metrics to express non-financial aspects, in this case environmental impacts. Two main schools here are the use of damage costs, and the use of prevention costs. With damage costs, impacts such as climate change, acidification and toxicity are converted into an estimate of the economic damage incurred, e.g. related to damage to property (buildings, crops), costs related to curing diseases, loss in income due to illness, or even a measure of the loss due to a decrease of the quality of life. With prevention costs, the basis is the costs that would have to be made to prevent the chemical from being emitted, or to prevent the damage from occurring. Monetarization is used for several purposes: as a form of weighting different environmental impacts (like in LCA), to incorporate environmental costs in an economic cost-benefit analysis, for determining environmental (Pigouvian) taxes, etc.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (3) Hofstetter, P.; Müller-Wenk, R. (2005). Monetization of health damages from road noise with implications for monetizing health impacts in life cycle assessment. Journal of Cleaner Production, 13, 1235-1245.
2. Specific references
- (1) Spadaro, Joseph V.; Rabl, Ari (1999). Estimates of Real Damage from Air Pollution: Site Dependence and Simple Impact Indices for LCA. International Journal of Life Cycle Assessment, 4, 4, 229-243.
- (2) Krewitt, W.; Heck, T.; Trukenmüller, A.; Friedrich, R. (1999). Environmental damage costs from fossil electricity generation in Germany and Europe. Energy Policy, 27, 173-183.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Spadaro & Rabl (1)

"In contrast to the various "potential impact" indices that have been proposed, we show that indices for real damage can be derived, based on the impact pathway methodology which involves the calculation of increased pollutant concentration in all affected regions due to an incremental emission (e.g. µg/m3 of particles, using models of atmospheric dispersion and chemistry), followed by the calculation of physical impacts (e.g. number of cases of asthma due to these particles, using a concentration-response function). The numbers are summed over all receptors of concern (population, crops, buildings, ...). We show that in a uniform world (linear dose-response function, uniform receptor density and uniform atmospheric removal rate) the conservation of matter implies a very simple formula for the total damage. The generalization to secondary pollutants is straightforward. By detailed numerical evaluations, using real data for atmospheric dispersion and geographic receptor distribution, we have demonstrated that this simple formula is an excellent representation of typical damages. Results are shown for the principal air pollutants emitted by smoke stacks of industrial installations or by road transport."

In this study the concept of "damage costs" is introduced: "Most of the impacts are incommensurate, for instance the mortality and soiling of buildings. For a comparison one needs either a multi-criteria analysis or else weighting or ranking by a common metric unit. Monetary valuation, as used by ExternE (1995; 1998), has the great advantage of yielding a single measure that is automatically consistent with the market. Note that even a non-monetary valuation cannot get around the basic problem of incommensurability; putting asthma attacks and mortality on the same scale necessarily involves a value judgment. [...] Here we use monetary valuation. However, since some people are strongly opposed to the monetary valuation of mortality, we note that the health damage costs can be expressed in terms of equivalent physical units such as YOLL or DALY (disability adjusted life years) (MURRAY and LOPEZ, 1996). We have found that when we convert the monetary values to YOLL using the cost per YOLL, the ranking of impacts is quite close to the ranking in terms of DALY.[...] For the monetary valuation of health impacts, the single most important number is the so-called value of statistical life (an unfortunate terminology for what is really the collective willingness-to-pay for reducing the risk of premature death) for which ExternE (1998) has used V = 3.1 MEuro » $ 3.5 million, comparable to values in the US. A crucial question for the monetization of mortality is whether one should multiply the number of premature deaths Ndeath by V [...] or whether one should base the valuation on the Years Of Life Lost (YOLL) due to a lifespan reduction DT [...]. This issue is particularly important for acute mortality, due to particulate matter (PM), SO2 or O3, which only shortens life by a brief period. For the present paper we choose the YOLL valuation [...]. We assume 0.084 MEuro per YOLL for chronic mortality and 0.155 MEuro per YOLL for acute mortality (for an explanation of these terms see Section 4.1). For the cost of a cancer we assume 1.5 MEuro, averaged by ExternE over fatal and nonfatal cancers [...]."

Krewitt et al. (2)

"While studies on external costs of electricity generation generally aim at the calculation of marginal costs for a new increment of power generation, we have applied an extended bottom-up modelling framework to calculate average health and environmental damage costs from fossil electricity generation in Germany and Europe. Aggregated average damage costs provide helpful complementary information to site and technology specific ‘point' values to be used for more general policy analysis. Environmental damage costs caused by fossil fired power plants in the EU-15 countries in 1990 amount to about 70 billion US $. Results show that damage costs per tonne of pollutant emitted might vary considerably by site and - as structural changes like those observed in the eastern part of Germany after the re-unification show - also over time. A comparison of damage costs and private costs of emission reduction measures in large combustion plants shows that on the European average the implementation of current best available emission reduction technologies is well justified. [...] The methodology follows the detailed bottom-up impact pathway approach developed in the ExternE project, in which we try to model the causal relationships from the release of pollutants through their interactions with the environment to a physical measure of impact and, where possible, a monetary valuation of the resulting welfare losses.”

The main difference with Spadaro & Rabl is that Krewitt et al. take an average approach instead of a marginal/incremental one as by Spadaro & Rabl: “Studies on external costs of electricity generation generally present results in terms of costs per unit electricity generation. However, external costs per unit electricity do very much depend on the specific technology in place and the site of the facility and thus are hardly transferable between fuel sources, technologies and different location, so that the calculation of total or average external costs from electricity generation in a country based on results derived for individual ‘reference plants' can be very much misleading. We have calculated *average* external costs per kWh from fossil electricity generation in Germany and Europe [...] by dividing the total annual damage costs [...] by the respective electricity generation [...]. The average damage costs result from the operation of fossil power plants in Europe and Germany, taking into account the spatial distribution of emission sources, and the respective fuel mix in the different parts of Germany and Europe. It is obvious that external costs calculated for a specific plant fuelled with coal, lignite, oil or natural gas might differ significantly from the average damage costs. While external costs from fossil fired power plants in the former Federal Territory of Germany are below the European average, and also much smaller than the private costs of electricity generation, the external costs from power plants in the former GDR in 1990 amount to more than 20 cent/kWh, which is much higher than the private costs. Although the external costs could be reduced significantly until 1996, they are still in the same order of magnitude as the private costs. The average damage costs from fossil "red power plants in the EU-15 Countries in 1990 were also close to the private costs.”

Hofstetter & Müller-Wenk (3)

“There are decision situations where environmental impacts need to be compared with other costs or benefits that by their nature are expressed in terms of money. Supporting these decisions may require the expression of environmental impacts in monetary units. Using the example of health impacts from road noise we apply five different monetization approaches and quantify the monetary values of one year of sleep disturbance (CHF 2500e16 000) and interference with communication (1500e10 000). In Life Cycle Assessment many health endpoints need to be evaluated at the same time. Therefore, we illustrate here the transferability problem between health impacts measured in disability adjusted life years (DALYs) and monetized health impacts, using the example of health impacts due to 1000 truck kilometres. It is concluded that available monetization methods need careful adaptation for their use to monetize environmental health impacts, that the DALY accounting system may support the systematic monetization and the selection of relevant health endpoints, and that it may well be justified for LCA purposes to perform some novel primary willingness to pay studies. [...]This paper shows how the choice of monetization method can impact the cost factors included [...] and even if they quantify the same cost factor the numbers show a wide range [...]. It also shows that adding up results from different monetization methods may often not be valid: the common unit of $ is no justification in itself. Our survey, that is limited to the application to road noise impacts, suggests that there is no monetary assessment method that does not suffer from major normative assumptions or biases. On the other side, systems like DALYs are also based on strong normative assumptions such as the time proportionality or the way premature death and morbidity outcomes are added. Therefore, the choice of method heavily depends on the needed units for the decision support."

Main advantages

Spadaro & Rabl (1)
Incremental modelling.

Krewitt et al. (2)
Average modelling.

Open questions

- It is as yet unclear in what cases incremental modelling (1) and in what cases average modelling (2) should be applied and how these two types of (monetary) modelling can be transposed to LC(I)A (see (3)).
- There are various methods for monetizing impacts and there is not one best: "the choice of method heavily depends on the needed units for the decision support" (3).

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Monetary values are not available for all relevant health impacts and values from different studies can often not be combined and/or aggregated (see R&D below).

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

The sector of application is not relevant.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. Hofstetter & Müller-Wenk (3) • General conversion factor between DALYs and monetary values. "There is no general conversion factor between DALYs and monetary values. This is because there are fundamental differences between the DALY system and observed behaviour/statements in monetization studies. If benefit transfers from one health state to another state are made using disability weights one should make sure that duration and severity of the symptoms are similar and that the resulting value will be used only for individuals in a similar socio-economic and cultural setting. If the probability of occurrence enters into the assessment of the primary study the probability of occurrence for the transferred symptom should be similar as well. If these conditions are borne in mind, synergies between monetization studies and health metrics can be expected. • Increase data availability on monetary values of health impacts and on DALYs, e.g. DALY studies to mild illnesses; mild illnesses tend to be very relevant within LCA but are poorly studied in the DALYs systems as well as in health economics. • For those health impacts that are likely to dominate most LCA case studies it may well be worth the effort to work out a consistent set of monetary values based on secondary but also primary studies in order to avoid the discussed problems of double accounting, known biases, and non-realistic assumptions.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/time –dependent & discounting

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.*
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Hellweg, Stefanie; Hofstetter, Thomas; Hungerbühler, Konrad (2003). Discounting and the Environment - Should Current Impacts be Weighted Differently than Impacts Harming Future Generations? International Journal of Life Cycle Assessment, 8, 1, 8-18.
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2. Specific references
- (2) Sumaila, U.R.; Walters, C. (2005). Intergenerational discounting: a new intuitive approach. Ecological Economics, 52, 135-142.
- (3) Fearnside, P.M. (2002). Time preference in global warming calculations: a proposal for a unified index. Ecological Economics 41, 21-31.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. Hellweg et al. (1) "In Life-Cycle Assessment (LCA), decision makers are often faced with tradeoffs between current and future impacts. One typical example is waste

incineration, where immediate emissions to the air from the incineration process have to be weighted against future emissions of slag landfills. Long-term impacts are either completely taken into account or they are entirely disregarded in case of a temporal cut-off. Temporal cut-offs are a special case of discounting. In this paper, discounting is defined as valuing damages differently at different points of time using a positive or negative discount rate. Apart from temporal cut-offs, discounting has rarely been applied in LCA so far. It is the goal of this paper to discuss the concept of discounting and its applicability in the context of LCA. For this purpose, we first review the arguments for discounting and its principles in economic sciences. Discounting in economics can be motivated by pure *time preference, productivity of capital, diminishing marginal utility of consumption, and uncertainties*. The nominal discount rate additionally includes changes in the price level. These arguments and their justification are discussed in the context of environmental impacts harming future generations. *It is concluded that discounting across generations because of pure time preference contradicts fundamental ethical values and should therefore not be applied in LCA*. However, it has to be acknowledged that in practice decision makers often use positive discount rates because of pure time preference – either because they might profit from imposing environmental damage on others instead of themselves or because people in the far future are not of immediate concern to them. Discounting because of the productivity of capital assumes a relationship between monetary values and environmental impact. If such a relationship is accepted, discounting could be applied. However, future generations should be compensated for the environmental damage. It is likely that they would demand a higher compensation if the real per capita income increases. As both the compensation and the discount rate are related to economic growth, the overall discount rate might be close to zero. It is shown that the overall discount rate might even be negative considering that the required compensation could increase (even to infinite) if natural assets remain scarce, whereas the utility of consumption diminishes with increasing income. Uncertainties could justify both positive and negative discount rates. Since the relationship between uncertainties and the magnitude of damage is generally not exponential, we recommend to model changes in the magnitude of damage in scenario analysis instead of considering it in discounting (which requires an exponential function of time in the case of a constant discount rate). We investigated the influence of discounting in a case study of heavy metal emissions from slag landfills. It could be shown that even small discount rates of less than 1% lead to a significant reduction of the impact score, whereas negative discount rates inflate the results. Discounting is only applicable when temporally differentiated data is available. In some cases, such a temporal differentiation is necessary to take sound decisions, especially when long emission periods are involved. An example is the disposal of nuclear or heavy metal-containing waste. In these cases, the results might completely depend on the discount rate. *This paper helps to structure arguments and thus to support the decision about whether or not discounting should be applied in an LCA.*

Sumaila & Walters (2)

"This paper proposes a new intergenerational discounting approach for computing net benefits from the use of environmental resources. The approach explicitly incorporates the perspectives of both the current and future generations, as argued for by Pigou and Ramsey, and required by most national and international laws related to the use of these resources. An equation for use in the calculation of net discounted benefits is developed, which provides a 'middle' position whereby both the 'reality' of 'personal' discounting and that of 'social' discounting are included in a social welfare function."

Fearnside (3)

“Many aspects of the calculation of the impacts of greenhouse gas (GHG) emissions and the costs and benefits of possible response options are highly sensitive to the way in which time preference is incorporated into the computations. The Intergovernmental Panel on Climate Change (IPCC) used global warming potentials (GWPs) to standardize inputs of different gases with differing radiative forcings and atmospheric lifetimes; in the results emphasized by the IPCC’s Second Assessment Report, a 100-year time horizon and no discounting is used, and this has been adopted by the Kyoto Protocol for use in the first commitment period (2008–2012). Here an alternative unified index is proposed that assigns explicit weights to the interests of different generations. In contrast to discounting (including the zero discount rate used by the IPCC), the generationally weighted index forces policy makers to face the moral assumptions that underlie their choices related to global warming.”
Main advantages
All Explicit choices as to time preferences (discounting, weighting etc.).
Open questions
Possible differences and (dis)advantages between Fearnside (3) and Sumaila & Walters (2) are unclear to persons not trained in welfare economics. In the end, it boils down to a matter of ethics, not of science, even though science can help to clarify the positions.
Practicability aspects
Practicability aspects refer to the availability of tool and data in order to implement the analysed approach. All Not suitable for use in LCIA yet.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. All Not suitable for use in LCIA yet.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

Hellweg et al. (1)
The first thing needed on the issues of time dependency and discounting is to take a decision about whether or not discounting should be applied in an LCA and if yes, in which cases and which methodological issues it should affect (inventory data, impact assessment factors, ...?).

Sumaila & Walters (2)
The approach proposed by Sumaila & Walters has been developed oustide the domain of LCA and has as yet no relation with LCA. There may thus be a research need to apply their (and other discounting approaches) approach to LCIA, possibly by adapting GWPs and other characterisation factors to their discounting proposals etc.

Fearnside (3)
Calculation of new lists of GWPs on the basis of this "unified index".

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

LIFE CYCLE IMPACT ASSESSMENT

IMPROVEMENT OF EXISTING METHODS

- Climate change
- Resources
- Acidification
- Eutrophication
- Toxicity
- Stratospheric ozone depletion
- Troposferic ozone formation

[Phase/Topic/Approach]

LCIA/improvement of existing methods/climate change

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. Climate change is defined here as the impact of human emissions on the radiative forcing (i.e. heat radiation absorption) of the atmosphere. This may in turn have adverse impacts on ecosystem health, human health and material welfare. Most of these emissions enhance radiative forcing, causing the temperature at the earth's surface to rise. This is popularly referred to as the 'greenhouse effect'. The areas of protection are human health, the natural environment and the man-made environment.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- UNEP-SETAC Life Cycle Initiative WG LCIA TF4 on transboundary impacts (http://www.lci-network.de/cms/content/LCIAcorner/lang/en/pid/593): Pro memori.
2. Specific references
- (1) Fearnside, P.M. (2002). Time preference in global warming calculations: a proposal for a unified indexEcological Economics, 41, 21-31.
- (2) Tol, R.S.J. (2002). Fearnside's unified index for time preference: a comment. Ecological Economics, 41, 33-34.
- (3) Fearnside, P.M. (2002). Time preference: reply to Tol. Ecological Economics, 41, 35-36.
- (4) Brakkee, K. (ongoing). PhD project: Life Cycle Impact Assessment of Climate Change. http://www.ru.nl/environmentalscience/staff/staff/k_w_brakkee/

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. <u>Fearnside (1)</u> "Many aspects of the calculation of the impacts of greenhouse gas (GHG) emissions and the costs and benefits of possible response options are highly sensitive to the way in which time preference is incorporated into the computations. The Intergovernmental Panel on Climate Change (IPCC) used global warming potentials (GWPs) to standardize inputs of different gases with differing radiative forcings and atmospheric lifetimes; in the results emphasized by the IPCC's Second Assessment Report, a 100-year time horizon and no discounting is used, and this has been adopted by the Kyoto Protocol for use in the first commitment period (2008–2012). Here an alternative unified index is proposed that assigns explicit weights to the interests of different generations. In contrast to discounting (including the zero discount rate used by the IPCC), the generationally weighted index forces policy makers to face the moral assumptions that underlie their choices related to global warming." Tol (2) and Fearnside (3) debated on some details of (1). <u>Brakkee (2)</u> Global climate change affects ecosystems and a wide range of human health impacts. There are a number of difficulties in the modelling of climate change for LCA purposes and therefore there is no model for that purpose. The IMAGE 2.2 model can calculate the influence of greenhouse gases and land use on global temperature change and change in vegetation. Temperature change might be a good midpoint indicator for LCA purposes. It can furthermore be a starting point to calculate the endpoints damage on human health and ecosystems. Experiments that change the emission input data of the model will give information in the behaviour in temperature changes due to marginal change in emissions. After deriving a relation between the temperature change and damage to human health and ecosystems the model might also provide information about the overall damage of green house gases. All the steps together may provide a method to include climate change effects in an LCA methodology.
Main advantages
Explicit choices as to time preferences (discounting, weighting etc.) Improvement of GWP modelling.
Open questions
No new CFs available.
Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approac. No new CFs available.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. Not suitable for use in LCIA yet.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. Calculation of new lists of GWPs on the basis of this "unified index".
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. This discussion on time preference in GWPs is not an LCA discussion (yet) but is an "outside the LCA domain" discussion at this moment. However, discounting is discussed within LCIA and this subject should then be part of that discussion.

[Phase/Topic/Approach]

LCIA/improvement of existing methods/resources

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. 'Abiotic resources' are natural resources (including energy resources) such as iron ore, crude oil and wind energy which are regarded as non-living. Abiotic resource depletion is one of the most frequently discussed impact categories and there is consequently a wide variety of methods available for characterising contributions to this category. To a large extent these different methodologies reflect differences in problem definition. Depending on the definition, this impact category has only natural resources, or natural resources, human health and the natural environment as areas of protection. 'Biotic resources' are material resources (including energy resources) regarded as living, e.g. rainforests, elephants. Depending on the precise definition adopted, this impact category has only natural resources, or natural resources, human health and the natural and the man-made environment as areas of protection.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Bengt Steen (2006). Abiotic Resource Depletion Different perceptions of the problem with mineral deposits. International Journal of Life Cycle Assessment, 11, Special Issue 1 , 49-54.
2. Specific references
- (2) Brentrup, Frank; Küsters, Jürgen; Lammel, Joachim; Kuhlmann (2002). Impact Assessment of Abiotic Resource Consumption : Conceptual Considerations. International Journal of Life Cycle Assessment,7,5, 301-307.
- (3) Brent, Alan (2004). A Life Cycle Impact Assessment Procedure with Resource Groups as Areas of Protection. International Journal of Life Cycle Assessment, 9, 3, 172-179.
- (4) Stewart, Mary; Weidema, Bo Pedersen (2005). A Consistent Framework for Assessing the Impacts from Resource Use - A focus on resource functionality. International Journal of Life Cycle Assessment, 10, 4, 240-247.

- (5) Weidema, Bo Pedersen; Finnveden, Göran; Stewart, Mary (2005).Impacts from Resource Use - A common position paper. International Journal of Life Cycle Assessment, 10, 6, 382.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Steen (1)

Steen (1) argues "that access to abiotic resources is vital for modern life styles, and that except for ozone depletion, no other environmental threat has a potentially larger impact on our everyday lives than shortage of abiotic resources. In 'Limits to Growth' the Club of Rome identified depletion of ores and minerals as becoming a major problem during the first or second decades of the twenty-first century, and the idea was widely spread. Since then, the attitude to the problem has shifted, and many institutions, such as the European Commission, do not consider the problem acute and does not give it priority in their present action plans. Regardless of when it happens, however, the social consequences of a shortage of abiotic resources will be a major problem and the significance and nature of the problem will depend on what the world looks like then at the time and afterwards."

Steen reviews existing LCIA methods in relation to depletion problem definitions. Existing methods for characterisation and weighting of abiotic resources appear to be based on four types of problem definitions, although not always explicit: 1) assuming that mining cost will be a limiting factor, 2) assuming that collecting metals or other substances from low-grade sources is mainly an issue of energy, 3) assuming that scarcity is a major threat and 4) assuming that environmental impacts from mining and processing of mineral resources are the main problem. In addition to differences in assumptions about what will be the limiting factor, there are different views on what time scales are of interest and how to integrate the issue in LCA."

He concludes that the main dividing line in views on abiotic resources has to do with time perspective. If only caring for the next hundred years or so, abiotic resources is a manageable problem. In taking an historic perspective with tens of thousands of years, abiotic resources become a major problem."

Brentrup et al. (2)

"The impact assessment of the consumption of abiotic resources, such as fossil fuels or minerals, is usually part of the Life Cycle Impact Assessment (LCIA) in LCA studies. The problem with the consumption of such resources is their decreasing availability for future generations. In currently available LCA methods (e.g. Eco-indicator' 99/Goedkoop and Spriensma 1999, CML/Guinée 2001), the consumption of various abiotic resources is aggregated into one summarizing indicator within the characterization phase of the LCIA. This neglects that many resources are used for different purposes and are not equivalent to each other. Therefore, the depletion of reserves of functionally non-equivalent resources should be treated as separate environmental problems, i.e. as separate impact sub-categories. Consequently, this study proposes assigning the consumption of abiotic resources to separate impact sub-categories and, if possible, integrating them into indicators only according to their primary function (e.g. coal, natural gas, oil → consumption of fossil fuels; phosphate rock → consumption of phosphate). [...] Following the general LCA framework (Consoli et al. 1993, ISO 1998), a normalization step is proposed separately for each of the subcategories. Finally, specific weighting factors have been calculated for the sub-categories based on the 'distance-to-target' principle. The weighting step allows for further interpretation and enables the aggregation of the consumption of different abiotic resources to one summarizing indicator, called the Resource Depletion Index (RDI). The proposed method has been applied to a wheat production system in order to illustrate the conceptual considerations and to compare the approach to an established impact assessment method for abiotic resources (CML method, Guinée 2001)."

Basically, Brentrup et al. (2) thus classify resources in functional groups that then form a sort of sub-impact category. The functional groups depend on a primary function and the resources are aggregated (characterisation step) in kg – without any further assessment - of the functional element of compound, for example P_2O_5. Subsequently, a normalization is performed at the level of separate groups of functionally equivalent resources (i.e. at the level of sub-impact categories) using values for the total European consumption of these resources in 1999 or 1998. Finally, a weighting is applied using the concept of "the tolerable annual production", which is calculated by dividing the "proved global recoverable reserve" of a specific resource by a target period (100, 300 or 1000 yrs in this study).

Note that the characterisation factor for a resource in this method is only the contents of a functional group in that resource (e.g. in MJ for fossil fuels).

Brent (3)

"Current Life Cycle Impact Assessment (LCIA) procedures have demonstrated certain limitations in the South African manufacturing industry context. The aim of this paper is to propose a modified LCIA procedure, which is based on the protection of resource groups. [...] A distance-to-target approach is used for the normalisation of midpoint categories, which focuses on the ambient quality and quantity objectives for four resource groups: Air, Water, Land and Mined Abiotic Resources. The quality and quantity objectives are determined for defined South African Life Cycle Assessment (SALCA) Regions and take into account endpoint or damage targets. Following the precautionary approach, a Resource Impact Indicator (RII) is calculated for the resource groups. Subjective weighting values for the resource groups are also proposed, based on survey results from the manufacturing industry sector and the expenditure trends of the South African national government. The subjective weighting values are used to calculate overall Environmental Performance Resource Impact Indicators (EPRIIs) when comparing life cycle systems with each other."

Stewart & Weidema (4) & Weidema et al. (5)

"The quantification of resource depletion in Life Cycle Assessment has been the topic of much debate; to date no definitive approach for quantifying effects in this impact category has been developed. In this paper we argue that the main reason for this extensive debate is because all methods for quantifying resource depletion impacts have focussed on resource extraction. To further the state of the debate we present a general framework for assessing the impacts of resource use across the entire suite of biotic and abiotic resources. The main aim of this framework is to define the necessary and sufficient set of information required to quantify the effects of resources use. Our method is based on a generic concept of the quality state of resource inputs and outputs to and from a production system. Using this approach we show that it is not the extraction of materials which is of concern, but rather the dissipative use and disposal of materials. Using this as a point of departure we develop and define two key variables for use in the modelling of impacts of resource use, namely the *ultimate quality* limit, which is related to the functionality of the material, and *backup technology*. Existing methodologies for determining the effects of resource depletion are discussed in the context of this framework. We demonstrate the ability of the general framework to describe impacts related to all resource categories: metallic and non-metallic minerals, energy minerals, water, soil, and biotic resources (wild or domesticated plants and animals). Recommendation focus on suggestions for a functionality measure for each of these categories; and how best the two modelling variables derived can be determined."

"[...] the *ultimate quality limit***.** We propose that this limit can be determined theoretically based on thermodynamic arguments as the upper bound of the variation in the steady-state background resulting from formation or redeposition (resulting from the dissipative use or disposal of the material), which may be natural or accelerated by human activities. It follows from this definition that the ultimate quality limit will have to be determined individually for each specific resource. A more detailed discussion of the definition of ultimate quality limits for all resource types considered is included in section 3 of this paper. We nevertheless acknowledge that the quantification of these limits may require further research."

"[...] This has moved our focus from the extraction of desired materials, to their dissipation through use and disposal."

Main advantages

Brentrup et al. (2)

This approach focuses on resource depletion with proposals for sub-impact categories, whereas the proposal by Brent is a mix of different impact categories and areas of protection.

Brent (3)

The Brent approach concerns resource groups as areas of protection and then also includes water quality, air quality etc., which in other approaches are not considered as resource groups, but rather as human health and ecosystem health related areas of protection. The only "new" aspect with respect to resource depletion is the adoption of a distance-to-target approach for normalisation, which usually is only applied as weighting and not as normalisation.

Stewart & Weidema (4) & Weidema et al. (5)

This approach focuses on dissipation rather than on depletion. It offers, however, merely a framework that needs further elaboration (see below).

Open questions

	Brentrup et al. (2)	Brent (3)	Stewart & Weidema (4) & Weidema et al. (5)
Impact category	resource depletion: • depletion of fossil fuels • depletion of phosphate rock • depletion of potash • depletion of limestone and	pm	resource depletion/dissipation

	dolomite • etc.		
intervention	extraction of minerals and fossil fuels (kg)	pm	pm
Indicator	Contents of a functional group	pm	• ultimate quality • backup technology
Characterisation model	Quantification of contents of functional group per resource.	pm	pm
Characterisation factor	Contents of a functional group in a resource (in MJ for fossil fuels; CFs only provided for 4 sub-impact categories listed above;	pm	No CFs provided

The table above illustrates the compliance of the Brentrup et al. (3), Brent (4) and Stewart & Weidema (5) / Weidema et al. (6) with the general structure of LCIA (see Annex X). There are various gaps for these methods, and moreover it is striking that each of the three methods covers a different (sub-) impact categories and/or fundamentally different set-ups of characterisation-normalisation-weighting. Furthermore, lists of CFs need to be further elaborated for a wider range of resources.

Brentrup et al. (2)
Only the primary function is taken. Resources often have more function and extraction of resources is, e.g. for metals, often a co-production process. This is not assessed in this method. Furthermore, the method needs elaboration to other resource types than the few included now, and it needs to be analyse to what extent the differences with CML (2002) are due to differences in the reserves taken, in the sub-impact categories distinguished or to the different set-up in the sequence of characterisation-normalisation-weighting (what is characterisation in CML (2002) is weighting in Brentrup et al. while adopting another reserve definition).

Brent (3)
See above under "Main advantages". The mineral resources approach is based on the CML (2002) characterisation method and factors.

Stewart & Weidema (4) & Weidema et al. (5)
See above under "Main advantages".

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Brentrup et al. (2)
Limited number of CFs available.

Brent (3)
CFs need to be calculated for each case-study separately.

Stewart & Weidema (4) & Weidema et al. (5)
No CFs available yet and proposed framework and methods need further elaboration. Ultimate quality limit needs to be defined for each specific resource.
The quality of the input and output flows should be recorded in the LCI.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Brentrup et al. (2)
"Since this approach has been developed in the context of LCA studies on agricultural production systems, the impact assessment of the consumption of fossil fuels, phosphate rock, potash salt and lime is of particular interest and serves as an example."

Brent (3)
See above.

Stewart & Weidema (4) & Weidema et al. (5)
See above.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

Steen (1)
"Today there seems to be some consensus on focusing on developing characterisation methods based on future increase of impacts from using lower grade resources with consideration of resource functionality. It is essential that the choice of temporal focus is given enough attention."

Brentrup et al. (2)
What is the relevant target time period?
Figures on reserves are uncertain by definition.

"As the use of the reserve base is dependent on such further technical development, these data do not seem to be appropriate for use in LCA. This applies even more to the ultimate reserve, which is used in the CML method [...]. This reserve definition comprises the total deposits of an element in the earth's crust independently from its concentration and thus, is not at all equivalent to what is commonly meant by a resource."

Brent (3)
"The application of the proposed EPRII procedure will be investigated further for Life Cycle Management purposes. Of specific interest is the evaluation of new technologies at governmental level, e.g. for Clean Development Mechanism (CDM) approval purposes, and company performances for supply chain management."

Stewart & Weidema (4) & Weidema et al. (5)
The quantification of ultimate quality limits may require further research.
The framework needs to be implemented: "In order to implement the general framework presented in this paper, it will be necessary to determine values for:

- Functionality/quality indicator for each resource
- Ultimate quality limit for each resource
- Backup technologies for each resource

The functionality for each resource needs to be recorded in the LCIs. Values determined for ultimate quality limits and backup technologies will be applicable across LCA studies and can therefore be integrated in impact assessment modelling. A significant amount of work already exists which can be used to inform the determination of these parameters, and this information remains to be collated and synthesized before any attempt is made to address gaps in information available."

Main discussion point over all (abiotic) resource depletion methods is the distinction between economy and environment. Whereas the CML (2002) approach strictly adopted resource depletion as an environmental problem, several other approaches above mix economic arguments and indicators into the resource depletion indicators. A firm discussion about this issue is still needed!!

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/improvement of existing methods/acidification

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings). Examples include fish mortality in Scandinavian lakes, forest decline and the crumbling of building materials. The major acidifying pollutants are SO_2, NO_x and NH_x. Areas of protection are the natural environment, the man-made environment, human health and natural resources.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Norris, G.A. (2003). Impact characterization in the Tool for the Reduction and Assessment of Chemical and other environmental Impacts. Journal of Industrial Ecology, 6:3-4, 79-101.
- (2) Hayashi, Kentaro; Okazaki, Masanori; Itsubo, Norihiro; Inaba, Atsushi (2004). Development of Damage Function of Acidification for Terrestrial Ecosystems Based on the Effect of Aluminium Toxicity on Net Primary Production. International Journal of Life Cycle Assessment, 9, 1, 13-22.
- (3) UNEP-SETAC Life Cycle Initiative WG LCIA TF4 on transboundary impacts (http://www.lci-network.de/cms/content/LCIAcorner/lang/en/pid/593): Pro memori.
2. Specific references
- (4) Jyri Seppälä; Maximilian Posch; Matti Johansson; Jean-Paul Hettelingh (2006). Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. International Journal of Life Cycle Assessment, 11, 6, 403-416.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Norris (1)

"The tool for the reduction and assessment of chemical and other environmental impacts (TRACI) is a set of life-cycle impact assessment (LCIA) characterization methods that has been developed by a series of U.S. Environmental Protection Agency research projects. TRACI facilitates the characterization of stressors that may have potential effects, including [...] acidification [...]. [...] The acidification model in TRACI makes use of the results of an empirically calibrated atmospheric chemistry and transport model to estimate total North American terrestrial deposition of expected H_ equivalents due to atmospheric emissions of NO*x* and SO2, as a function of the emissions location. The model used is the advanced statistical trajectory regional air pollution (ASTRAP) model originally developed to support the U.S. National Acid Precipitation Assessment Program. ASTRAP treats vertical diffusion, dry deposition, and chemical transformation to calculate normalized long-term average surface air concentrations, total airborne loading, and dry deposition increments as functions of effective emission height and time since release. A two-dimensional program calculates seasonal mean horizontal trajectories and wet removal occurrences for a grid of source areas consisting of the 48 contiguous U.S. states and the District of Columbia, the Canadian provinces, and northern Mexico. Finally, a concentration and deposition calculation combines the statistics from the first two programs with an emission field to produce source-receptor coefficients that relate seasonal emissions by source area to deposition (wet and dry) per hectare in a grid of receiving areas. [...]Next, N and S deposition are each converted to moles of H_ equivalents per kilogram."

Hayashi et al. (2)

"This study aimed at developing damage function of acidification for terrestrial ecosystems in Japan. Damage function expresses a quantitative relationship between the inventory and endpoint damage. The geographical boundary was limited in Japan both for emission and impact. In this study, sulfur dioxide (SO2), nitrogen monoxide (NO), nitrogen dioxide (NO2) (NO and NO2 collectively mean NOx), hydrogen chloride (HCl), and ammonia (NH3) were considered as major causative substances of acidification. Net primary production (NPP) of existing vegetation was adopted as an impact indicator of terrestrial ecosystems. The aluminum toxicity was adopted as the major factor of effect on terrestrial ecosystems due to acidification. The leachate concentration of monomeric inorganic aluminum ions was selected to express the plant toxicity of aluminum. [...] Although several later studies (e.g. Potting et al. 1998, Huijbregts 1999) improved the circumstances considering regional sensitivity of ecosystems and atmospheric fate of causative substances, these were still confined to an equivalent load without information on concrete damage caused by acidification. [...] This study, forming a part of LIME, focused on the impact on terrestrial ecosystems with priority among various endpoints regarding acidification. A reason was that terrestrial acidification tends to precede aquatic acidification, namely inland water is acidified after the depletion of acid neutralization capacity of its watershed. Moreover, since the major part of land is covered by vegetation, acidification has a potential to induce remarkable damage to terrestrial ecosystems, i.e. it is a primary producer of ecosystems. [...] The purpose of this study is to develop the damage function of acidification for terrestrial ecosystems; damage function is defined as quantitative relationship between emission of causative substance and endpoint damage. [...] The geographical boundary was limited to Japan, namely both emission and impact only in Japan were considered. The damage function of acidification for terrestrial ecosystems consists of two factors. One is termed Atmospheric Deposition Factor (ADF) and reveals an average increase of H+ load per unit area in Japan due to additional emission of causative substance. The other is termed Damage Factor (DF) which gives a total NPP decrease in all of Japan due to the additional emission of causative substances. ADF was determined using the fate of an emitted causative substance expressed as the product of Source-Receptor Relationship (SRR) by Non-Neutralization Ratio (NRR) of acid in the atmosphere. SRR denotes the mean deposition fraction of an acidifying substance in Japan due to the emission of its causative substance in Japan. ADF is also utilizable for a midpoint approach; the summation of the products of ADF for each causative substance by its emission amount, namely, stands for the Category Indicator (CI) of acidification. Meanwhile, DF was given by the product of ADF by Effect Factor (EF) that gives a total NPP decrease in all of Japan due to unit increase of atmospheric deposition load of H+ per unit area, namely per ADF. EF was defined as the slope of the relationship between the increase of H+ deposition load per unit area and total NPP decrease in the whole of Japan. The relationship was derived from quantitatively connecting the following processes; increase of H+ load → decrease of leachate pH → increase of leachate Al3+ concentration → decrease of plant growth rate → NPP damage. DF is utilizable for an endpoint approach, namely the summation of the products of DF for each causative substance by its emission inventory provides the Damage Indicator (DI) of acidification. DI denotes the concrete damage due to additional emissions of causative substances."

<u>Seppälä et al. (4)</u>

Several authors have shown that spatially derived characterisation factors used in life cycle impact assessment (LCIA) can differ widely between different countries in the context of regional impact categories such as acidification or terrestrial eutrophication. Previous methodology studies in Europe have produced country-dependent characterisation factors for acidification and terrestrial eutrophication by using the results of the EMEP and RAINS models and critical loads for Europe. The unprotected ecosystem area (UA) is commonly used as a category indicator in the determination of characterisation factors in those studies. However, the UA indicator is only suitable for large emission changes and it does not result in environmental benefits in terms of characterisation factors if deposition after the emission reduction is still higher than the critical load. For this reason, there is a need to search for a new category indicator type for acidification and terrestrial eutrophying in order to calculate site-dependent characterisation factors. The aim of this study is to explore new site-dependent characterisation factors for European acidifying and eutrophying emissions based on accumulated exceedance (AE) as the category indicator, which integrates both the exceeded area and amount of exceedance. In addition, the results obtained for the AE and UA indicators are compared with each other. The chosen category indicator, accumulated exceedance (AE), was computed according to the calculation methods developed in the work under the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (LRTAP). Sulphur and nitrogen depositions to 150x150 km2 grid cells over Europe were calculated by source-receptor matrices derived from the EMEP Lagrangian model of long-range transport of air pollution in Europe. Using the latest critical load data of Europe, the sitedependent characterisation factors for acidification and terrestrial eutrophication were calculated for 35 European countries and 5 sea areas for 2002 emissions and emissions predicted for 2010. In the determination of characterisation factors, the emissions of each country/area were reduced by various amounts in order to find stable characterisation factors. In addition, characterisation errors were calculated for the AE-based characterisation factors. For the comparison, the results based on the use of UA indicator were calculated by 10% and 50% reductions of emissions that corresponded to the common practice used in the previous studies.

The characterisation factors based on the AE indicator were shown to be largely independent of the reduction percentage used to calculate them. Small changes in emissions (≤100 t) produced the most stable characterisation factors in the case of the AE indicator. The characterisation errors of those characterisation factors were practically zero. This means that the characterisation factors can describe the effects of small changes in national emissions that are mostly looked at in LCAs. The comparison between country-dependent characterisation factors calculated by the AE and UA indicators showed that these two approaches produce differences between characterisation factors for many countries/areas in Europe. The differences were mostly related to the Central and Northern European countries. They were greater for terrestrial eutrophication because the contribution of ammonia emission differ remarkably between the two approaches. The characterisation factors of the AE indicator calculated by the emissions of 2002 were greater than the factors calculated by the predicted emissions for 2010 in almost all countries/sea areas, due to the presumed decrease of acidifying and eutrophying emissions in Europe. [...] It would also be useful to compare the approach based on the AE indicator with the method of the hazard index, as recommended in the latest CML guidebook."

Main advantages

Norris (1)

Advantage: regionalised factors.

Main disadvantage compared to Seppälä (4) (and also Huijbregts (1999, 2001): "The modeling stops at the midpoint in the cause-effect chain (deposition) because in the United States there is no regional database of receiving environment sensitivities (as is available in Europe). Thus, the source-region-based variability in total terrestrial deposition has been captured, but not the receiving-region-based variability in sensitivity or ultimate damages." This disadvantage may also well become an advantage if the added uncertainty of damage modelling compared to midpoint modelling becomes significant.

Only US.

Hayashi et al. (2)

Advantage: damage modelling -> increased environmental relevance, but also increased modelling uncertainties.

Disadvantage: only Japan, no further regionalisation.

Seppälä et al. (4)

Advantage: regionalised factors.

Disadvantage: only Europe; method (4) lacks characterisation factors for direct emissions to water and soil.

Open questions

	Norris (1)	Hayashi et al. (2)	Seppälä et al. (4)
Impact category	acidification in US	acidification of terrestrial ecosystems in Japan	acidification in Europe
intervention	emissions of SO_2, NO_2, HCl and HF to air	emissions of SO_2, NO_x, NH_3 and HCl to air	emissions of SO_2, NO_2 and NH_3 to air
Indicator	Terrestrial deposition	Nett Primary production (NPP) distribution of existing vegetation	Accumulated Exceedance (EA): the weighted sum of all the critical load exceedances within the area of interest, the weighing factors being the individual ecosystem areas
Characterisation model	US ASTRAP model (Advanced Statistical trajectory Regional Air Pollution): fate and transport modelling among states and provinces combined with site-generic effect modelling (H^+-ions/mole of deposited species)	Atmospheric Deposition Factor (ADF) combined with a Damage Factor (DF)	EMEP and RAINS models and critical loads for Europe
Characterisation factor	Acidification factors (in H+-moles equivalent depsition/kg emission) provided for emissions of SO_2, NO_2, HCl and HF to air for different 49 US states, and for larger regions and for the United States as a whole	Acidification factors (eq $km^{-2}.yr^{-1}.kg^{-1}$)	no name given; list of CFs (kgeq/t) provided for emissions of SO_2, NO_2 and NH_3 to air for different European countries

The table above illustrates the compliance of the Norris (1), Hayashi et al. (2) and Seppälä et al. (4) with the general structure of LCIA (see Annex X). There are little gaps for these methods, but it is striking that each of the three methods covers a different region of the world and each time in a different way, which makes it difficult to combine them. The discussion between the methods thus merely focuses on modelling differences.

Norris (1)
See below at R&D.

Hayashi et al. (2)
See below at R&D.

Seppälä et al. (4)
Main open question is a comparison of this approach (4) with the proposal by Huijbregts (1999; 2001), which has (surprisingly) not been done as part of this paper. “In the LCA terminology, the method based on AE indicator represents the 'only above' approach. The same concerns one version of the hazard index (HI) method developed by Huijbregts and his colleagues (2001). The main difference between these two approaches seems to be that the hazard index method uses a ratio scale in the calculation of exceedance, whereas the AE approach uses the absolute difference. [...] In both cases, the values of exceedance are weighted by the areas of ecosystems. In order to clarify the meaning of ratio scale of the HI method in terms of characterisation factors, there is a need to calculate the corresponding characterisation factors with the same input data and an integrated assessment model. In addition, there is a need to discuss the philosophical/conceptual aspects related to the calculation rules of both methods. The discussion should also include the hazard index approach in which all deposition situations above and below critical loads in Europe were taken into account. It should be noted that both HI approaches were only applied in the marginal way, i.e. country-dependent characterisation factors for acidification and terrestrial eutrophication were calculated by the derivation in the deposition situation. In this work, the AE approach was studied from the point of view of various emission reductions. Are the conclusions made for the AE indicator also suitable for the HI indicator? This is a question to be explored in depth in future studies.”

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Norris (1)
Acidification factors (in H^+-moles equivalent deposition/kg emission) provided for emissions of SO_2, NO_2, HCl and HF to air for different 49 US states, and for larger regions and for the United States as a whole.

Hayashi et al. (2)
Acidification factors (eq $km^{-2}.yr^{-1}.kg^{-1}$)) provided for emissions of SO_2, NO_x, NH_3 and HCl to air for Japan as a whole, without any further spatial differentiation.

Seppälä et al. (4)
List of characterisation factors for emissions of SO_2, NO_2 and NH_3 to air is supplied for different European countries.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Norris (1)
US

Hayashi et al. (2)
Japan

Seppälä et al. (4)
Europe

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. Norris (1) "Future advances of the TRACI acidification method may address regionalized transport and deposition of ammonia emissions and investigate the potential for regional differentiation of receiving environment sensitivities." Furthermore, it could be investigated how the current model can include impact outside US and/or how the model can be extended to other continents besides US. Hayashi et al. (2) "Expansion of endpoints, not only NPP damage of terrestrial ecosystems but also reproduction damage of aquatic ecosystems, material degradation, human health with regard to drinking water toxicity, and of course the aspects of biodiversity, is an important subject for future work to comprehend the present LCIA framework of the impact category of acidification. Further, uncertain analyses for major relevant parameters will provide helpful information on the reliability of damage function. The SRR, in particular, plays an important role in determining the effects of a load of acid on the surface through the atmosphere." Seppälä et al. (4) It should be investigated how this method (4) compares to the method of Huijbregts (1999; 2001) and it should be investigated how the current model can include impact outside Europe and/or how the model can be extended to other continents besides Europe.
Comments

[Phase/Topic/Approach]

LCIA/improvement of existing methods/eutrophication

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. Eutrophication covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In addition, high nutrient concentrations may also render surface waters unacceptable as a source of drinking water. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition (measured as BOD, biological oxygen demand). As emissions of degradable organic matter have a similar impact, such emissions are also treated under the impact category 'eutrophication'. The areas of protection are the natural environment, natural resources and the man-made environment.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Finnveden, Göran; Potting, José (1999). Eutrophication as an Impact Category. State of the Art and Research Needs. International Journal of Life Cycle Assessment, 4, 6, 311-314.
- UNEP-SETAC Life Cycle Initiative WG LCIA TF4 on transboundary impacts (http://www.lci-network.de/cms/content/LCIAcorner/lang/en/pid/593): Pro memori.
2. Specific references
- (2) Kärrman, Erik; Jönsson, Håkan (2001). Including Oxidisation of Ammonia in the Eutrophication Impact Category. International Journal of Life Cycle Assessment, 6, 1, 29-33.
- (3) Seppälä, Jyri; Knuuttila, Seppo; Silvo, Kimmo (2004). Eutrophication of Aquatic Ecosystems - A New Method for Calculating the Potential Contributions of Nitrogen and Phosphorus. International Journal of Life Cycle Assessment, 9, 2, 90-100.
- (4) Seppälä, Jyri; Maximilian Posch; Matti Johansson; Jean-Paul Hettelingh (2006). Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. International Journal of Life Cycle Assessment, 11, 6, 403-416.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Finnveden & Potting (1)

Finnveden & Potting give a state of the art and research needs for the impact category eutrophication. This review stems from 1999 but is included here as their identification of research needs & trends –largely based on work in the SETAC working group on LCIA – is still relevant. they argue that eutrophication is a difficult impact category because it includes emissions to both air and water − both subject to different environmental mechanisms − as well as impacts occurring in different types of terrestrial
and aquatic ecosystems. The possible fate processes are complex and include transportation between different ecosystems.

Kärrman & Jönsson (2)

Kärrman & Jönsson propose a method for including primary and secondary oxygen consumption in the eutrophication impact assessment. Primary oxygen consumption due to nitrification was not considered in Heijungs et al. (1992) or Nord (1995).
The authors write: "Oxygen depletion of lake and seawater is a serious condition with large implications for biodiversity. Therefore, in LCA, the potential oxygen demand of water emissions is estimated under the label eutrophication impact category. This impact category should contain the impact of water emissions on the total oxygen consumption in the receiving water. This means that it should include both primary and secondary oxygen consumption. In spite of this, the oxygen needed to oxidise ammonia has normally not been taken into account when quantifying the eutrophication impact category. In this paper, weighting factors for ammonium/ammonia are suggested for the eutrophication impact category. It is shown that, for treated wastewater, the amount of oxygen needed for nitrification of ammonia is important when compared to the potential eutrophication calculated using the current recommended weighting factors (meaning: redfield based characterisation factors for COD, e.g. those proposed by of Heijungs et al. 1992 and Nordic 1995; JG). These weighting factors take into account oxygen needed to oxidise the organic matter in the wastewater emission and that needed to degrade the algae potentially grown due to the emission of nutrients. [...] When comparing different wastewater treatment methods, Ødegaard (1995) introduced the term 'Oxygen Compound Potential' (OCP), which includes both primary oxygen consumption (bacterial degradation of BOD and ammonia) and secondary oxygen consumption (bacterial degradation of algae caused by the nutrients, phosphorus and nitrogen). OCP, thus, closely resembles the measure required in LCA. In this paper we suggest including weighting factors for the oxygen demand of nitrification in the eutrophication impact category. The importance of taking into account the oxidisation of ammonia is also illustrated by a case study of different wastewater systems."

Seppälä et al. (3)

Seppälä et al. (3) present a "characterisation method in which the potential contributions of nitrogen and phosphorus to eutrophication of aquatic ecosystems are calculated. The use of the method was demonstrated by producing site/sector-specific characterisation factors and by constructing a reference value of aquatic eutrophication for Finland. A discussion of sensitivity and uncertainty aspects related to input data is also presented. The

potential contribution to eutrophication from a product system is calculated as a result of the nutrient inputs causing increased production of biomass within aquatic systems. Accordingly, direct nitrogen and phosphorus emissions as well as nitrogen and phosphorus deposition into the watercourses can be included. In the method, characterisation factors for nitrogen and phosphorus emissions are generated by multiplying commonly used equivalency factors (meaning: redfield based characterisation factors, e.g. those proposed by of Heijungs et al. 1992 and Nordic 1995; JG) by transport and effect factors. Transport and effect factors of the nutrient sources are case-specific and can be determined for each substance individually on the basis of scientific models, empirical data or expert judgements. In
this paper, transport and effect factors are determined for different sectors (forest industry, field cultivation, fish farming, etc.) in Finland. In addition, temporal aspects can be taken account of in the model by coefficients representing the proportion of nutrient load in the productive period of the total annual load. The model uncertainty was studied by using three different scenarios based on different input data and assumptions. Uncertainties within the input data were assessed as ranges and the effects of input data uncertainty on the results were studied by varying maximum and minimum values of each input variable in the same time. [...] differentiation of nutrient forms in various sectors means that the question of determination of characterisation factors is also related to sector-specific issues. [...]The biological availability of total N and P released from various anthropogenic sources varies considerably. An average phosphorus emission from agriculture, for example, may cause less eutrophication than the same amount of phosphorus from a pulp mill in the same watercourse, because of the different chemical forms of nutrients in the emissions."

<u>Seppälä et al. (4)</u>
Several authors have shown that spatially derived characterisation factors used in life cycle impact assessment (LCIA) can differ widely between different countries in the context of regional impact categories such as acidification or terrestrial eutrophication. Previous methodology studies in Europe have produced country-dependent characterisation factors for acidification and terrestrial eutrophication by using the results of the EMEP and RAINS models and critical loads for Europe. The unprotected ecosystem area (UA) is commonly used as a category indicator in the determination of characterisation factors in those studies. However, the UA indicator is only suitable for large emission changes and it does not result in environmental benefits in terms of characterisation factors if deposition after the emission reduction is still higher than the critical load. For this reason, there is a need to search for a new category indicator type for acidification and terrestrial eutrophying in order to calculate site-dependent characterisation factors. The aim of this study is to explore new site-dependent characterisation factors for European acidifying and eutrophying emissions based on accumulated exceedance (AE) as the category indicator, which integrates both the exceeded area and amount of exceedance. In addition, the results obtained for the AE and UA indicators are compared with each other. The chosen category indicator, accumulated exceedance (AE), was computed according to the calculation methods developed in the work under the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (LRTAP). Sulphur and nitrogen depositions to 150x150 km2 grid cells over Europe were calculated by source-receptor matrices derived from the EMEP Lagrangian model of long-range transport of air pollution in Europe. Using the latest critical load data of Europe, the sitedependent characterisation factors for acidification and terrestrial eutrophication were calculated for 35 European countries and 5 sea areas for 2002 emissions and emissions predicted for 2010. In the determination of characterisation factors, the emissions of each country/area were reduced by various amounts in order to find stable characterisation factors. In addition, characterisation errors were calculated for the AE-based characterisation factors. For the comparison, the results based on the use of UA

indicator were calculated by 10% and 50% reductions of emissions that corresponded to the common practice used in the previous studies.
The characterisation factors based on the AE indicator were shown to be largely independent of the reduction percentage used to calculate them. Small changes in emissions (≤100 t) produced the most stable characterisation factors in the case of the AE indicator. The characterisation errors of those characterisation factors were practically zero. This means that the characterisation factors can describe the effects of small changes in national emissions that are mostly looked at in LCAs. The comparison between country-dependent characterisation factors calculated by the AE and UA indicators showed that these two approaches produce differences between characterisation factors for many countries/areas in Europe. The differences were mostly related to the Central and Northern European countries. They were greater for terrestrial eutrophication because the contribution of ammonia emission differ remarkably between the two approaches. The characterisation factors of the AE indicator calculated by the emissions of 2002 were greater than the factors calculated by the predicted emissions for 2010 in almost all countries/sea areas, due to the presumed decrease of acidifying and eutrophying emissions in Europe. [...] It would also be useful to compare the approach based on the AE indicator with the method of the hazard index, as recommended in the latest CML guidebook."

Main advantages

Kärrman & Jönsson (2)
Advantage: The modelling of the oxidisation of ammonia and ammonium in water.
Disadvantage: no regionalisation; no complete and integrated model but focus on one environmental process.

Seppälä et al. (3)
Advantage: regionalisation; integrated model.
Disadvantage: no modelling of the oxidisation of ammonia and ammonium in water.

Seppälä et al. (4)
Advantage: regionalisation; integrated model.
Main disadvantage: method (4) lacks characterisation factors for direct emissions to water and soil; no modelling of the oxidisation of ammonia and ammonium in water.

Open questions

	Kärrman & Jönsson (2)	Seppälä et al. (3)	Seppälä et al. (4)
Impact category	aquatic eutrophication	aquatic eutrophication in Finland	terrestrial eutrophication In Europe
intervention	emission of COD to water	emissions of N and P to water	emissions of NO_2 and NH_3 to air
Indicator	deposition/N/P equivalents in biomass	deposition/N/P equivalents in biomass	Accumulated Exceedance (EA): the weighted sum of all the critical load exceedances within the area of interest, the weighing factors being

			the individual ecosystem areas
Characterisation model	Redfield ratio approach of Heijungs et al. (1992) and Nordic (1995) supplemented with factors for oxidisation of ammonium and ammonia	Redfield ratio approach of Heijungs et al. (1992) and Nordic (1995) replenished with expert judgment-based transport and effect factors	EMEP and RAINS models and critical loads for Europe
Characterisation factor	no name given; list of generic and to oxidisation adapted CFs from (Nord (1995) provided	no name given; but list of CFs provided for Finnish sectors	no name given; list of CFs (kgeq/t) provided for emissions of NO_2 and NH_3 to air for different European countries

The table above illustrates the compliance of the Kärrman & Jönsson (2), Seppälä et al. (3) and Seppälä et al. (4) with the general structure of LCIA (see Annex X). There are little gaps for these methods, but it is striking that each of the three methods covers only a part of the total range of relevant eutrophication emissions and compartments. For (2) it must be noted that (2) provides an addition on COD modelling of a method (Nord, 1995) that more or less does cover the whole range of relevant eutrophication emissions and compartments. Furthermore, the discussion between the methods merely focuses on modelling differences.

Kärrman & Jönsson (2)
Main open question is if The modelling of the oxidisation of ammonia and ammonium is not included in (3) and (4), and – if so – if and how this could be added to (3) and (4).

Seppälä et al. (3)
Main open question is why the authors do not compare their proposals to the proposal by Huijbregts (1999; 2001) which was based on fate and site-dependent effect modelling as applied in the RAINS model. It now remains unclear what the advantages of their approach compared to Huijbregts (1999; 2001) would be.

Seppälä et al. (4)
Main open question is a comparison of this approach (4) with the proposal by Huijbregts (1999; 2001), which has (surprisingly) not been done as part of this paper. “In the LCA terminology, the method based on AE indicator represents the 'only above' approach. The same concerns one version of the hazard index (HI) method developed by Huijbregts and his colleagues (2001). The main difference between these two approaches seems to be that the hazard index method uses a ratio scale in the calculation of exceedance, whereas the AE approach uses the absolute difference. [...] In both cases, the values of exceedance are weighted by the areas of ecosystems. In order to clarify the meaning of ratio scale of the HI method in terms of characterisation factors, there is a need to calculate the corresponding characterisation factors with the same input data and an integrated assessment

model. In addition, there is a need to discuss the philosophical/conceptual aspects related to the calculation rules of both methods. The discussion should also include the hazard index approach in which all deposition situations above and below critical loads in Europe were taken into account. It should be noted that both HI approaches were only applied in the marginal way, i.e. country-dependent characterisation factors for acidification and terrestrial eutrophication were calculated by the derivation in the deposition situation. In this work, the AE approach was studied from the point of view of various emission reductions. Are the conclusions made for the AE indicator also suitable for the HI indicator? This is a question to be explored in depth in future studies."

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Kärrman & Jönsson (2)
List of generic characterisation factors is provided.

Seppälä et al. (3)
"Transport and effect factors of the nutrient sources are case-specific and they can be determined for each substance individually on the basis of scientific models, empirical data or expert judgments." Currently, factors are only available on the basis of *expert judgement* for sectors in Finland, for emissions of N and P to water. This implies that factors for other countries, other sector definitions or based on scientific modesl/experimental data instead of expert judgement need to be calculated by practitioners themselves. If indeed the factors are also case- specific (it is not clear from the paper if this case-specificity is more that site- and sector-dependent; JG), then such calculations would have to be made by practitioners for each case-study again, which would clearly decrease the practicability of this method. Moreover, emissions to other compartments should be included in the modelling.
"The weakness of the method presented in this paper is related to the accessibility of input data." The authors expect, however, that "this will not be a problem in future [...] due to the fact that directive 2000/60/EC of European Union requires that Member States determine 'target nutrient loads' of aquatic eutrophication in the catchments of each country (European Union 2000). It is expected that this work will produce more accurate bases for transport and effect factors of nutrients in inland and coastal waters in different European countries."

Seppälä et al. (4)
List of characterisation factors for emissions of NO_2 and NH_3 to air is supplied for different European countries.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Kärrman & Jönsson (2)
No limitations

Seppälä et al. (3) Limited to Finland and Finnish sectors Seppälä et al. (4) Europe

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. Finnveden & Potting (1) • Appropriate modelling of complex fate and transportation processes between different ecosystems. • The definition of the impact indicator (taking into account sensitivity of area, background concentrations, thresholds, spatial differentiation etc.). • The inclusion of other nutrients than those typically considered should also be investigated. Kärrman & Jönsson (2) N.a. Seppälä et al. (3) "[...] further research is needed, in particular on the roles of different nutrient forms as sources for aquatic biota, on spatial differentiation of nitrogen and phosphorus as production limiting factors, and on fate of nitrogen in catchments." Furthermore, the method should be elaborated for other countries and sectors beyond the current the Finnish ones. Seppälä et al. (4) It should be investigated how this method (4) compares to the method of Huijbregts (1999; 2001) and it should be investigated how the current model can include impact outside Europe and/or how the model can be extended to other continents besides Europe.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/improvement of existing methods/toxicity assessment

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es.
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

See general criteria.

This impact category includes human toxicity and ecotoxicity. Human toxicity covers the impacts on human health of toxic substances present in the environment. Health risks of exposure in the workplace are assessed separately under the heading of "indoor and occupational exposure".

This impact category covers the impacts of toxic substances on aquatic, terrestrial and sediment ecosystems. The area of protection is the natural environment (and natural resources).

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. **General references**
   - (1) Henrik Fred Larsen; Michael Z. Hauschild (2007). Evaluation of Ecotoxicity Effect Indicators for Use in LCIA. International Journal of Life Cycle Assessment, 12,1, 24-33.
2. **Specific references**
   - (2) Rosenbaum R.K., Bachmann T.M., Hauschild M.Z., Huijbregts M.A.J., Jolliet O., Juraske R., Köhler A., Larsen H.F., MacLeod M., Margni M., McKone T.E., Payet J., Schuhmacher M., Russel A., van de Meent D. (submitted). USEtox - The UNEP/SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in Life Cycle Impact Assessment. International Journal of Life Cycle Assessment (2007).
   - (3) Gandhi, Nilima, Miriam Diamond, Dik van de Meent, Mark Huijbregts, Jeroen Guinée, Gjalt Huppes, Willie Peijnenburg & Bart Koelmans (2007). Estimation of characterisation factors for metals in life cycle impact assessment of ecotoxicity – addressing the metal's fate, exposure and effects issues. Abstract book (MO464) of the SETAC Europe 17th annual meeting, 20-24 May 2007, Porto, Portugal.

2^nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. <u>Larsen & Hauschild (1)</u> Larsen & Hauschild describe "different ecotoxicity effect indicator methods/approaches. The approaches cover three main groups, viz. PNEC approaches, PAF approaches and damage approaches. Ecotoxicity effect indicators used in life cycle impact assessment (LCIA) are typically modelled to the level of impact, indicating the potential impact on 'ecosystem health'. The few existing indicators, which are modelled all the way to damage, are poorly developed, and even though relevant alternatives from risk assessment exist (e.g. recovery time and mean extinction time), these are unfortunately at a very early stage of development, and only few attempts have been made to include them in LCIA. The approaches are described and evaluated against a set of assessment criteria comprising compatibility with the methodological requirements of LCIA, environmental relevance, reproducibility, data demand, data availability, quantification of uncertainty, transparency and spatial differentiation. The results of the evaluation of the two impact approaches (i.e. PNEC and PAF) show both pros and cons for each of them. The assessment factor-based PNEC approach has a low data demand and uses only the lowest data (e.g. lowest NOEC value). Because it is developed in tiered risk assessment, and hence makes use of conservative assessment factors, it is not optimal, in its present form, to use in the comparative framework of LCIA, where best estimates are sought. The PAF approaches have a higher data demand but use all data and can be based on effect data (PNEC is no-effect-based), thus making these approaches non-conservative and more suitable for LCIA. However, indiscriminate use of ecotoxicity data tends to make the PAF-approaches no more environmentally relevant than the assessment factor-based PNEC approaches. The PAF approaches, however, can at least in theory be linked to damage modelling." <u>Rosenbaum et al. (2)</u> "In 2005 a comprehensive LCIA toxicity characterisation model comparison 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." Rosenbaum et al. describe in their paper the model-comparison process and the resulting consensus model "USEtox". "The main objectives were to identify specific sources of differences both in model results and structure, what were the indispensable model components, and to build a consensus model from them, representing recommended practice. A consistent chemical test set of 45 organics was selected. In three workshops, the model comparison participants identified crucial fate, exposure and effect issues. Through this process, we were able to reduce inter-model variation from initially up to 13 orders of magnitude to 2 orders of magnitude for any substance compared to 12 orders of magnitude variation of characterisation factors (CF) between substances. This process led to the development of USEtox, a scientific consensus model that contains only the most influential model elements. USEtox provides a parsimonious and transparent tool for human health and ecosystem CF estimates. Based on a well-referenced database, the consensus model has now been used to calculate CFs for [more than] 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."

Gandhi et al. (3)

The UNEP-SETAC Life Cycle Initiative has launched a research project with ICMM aiming to improve characterisation factors (CFs) for metals. The goal is to address key issues in the life cycle assessment of metals that need improvement for developing a robust method and guidance on the assessment of environmental fate and ecotoxicological effects of metals. The project is executed by Toronto University –Dept. of Geography in cooperation with Radboud University Nijmegen – Dept. of Environmental Science, Leiden University - Institute of Environmental Sciences (CML), National Institute of Public Health and the Environment (RIVM) Bilthoven, and Wageningen University and Research Centre.

To address this need, the project team designed a three-tiered approach to develop and evaluate improved CFs for metals. First, the core elements of TRANSPEC, a coupled metal speciation and fate model, were included in a newly developed LCIA consensus model for organic chemicals to make it suitable for metal-specific fate calculations. Second, BLM was used to calculate the effects of Cu, Ni and Zn. Third, in parallel to BLM, FIAM was applied to these metals to compare the effects estimates from these two models. To assess the influence of environmental variability (e.g., pH, DOC etc.) on the fate and effect calculations, a multi-variant sensitivity analysis was performed. Preliminary model estimates of CFs from this exercise have been calculated and compared with previously reported values. The final results will be modelled as part of the UNEP-SETAC USEtox model for organics. This project is ongoing until 2009.

Main advantages

Rosenbaum et al. (2)

This approach is supported by all relevant players in the LCIA field. An utmost important advantage is thus its “consensus” aspect. The approach is developed to cover as many chemicals as possible in a currently best practicable state-of-the-art scientific way. This implies that not the latest knowledge is included as this often is still debated heavily and requires data that are not readily available for the majority of potentially toxic chemicals.

Gandhi et al. (3)

This approach is still developing but will explicitly link to (2) and provide best practical solutions for the modelling of metals, which is a long-standing issue of debate within LCIA of toxic releases.

Open questions

	Rosenbaum et al. (2)
Impact category	human toxicity and aquatic freshwater ecotoxicity
intervention	emissions of toxic substances to air, water and soil (kg)
Indicator	predicted intake fraction/ED50 predicted environmental concentration/HC50
Characterisation model	USEtox model: The UNEP/SETAC toxicity (multi-media) model
Characterisation factor	• human health CF for each emission of a toxic substance to air, water and/or soil (cases/kg) • freshwater ecotoxicity CF for each emission of a toxic substance to air, water and/or soil ($m^3.day.kg^{-1}$)

The table above illustrates the compliance of the Rosenbaum et al. (2) with the general structure of LCIA (see Annex X). There are little gaps for this method. The other approaches discussed are no method or are still under development and can therefore not be included in this table. Larsen & Hauschild (1) Damage approaches need to be developed further and then it remains to be seen if the data problem attached to these approaches, can be adequately solved, and if the efforts needed to collect these data are worth the added value of the damage approach. Rosenbaum et al. (2) Gandhi et al. (3) Not yet available.
Practicability aspects
Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. Rosenbaum et al. (2) No problems; CFs provided for more than 1000 chemicals. Gandhi et al. (3) Not yet available.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

Larsen & Hauschild (1)

All the approaches for damage modelling which are included here have a high environmental relevance but very low data availability, apart from the 'media recovery-approach', which depends directly on the fate model. They are all at a very early stage of development. An analysis of the different PAF approaches shows that the crucial point is according to which principles and based on which data the hazardous concentration to 50% of the included species (i.e. HC50) is estimated. The ability to calculate many characterisation factors for ecotoxicity is important for this impact category to be included in LCIA in a proper way. However, the access to effect data for the relevant chemicals is typically limited. So, besides the coupling to damage modelling, the main challenge within the further development and improvement of ecotoxicity effect indicators is to find an optimal method to estimate HC50 based on little data.

Rosenbaum et al. (2)

“A full quality check of effect data from the two freshwater ecotoxicity data sets is recommended for the second phase of the UNEP/SETAC life cycle initiative, including a check for the occurrence of NOEC extrapolation and for the representation of taxa and trophic levels. Furthermore, research on how to include chronic data and how to estimate average toxicity (based on data for individual single species or averaged on trophic levels) is also needed and strongly recommended for the second phase of the UNEP/SETAC Life Cycle Initiative.

For the upcoming second phase of the UNEP/SETAC Life Cycle Initiative the following future activities are foreseen:

- Increase of substance coverage and quality assurance of substance data;
- User-friendly programming of the consensus model, which currently only exists as a research model in Excel;
- Including parameter uncertainty in the uncertainty estimates on the USEtox CFs;
- Development of USEtox to accommodate the metals;
- Development of USEtox to accommodate indoor emissions;
- Recommendations regarding differentiation between midpoint and endpoint characterisation;
- Full documentation of USEtox;
- Research on how to include chronic data and how to estimate average toxicity (single species or trophic levels)
- Inclusion of terrestrial and marine ecotoxicity as endpoints in USEtox;
- Reliability check of freshwater ecotoxicity CFs based on two effect data only (including a check for the occurrence of NOEC extrapolation and on the representation of taxa and trophic levels)
- Industry workshops on comparative assessment of chemicals and training courses in USEtox.”

Gandhi et al. (3)

Ongoing research project.

Comments

Comments of the person who fill in the scheme in order to understand the “importance” of the approach analysed.

[Phase/Topic/Approach]

LCIA/improvement of existing methods/stratospheric ozone depletion

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. Stratospheric ozone depletion refers to the thinning of the stratospheric ozone layer as a result of anthropogenic emissions. This causes a greater fraction of solar UV-B radiation to reach the earth's surface, with potentially harmful impacts on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and materials (UNEP, 1998). Stratospheric ozone depletion thus impinges on all four areas of protection: human health, the natural environment, the man-made environment and natural resources.
Relevant references *The relevant references should be organised along two lines:* *- General references (related to the topic addressed)* *- Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- UNEP-SETAC Life Cycle Initiative WG LCIA TF4 on transboundary impacts (http://www.lci-network.de/cms/content/LCIAcorner/lang/en/pid/593): Pro memori.
2. Specific references
- (1) Hayashi, Kentaro; Itsubo, Norihiro; Inaba, Atsushi (2000). Development of Damage Function for Stratospheric Ozone Layer Depletion. A Tool Towards the Improvement of the Quality of Life Cycle Impact Assessment. International Journal of Life Cycle Assessment, 5, 5, 265-272.
- (2) Hayashi, Kentaro; Ai Nakagawa; Norihiro Itsubo; Atsushi Inaba (2006). Expanded Damage Function of Stratospheric Ozone Depletion to Cover Major Endpoints Regarding Life Cycle Impact Assessment. International Journal of Life Cycle Assessment, 11, 3, 150-161.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. <u>Hayashi et al. (1,2)</u> "Hayashi et al. developed a damage function for stratospheric ozone depletion. The purpose of their study was to develop damage functions due to ozone layer depletion, that related the emission of ozone depleting substances (ODS) to the damage of category endpoints. The ozone layer depletion causes many types of damage such as skin cancer, cataract, adverse effect to crop and plant growth. We assessed the increase of skin cancer incidence risk. The damage functions have been developed with connecting the main processes on ozone depletion, emission of ODS, increase of tropospheric ODS, increase of stratospheric ODS, change of total ozone, change of B region ultra-violet (UV-B) at the surface, and the increase of skin cancer incidence. As the result, they could introduce damage functions of melanoma and non-melanoma skin cancer incidence for 13 species of ODSs and damage factors based on the disability-adjusted life years (DALYs). They also compared the DALYs value with the damage factors of Eco-indicator 99 (egalitarian and hierarchic value), and it was found that their result was several ten times as small except for methyl bromide." The latter merely seems to indicate that both methods are quite well compatible. The publication of Hayashi et al. by was followed up by a publication by Hayashi et al. in 2006, focusing on expanding the target endpoints. [...] Marginal damage due to the unit emission of ODS was calculated for 13 substances for which quantitative information was available as follows: (1) the increase of UVB radiation at the earth's surface per unit emission of ODS was estimated, (2) the increase of potential damage per unit increase of UVB radiation was estimated, (3) the increase of potential damage per unit emission of ODS was determined by connecting the two relationships, and (4) correcting by the atmospheric lifetime of ODS, so that the damage function was then obtained. *For other ODSs regulated by the Montreal Protocol, their damage functions were estimated by multiplying the ratio of ODP compared to the corresponding reference substance by the damage function of this reference substance*. The damage function of ozone depletion included the following endpoints: skin cancer and cataract for human health, crop production and timber production for social assets, and terrestrial NPP and aquatic NPP for primary productivity. And damage factors for each safeguard subject were also obtained. [...] Uncertainty of damage function is also an important point to be elucidated. Preliminary studies of uncertainty analysis have begun for the damage function of ozone depletion. However, further analysis is required to comprehensively evaluate the uncertainty of the damage function.
Main advantages
Not applicable.
Open questions

	Hayashi et al. (1,2)
Impact category	stratospheric ozone depletion
intervention	emissions of ODS (kg)
Indicator	damage (on human health; primary production; social assets) due to stratospheric ozone breakdown
Characterisation model	Adapted WMO-model extended with damage modelling ??
Characterisation factor	Damage factor indicating the total damage for each safeguard subject (human health; primary production; social assets) per unit emission of ODS

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Full list of CFs available; no practical problems.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

The increased uncertainty due to damage modelling needs to be elucidated, in relation to the increased environmental relevance of this type of modelling.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCIA/improvement of existing methods/tropospheric ozone formation

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* See general criteria. Photo-oxidant formation is the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants. These reactive compounds may be injurious to human health and ecosystems and may also damage crops. The relevant areas of protection are human health, the man-made environment, the natural environment and natural resources. Photo-oxidants may be formed in the troposphere under the influence of ultraviolet light, through photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx). Ozone is considered the most important of these oxidising compounds, along with peroxyacetylnitrate (PAN). Photo-oxidant formation, also known as summer smog, Los Angeles smog or secondary air pollution, contrasts with winter smog, or London smog, which is characterised by high levels of inorganic compounds, mainly particles, carbon monoxide and sulphur compounds. This latter type of smog causes bronchial irritation, coughing, etc. Winter smog, as far as considered in this Guide, is part of human toxicity.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- UNEP-SETAC Life Cycle Initiative WG LCIA TF4 on transboundary impacts (http://www.lci-network.de/cms/content/LCIAcorner/lang/en/pid/593): Pro memori.
2. Specific references
- (1) Norris, G.A. (2003). Impact characterization in the Tool for the Reduction and Assessment of Chemical and other environmental Impacts. Journal of Industrial Ecology, 6:3-4, 79-101.
- (2) Labouze, Eric; Honoré, Cécile; Moulay, Lamya; Couffignal, Bénédicte; Beekmann, Matthias (2004). Photochemical Ozone Creation Potentials. A new set of characterization factors for different gas species on the scale of Western Europe. International Journal of Life Cycle Assessment, 9, 3, 187-195.

- (3) Michael Z. Hauschild; José Potting; Ole Hertel; Wolfgang Schöpp; Annemarie Bastrup-Birk (2006). Spatial Differentiation in the Characterisation of Photochemical Ozone Formation: The EDIP2003 Methodology. International Journal of Life Cycle Assessment, 11, Special Issue 1, 72-80.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Norris (1)

"The tool for the reduction and assessment of chemical and other environmental impacts (TRACI) is a set of life-cycle impact assessment (LCIA) characterization methods that has been developed by a series of U.S. Environmental Protection Agency research projects. TRACI facilitates the characterization of stressors that may have potential effects, including [...] acidification [...]. [...]The approach to smog characterization analysis for VOCs and NO*x* in TRACI has the following components. For the relative influence of NO*x* emissions in comparison to the base reactive organic gas mixture, we use a midrange factor of 2, which is in agreement with empirical studies [...]. To characterize the relative influence on O_3 formation among the individual VOCs, we use Carter's latest MIR calculations (Carter 2000). These reflect the estimated relative influence for conditions under which NO*x* availability is moderately high and VOCs are at their most influential upon O3 formation. [...] We [...] assume similar regional transport for VOCs and NO*x*. Finally, the outcome of the source/transport modelling is proportional to estimated O3 concentration impacts (in grams per square meter) per state, given an assumed linear relationship between the change in concentration in NO*x* (with VOC concentrations converted to NO*x* equivalents). [...] Exposures leading to human health impacts are related to the product of state-level ambient concentrations times state populations, assuming uniform population density within a state and assuming a linear relationship between dose and risk of impact. Damages from impacts on forest and agricultural productivity are related in part to the scale of sensitive agricultural and forest output per state. In the present version of TRACI, we address human health impacts, scaling the state-level concentration outcomes by state population before aggregating across states."

Labouze et al. (2)

"Photochemical ozone creation potentials (POCPs) typically used in life cycle impact assessment (LCIA) to address the impact category 'photo-oxidant formation' only provide factors for particular volatile organic compounds and do not take into account background concentrations and meteorological conditions. However, the formation of ozone from volatile organic compounds (VOCs), carbon monoxide (CO) and nitrogen oxides (NOx) is highly dependent on the background pollutant concentrations and meteorological conditions. [...] This study has introduced an improved set of POCPs independently of meteorological and emission conditions specific to a given period or location. Whereas current POCP values may be relevant to estimate the photo-oxidant formation over a certain (temporally and spatially well-defined) domain, this study has further introduced more relevant values with respect to potential impacts of ozone on human health and environment. For the computation of POCP values on the scale of Western Europe, independently of meteorological and emission conditions specific to a given period or location, a Eulerian chemistry-transport numerical model (CHIMERE-continental) has been implemented over three summer seasons. POCPs have been evaluated for *ten VOC species (including the whole VOC group), CO and NOx*. The coherence of this new set of POCP values with previous studies has been checked. The spatial representativity of POCP values over the simulation domain in *Europe* has also been addressed. The robustness of these POCP values to changes in the implemented chemical mechanism used in our model has been checked. The POCPs computed in this study were generally lower than the POCPs calculated in previous studies. In the previous studies, but not here, the POCPs have been calculated with particular meteorological conditions (during anticyclonic, fair weather conditions) or emission levels (high polluted backgrounds) known to be optimal with respect to ozone formation. Despite the quantitative variations in the POCP values, we have found a good agreement in the relative ranking of the pollutant species between this study and previous studies. It was also shown that POCP values display significant spatial variability over Western Europe (the largest spatial differences were obtained for NOx where the sign of the POCP value even changes from region to region). Finally, the temporally and spatially averaged values obtained here for the POCP index update previous values and represent an attempt to generate the most appropriate and accurate scale for European conditions independently of meteorological and emission conditions specific to a given period or location. These new POCPs should be useful to LCIA-practitioners in further life cycle impact assessment. However, for the NOx species, we do not recommend the use of the POCP value for LCIA."

<u>Hauschild et al. (3)</u>
"In the life cycle of a product, emissions take place at many different locations. The location of the source and its surrounding conditions influence the fate of the emitted pollutant and the subsequent exposure it causes. This source of variation is normally neglected in Life Cycle Impact Assessment (LCIA), although it is well known that the impacts predicted by site-generic LCIA in some cases differ significantly from the actual impacts. Environmental impacts of photochemical ozone (ground-level ozone) depend on parameters with a considerable geographical variability (like emission patterns and population densities). A spatially differentiated characterisation model thus seems relevant. The European RAINS model is applied for calculation of site-dependent characterisation factors for Non-Methane Volatile Organic Compounds (NMVOCs) and nitrogen oxides (NOx) for 41 countries or regions within Europe, and compatible characterisation factors for carbon monoxide (CO) are developed based on expert judgement. These factors are presented for three emission years (1990, 1995 and 2010), and they address human health impacts and vegetation impacts in two separate impacts categories, derived from AOT40 and AOT60 values respectively. Compatible site-generic characterisation factors for NMVOC, NOx, CO and methane (CH4) are calculated as emission-weighted European averages to be applied on emissions for which the location is unknown. The site-generic and site-dependent characterisation factors are part of the EDIP2003 LCIA methodology. The factors are applied in a specific case study, and it is demonstrated how the inclusion of spatial differentiation may alter the results of the photochemical ozone characterisation of life cycle impact assessment. Compared to traditional midpoint characterisation modelling, this novel approach is spatially resolved and comprises a larger part of the cause-effect chain including exposure assessment and exceeding of threshold values. This positions it closer to endpoint modelling and makes the results easier to interpret. In addition, the developed model allows inclusion of the contributions from NOx, which are neglected when applying the traditional approaches based on Photochemical Ozone Creation Potentials (POCPs). The variation in site-dependent characterisation factors is far larger than the variation in POCP factors. It thus seems more important to represent the spatially determined variation in exposure than the difference in POCP among the substances."

Main advantages

Norris (1)
Regionalised factors for VOC as group, individual VOCs and NOx for US states and US generic.

Labouze et al. (2)
Regionalised factors for ten VOC-species (including the whole VOC group), CO and NOx for Western European regions and Western Europe generic. Improved set of POCPs independently of meteorological and emission conditions specific to a given period or location. Eulerian chemistry-transport numerical model.

Hauschild et al. (3)
Regionalised factors for NMVOC, CO and NOx for 41 European states and Europe generic. RAINS-based model.
Compared to the other approaches, this approach comprises a larger part of the cause-effect chain including exposure assessment and exceeding of threshold values. This positions it closer to endpoint modelling and makes the results easier to interpret.

Open questions

	Norris (1)	Labouze et al. (2)	Hauschild et al. (3)
Impact category	photochemical oxidant formation	photochemical oxidant formation	photochemical oxidant formation
intervention	emissions of VOC as group, individual VOCs and NOx to air (kg)	emissions of ten VOC-species (including the whole VOC group), CO and NOx to air (kg)	emissions of NMVOC, CO and NOx to air (kg)
Indicator(s)	tropospheric ozone formation	tropospheric ozone formation	• exposure of vegetation to photochemical ozone • exposure of humans to photochemical ozone
Characterisation model	Incremental Reactivity single-cell box model by Carter's (2000)	Eulerian chemistry-transport numerical model (CHIMERE-continental)	RAINS model
Characterisation factor	maximum incremental reactivity (MIR) for each emission of VOC or CO to the air (in kg ethylene equivalents/kg	photochemical ozone creation potentials (POCP) for ten VOC-species (including the whole VOC group), CO and NOx	site-dependent and site-generic characterisation factors for exposure of vegetation to photochemical ozone (in

emission)	emitted to air (in kg ethylene equivalents/kg emission)	m^2.ppm.hours/g emission) and for exposure of humans to photochemical ozone, emissions of NMVOC, CO and NOx to air (in pers.ppm.hours/g emission)

The table above illustrates the compliance of the Norris (3), Labouze et al. (2) and Hauschild et al. (3) with the general structure of LCIA (see Annex X). There are little various gaps for these methods, but it is striking that each of the three methods covers a different (sub-) impact categories and/or different interventions.

Norris (1)
See below at R&D.

Labouze et al. (2)

Hauschild et al. (3)
What the added value of a RAINS-based model compared to the Eulerian model applied by Labouze et al. (2) is, remains unclear in Hauschild et al. as they don't discuss the paper by Labouze et al.
Hauschild et al. claim that "the variation in site-dependent characterisation factors is far larger than the variation in POCP factors. It thus seems more important to represent the spatially determined variation in exposure than the difference in POCP among the substances." This should be checked with the other models that are also regionalised. It would means that no CFs for individual VOCs would be necessary to derive.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Norris (1)
MIRs (in kg ozone formed/kg emission) provided for emissions of VOC, CO and NO_x to air for different 49 US states, and for larger regions and for the United States as a whole.

Labouze et al. (2)
POCPs for ten VOC species (including the whole VOC group), CO and NOx.

Hauschild et al. (3)
Site-dependent and site-generic characterisation factors for exposure of vegetation to photochemical ozone (in m^2.ppm.hours/g emission) and for

exposure of humans to photochemical ozone, emissions of NMVOC, CO and NOx to air (in pers.ppm.hours/g emission).

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Norris (1)
US.

Labouze et al. (2)
Western Europe.

Hauschild et al. (3)
Europe.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

Norris (1)
It could be investigated how the current model can include impact outside US and/or how the model can be extended to other continents besides US.

Labouze et al. (2)
Extension of list of POCPs for VOC species ; currently only 10 different VOC species are included.

Hauschild et al. (3)
Hauschild et al. claim that "the variation in site-dependent characterisation factors is far larger than the variation in POCP factors. It thus seems more important to represent the spatially determined variation in exposure than the difference in POCP among the substances." This should be checked with the other models that are also regionalised. It would means that no CFs for individual VOCs would be necessary to derive.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

Norris (1) is actually afterwards not really a "beyond ISO" development and should probably be left out of this analysis as yet.

LIFE CYCLE INTERPRETATION

UNCERTAINTY

- Parameter
- Model
- Scenario

DATA QUALITY

[Phase/Topic/Approach]

Life Cycle Interpretation/Uncertainty/Parameter Uncertainty

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* Parameter uncertainty reflects our incomplete knowledge about the true value of a parameter and it is generally introduced by measurements errors in input data. It includes data uncertainty regarding process inputs, environmental discharges and technology characteristics. Parameter uncertainty is tackled with several techniques, such as: stochastic modelling (e.g. Monte Carlo simulation, Latin Hypercube), Bayesian statistics, analytical uncertainty propagation methods, calculation with intervals and fuzzy logic. These models can make use of different parameter distributions: uniform, triangular, normal, lognormal. The use of these methodologies gives as a result the possibility to quantify and verify the reliability of parameters and results. The papers selected described different approaches, with particular reference to Monte Carlo analysis and Fuzzy Analysis. The reasons for using the various sampling techniques were not discussed. A comparison between the different methodologies to define the best one in relation with the analysed system has not been treated yet.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Lloyd S.M., Ries R, **Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: A survey of quantitative approaches**, Journal of Industrial Ecology, 11 (1) 2007, 161-179
- (8) Huijbregts M., **Part I: A general framework for the analysis of uncertainty and variability in Life Cycle Assessment**, Int J LCA 3 (5) 273-280, 1998.
2. Specific references
- (2) Lo S.-C., Ma H.-W., Lo S.-L., **Quantifying and reducing uncertainty in life cycle assessment using the Bayesian Monte Carlo method**, Science of the Total Environment, 340 (1-3) 2005, 23-33
- (3) Sonnemann G.W., Schuhmacher M., Castells F., **Uncertainty assessment by a Monte Carlo simulation in a life cycle inventory of electricity produced by a waste incinerator**, Journal of Cleaner Production, 11 (3) 2003, 279-292

-	(4) LaPuma P.T., McCleese D.L., **Using Monte Carlo Simulation in Life Cycle Assessment for Electric and Internal Combustion Vehicles**, International Journal of Life Cycle Assessment, 7 (4) 2002, 230-236
-	(5) Cellura M., Ardente F., Beccali M., **F.A.L.C.A.D.E.: a fuzzy software for the energy and environmental balances of products**, Ecological Modelling, 176 (2004), 359-379
-	(6) Tan R.R., Lee Michael A. Briones and Alvin B. Culaba, **Fuzzy data reconciliation in reacting and non-reacting process data for life cycle inventory analysis**, Journal of Cleaner Production, 15 10) 2007, 944-949
-	(7) Schwan A., Weckenmann A., **Environmental Life Cycle Assessment with Support of Fuzzy-Sets**, International Journal of Life Cycle Assessment, 6 (1) 2001, 13-18
-	(9) Bjorklund A.E., **Survey of approaches to improve reliability in LCA**, International Journal of LCA (2002)
-	(10) Huijbregts, M.A.J., Thissen, U.b , Jager, T.c , Van De Meent, D.c , Ragas, A.M.J.b, **Priority assessment of toxic substances in life cycle assessment. Part II: Assessing parameter uncertainty and human variability in the calculation of toxicity potentials**, Chemosphere, 41 (4) pp 575-588 (2000)

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Two approaches have been analysed in detail: Monte Carlo Analysis and Fuzzy Analysis.

Monte Carlo

Monte Carlo simulation can be defined as a method to generate random sample data based on some known distribution. This means that to perform Monte Carlo simulation, parameters have to be specified as uncertainty distributions. The method varies all the parameters at random, but the variation is restricted by the given uncertainty distribution for each parameter. The randomly selected values from all the parameter uncertainty distributions are inserted in the output-equation. Repeated calculations produce a distribution of the predicted output values, reflecting the combined parameter uncertainties (8)

The presented methods are especially applicable for uncertainty analysis of life cycle inventories. (3)

Fuzzy analysis

The "fuzzy set theory" is an alternative way to represent the uncertainty, which allows to use, in a formal way, both linguistic expressions and numerical values (5). *In particular, the model allows to give further attributes to the numerical data of the inventory based to the expert knowledge. (5)* These fuzzy numbers consist of a set of intervals for a range of possibility values ranging from zero to unity; possibility is typically interpreted as a degree of plausibility or degree of truth of a particular interval. The intervals are stacked to define a fuzzy membership function (or possibility

distribution) (6).
The model is suitable for life cycle inventory analysis as well as related procedures such as substance flow analysis. (6)

<u>Importance Analysis</u>
Uncertainty importance analysis focuses on how the uncertainty of different parameters contributes to the total uncertainty of the result. A parameter can have large uncertainty, but still contribute insignificantly to the overall uncertainty. This is identified by determining the uncertainty of a parameter, either qualitatively or quantitatively, and combining this information with a sensitivity analysis. It gives more specific information than ordinary sensitivity analysis, and can be used to prioritize efforts to reduce uncertainty. (9)

Main advantages

<u>Monte Carlo simulation</u>
Like the other probabilistic approach, Monte Carlo is useful in making the influence of parameter uncertainty on the uncertainty of the model outcomes operational (8). Furthermore, it provides decision makers with far more information than a single estimate of damage (3), and allows modeller to estimate the uncertainty in each input variable and predict the impact of that variable on the outputs. The tool is well suited to understand the magnitude of the uncertainties and variability that are difficult to observe using deterministic methods (4).

<u>Fuzzy Analysis</u>
Fuzzy sets allow the influence of uncertainties of ingoing data on evaluation results to become transparent. Furthermore, due to the fact that with the fuzzy set only the exact quantification of a few important flow is necessary, time and cost saving is expected (7).
Fuzzy model allows to easily handle highly asymmetrical distributions (6).

Open questions

Parameter uncertainty was the type of uncertainty most frequently addressed, but it is not possible to determine this is because parameter uncertainty is the most commonly recognised form of uncertainty, whether it is generally considered the most important, or whether it is because of the availability of data for characterising this type of uncertainty (1)

<u>Monte Carlo</u>
There are controversy over the most appropriate inputs to use in Mote Carlo simulation (4).

Another aspect pointed out is the interdependency of parameters: it should be investigated more in detail (1).

<u>Fuzzy Analysis</u>
By failing to incorporate correlation among input variables, fuzzy data sets may overestimate uncertainty. It is important to underline that also the

use of a fuzzy approach does not aim to “exact” results, because of the introduction of uncertainty related to the use of fuzzy rules (5).

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.
Some LCA software platforms now provide the ability to calculate uncertainty using Monte Carlo analysis.
Also current databases start to include quantitative uncertainty values for parameters in many of their processes (1).

Fuzzy analysis can be performed with the software tool F.A.L.C.A.D.E. /Fuzzy Approach to Life Cycle Analysis and Decision Environment): it is designed for the calculation of the eco-profile of products, based on a fuzzy logic approach. The originality of the method is to use the fuzzy representation to manage the complex relationships that arise in compiling an eco-balance. The software allows the users to investigate how the data uncertainties affect the final results (5).
Importance Analysis
Crystal Ball is also equipped with a tool which calculates the uncertainty importance of each parameter. This tool calculates the uncertainty importance by computing rank correlation coefficients between every parameter uncertainty and every model outcome during the simulation. If a parameter and a model outcome have a high correlation coefficient, this means that the uncertainty in the parameter has a relatively large impact on the uncertainty in the model outcome. (10)

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

The needs to reduce parameter uncertainty are related to the availability of more reliable data by: literature research; expert judgements; measurements (8).

Logic checks should be performed to assess the appropriateness of distributions and a more detailed understanding of the interdependencies of parameters should be investigated (1)

Comments

Comments of the person who fill in the scheme in order to understand the “importance” of the approach analysed.

[Phase/Topic/Approach]

Life Cycle Interpretation/Uncertainty/Model Uncertainty

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.

"Model uncertainty" has been defined as the uncertainty related to the modelling and it is introduced through simplifications of aspects that cannot be modelled within the present LCA structure, such as [1]:

- Temporal and spatial characteristics lost by aggregation;
- Linear instead non-linear models: in Impact Assessment it is assumed that ecological processes respond in a linear manner to environmental interventions and that thresholds of interventions are disregarded;
- The derivation of characterisation factors. They are computed with the help of simplified environmental models which also suffer from model uncertainties;
- The lack of characterisation factors for toxicological important substances or important sum emissions, such as metals.

The papers selected for the analysis focus more on the model uncertainty in multi-media fate and exposure models for toxicity potentials.

Relevant references

The relevant references should be organised along two lines:

- *General references (related to the topic addressed)*
- *Specific references (related to the approach analysed)*

In this case, the list of references is not in its final version

1. **General references**

- [1] Huijbregts M., **Part I: a general framework for the analysis of uncertainty and variability in Life Cycle Assessment,** Int. J. LCA 3 (5) 273-280, 1998.
- [2] Lloyd S.M., Ries R., **Characterizing, propagating, and analysing uncertainty in Life-Cycle Assessment**, Journal of Industrial Ecology Vol. 11, Issue 1, December 2007, Pages 161-179.

2. **Specific references**

- [3] Hertwich E.G., McKone T.E., Pease W.S., **A systematic uncertainty analysis of an evaluative fate and exposure model**, Risk Analysis Vol. 20, No 4, 2000
- [4] McKone T.E., Hertwich E.G., **The Human Toxicity Potential and a strategy for evaluating model performance in life cycle impact assessment**, Int J LCA 6 (2) 106-109, 2001
- [5] Rosenbaum R., Pennington D.W., Jolliet O., **An implemented approach for estimating uncertainties for toxicological impact**

characterisation, In Pahl-Wostl, C., Schmidt, S., Rizzoli, A.E. and Jakeman, A.J. (eds), Complexity and Integrated Resources Management, Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society, iEMSs: Manno, Switzerland, 2004. ISBN 88-900787-1-5

- [6] Huijbregts M., Guinée J.B., Reijnders L., **Priority assessment of toxic substances in life cycle assessment. III: export of potential impact over time and space**, Chemosphere 44 (2001), 59-65.
- [7] Huijbregts M., Thissen U., Jager T.,van de Meent D., Ragas A.M.J., **Priority assessment of toxic substances in life cycle assessment. Part II: assessing parameter uncertainty and human variability in the calculation of toxicity potentials,** Chemosphere 41 (2000), 575-588.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

It is unclear from ISO standards how the uncertainty (and variability) in toxicity potentials should be assessed and how these uncertainty estimates should be implemented in LCA case studies.
In the approaches described below, model uncertainty is often evaluated in combination with parameter uncertainty: indeed, the correlation between these two type of uncertainty is very high. According to [1] when a model suffers from large model uncertainties, the results of a parameter uncertainty analysis may be misleading: for this reason is important to operationalise parameter uncertainty in the model.

Usually model uncertainty can be tackled with scenario analysis. Huijbregts [1] suggested also the following techniques: the reduction of model uncertainties in the inventory analysis through use of non-linear modelling; the reduction of model uncertainty in the characterization phase, through use of multi-media modeling. Co-operation with specialists of other scientific disciplines will facilitate the implementation of these improvement options.

Hertwich et al. [3], [4]
In [3] and [4] the authors proposed an uncertainty analysis framework for multimedia risk assessment, a framework that addresses parameter uncertainty/variability as well as model uncertainty and decision rule uncertainty. In particular, the CAITOX model is used to calculate the potential dose (on which the uncertainty analysis is performed), an outcome that is combined with the toxicity of the chemical to determine the Human Toxicity Potential (HTP), used to aggregate and compare emissions.
The authors put great efforts in identifying the different and several sources of model uncertainty, focusing on two model components that have been found to be important among the range of model assumptions in CAlTOX: the steady state assumption for the pollutant transfer by rain from

air to soil, and the modeling of the pollutant concentration in plants.

Rosenbaum et al. [5]
One approach accounting for parameter and model uncertainty is implemented in the LCIA 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. The approach is very transparent, quick to use and it can be easily applied to combine the uncertainty of the emissions inventory with those of the impact assessment phase in a LCA study.

[6] Huijbregts et al.
The authors quantified the variance in toxicity potentials resulting from choices in the modelling procedure in USES-LCA by means of scenario analysis. The choices analysed are: i) time horizon and ii) the decision whether or not to include potential impacts exported from the continental scale to the global scale. In fact box models such as USES-LCA do not account for subcompartimental differences in fate and corresponding effects. Time horizon dependency has been addressed by performing a dynamic calculation by implementing a routine that numerically solves the mass balance equations of the fate part of USES-LCA. Three time horizons have been selected (20, 100 and 500 years) in order to provide a practical range for policy applications. The exclusion of the global scale has been addressed by intervening on the USES-LCA model, by setting the weighting factors for the artic, tropic and moderate zone of the impact categories involved to zero. The results show that time horizon dependent differences can be up to several orders of magnitude for the metal toxicity potential, and that the exclusion of potential impacts on the global scale changed the toxicity potentials of metals and volatile persistent halogenated organics. That means that the value choice of the time and spatial horizon in the LCA impact assessment of toxic substances is an important one.

[7] Huijbregts et al.
This paper presents the results of an uncertainty assessment of toxicity potentials that were calculated with the global nested multi-media fate, exposure and effects model USES-LCA. The variance in toxicity potentials resulting from input parameter uncertainties and human variability was quantified by means of Monte Carlo analysis with Latin Hypercube sampling. Considerable correlations were found between the toxicity potentials of one substance, in particular within one impact category. The uncertainties and correlations reported in the present study may have a significant impact on the outcome of LCA case studies.
In another paper Huijbregts et al (2000) tentatively assessed the impact of model uncertainties on the toxicity potentials by comparing the outcome of the models USES±LCA and USES 1.0. Comparing the results of Huijbregts et al. (2000) this study reveals that uncertainty in model structure is the dominant source of uncertainty in the toxicity potentials of Lead, except for the toxicity potentials after emission to fresh water. In contrast, uncertainty in the toxicity potentials of 2,3,7,8-TCDD and Atrazine, except for the AETPs after emission to the soil compartments, is dominantly caused by parameter uncertainty and human variability. This suggests that the dominant source of uncertainty depends on the nature of the substance under study and on the initial emission compartment chosen.

It is of interest to mention another important approach conducted by Itsubo et al. (2002) on uncertainty of damage function. Unfortunately, a paper in not available but in the abstract presented at SETAC Europe in 2002 he refers to the development of an impact assessment system to be applied in LCIA for Japanese products in LCA National Project of Japan funded by METI and NEDO. This system involves several damage functions that relate inventory data with actual damage of category endpoint. They adopted Monte Carlo simulation to implement uncertainty analysis for several damage functions (the increase of skin cancer and cataract caused by ozone depletion substances) as a trial. Damage functions applied uncertainty analyses in this study belong to marginal approach that estimate the increment of damage caused by additional release of pollutant. To relate inventory with category endpoint in this approach, they need to extract several midpoints and to establish the relationship of each step. Correlations for all of the steps have to be analyzed before the implementations of Monte Carlo simulation. Through this study, they found that the significant steps and parameters could be identified in order to improve the reliability of calculated results as well as the uncertainty of damage functions analyzed in this study could be reduced reasonably.

Main advantages

Hertwich et al. [3], [4]

The framework is helpful in organizing the analysis and identifying significant sources of uncertainty.

The method of comparing different models or decisions allows for the evaluation of the importance of these uncertainties, that can alter the results by several order of magnitude.

Rosenbaum et al. [5]

The presented approach proved to be very transparent, quick to use, and it 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.

Combining uncertainties is a vital step throughout the process of deriving a final overall uncertainty estimate for the model results. It also provides a basis to quickly identify what is causing the highest uncertainty.

Open questions

Hertwich et al. [3], [4]

The analysis of model uncertainties has been only exploratory since these two types of uncertainty are difficult to analyse quantitatively. The importance of model uncertainty must be evaluated with systematic efforts to compare how different model choice has an influence.

Rosenbaum et al. [5]

N.a.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose. See General description.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. In [3] the authors identified the need of a deeper uncertainty analysis, not giving indication on how to perform it but on what issues it should focus: modelling questions concerning metals and speciating organic chemicals, the fate and effect of transformation products, and the modelling of plants. They underline the lack of methods to investigate synergic effects and the need of a framework helpful in organising the analysis and identifying significant sources of uncertainties. <u>Rosenbaum et al. [5]</u> Further research is required to account for the scenario and model uncertainty associated with these effect factor estimates, particularly in the context of estimating toxicological effects at likely low concentrations in the context of complex mixtures at regional scales that are relevant in LCA. In future it will be advantageous to determine relevant probability distributions for input variables on the basis of experimental data in order to obtain more relevant uncertainty intervals. This would provide the possibilities to calculate confidence intervals for model results, which would help decision making because of smaller value ranges compared with the minimum and maximum values (Seppala et al., 2004). Discussion of strategies for identifying model uncertainty that are important contributors to overall uncertainty was limited. In general LCA practitioners should explicit define the types of uncertainty that are included in a study and discuss the reasons for and potential implications of omitting other types of uncertainty [2]. Further analysis is required to comprehensively evaluate the uncertainty of the damage function.
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. No much efforts have been spent on model uncertainty, on the contrary of parameter uncertainty. Most of the studies focus on identifying the source of model uncertainty, but not a defined framework for the analysis is available so far. Still very few studies enclose the results with an analysis on model uncertainty, despite its importance has been recognized by several authors: much efforts should be put on this issue, in order to improve the reliability of studies.

[Phase/Topic/Approach]

Life Cycle Interpretation/Uncertainty/Scenario Uncertainty

1st Part: GENERALITIES

General description

Describe the criteria for the literature selection and the analysed topic/approach(es).
In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.
 	
"Scenario uncertainty" or "Uncertainty due to choice" or "Decision rule uncertainty" reflects that LCA outcomes inherently depend on normative choices [1]. A general overview of sources of uncertainties in the phase of LCA:
- Goal and scope
    o Functional unit
    o System boundaries
- Inventory analysis
    o Allocation, i.e. choice of the procedure to allocate environmental impacts for multi-output processes, multi-waste processes and open-loop recycling
    o Waste handling of long-life products, i.e. choice how to asses future situations
- Impact assessment
    o Number of impact categories
    o Impact definition
    o Time horizon of impacts
    o Spatial horizon of impacts
    o Expected technology trends
 	
The majority of the papers selected tackle uncertainty scenario by means of scenario analysis and often they are more focused on identifying the source of uncertainty than in dealing with them. Where an approach is proposed, the relevance is given not on the approach itself but on the source of uncertainty analysed (e.g. functional unit vs allocation vs etc.).

Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*

1. **General references**
- [1] Huijbregts M., **Part I: a general framework for the analysis of uncertainty and variability in Life Cycle Assessment,** Int. J. LCA 3 (5) 273-280, 1998. - [2] Lloyd S.M., Ries R., **Characterizing, propagating, and analysing uncertainty in Life-Cycle Assessment**, Journal of Industrial Ecology Vol. 11, Issue 1, December 2007, Pages 161-179.
2. **Specific references**
- [3] Huijbregts M., Gilijamse W., Ragas M.J, Reijnders L., **Evaluating uncertainty in environmental life cycle assessment. A case study comparing two insulation options for a dutch one-family dwelling**, Environmental Science and technology, vol. 37, No 11, 2003. - [5] Benetto E., Dujet C., Rousseaux P., **Possibility Theory : a new approach to uncertainty analysis ?**, Int J LCA 11 (2) 114-116, 2006. - [6] Hellweg S., Geisler G., Hungerbühler K., **Uncertainty analysis in life cycle assessment (LCA): case study on plan-protection products and implications for decision making**, Int J LCA 10 (3) 184-192, 2005. - [7] Basson L., Petrie J.G., **An integrated approach for the consideration of uncertainty in decision making supported by life cycle assessment**, Environmental Modelling&Software 22 (2007), 167-176.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. Uncertainties resulting from methodological choices, both in LCI and LCIA, cannot be eliminated but could be addressed by identifying the relevant alternatives and performing sensitivity analysis by scenario modeling, by using cultural theory perspectives and by probabilistic simulation. *Scenario analysis* can show the effect on LCA outcomes of several combinations of choices by identifying the relevant alternatives and performing sensitivity analysis [1]. Scenario modeling show how results vary depending on the methodological choices, but do not allow evaluating belief-related uncertainties of each. *Cultural theory perspectives* are fixed and it is sometimes difficult to relate them to the practitioner's belief in specific choices. *Probabilistic simulation* is a detailed approach and it is considered a possible way to evaluate belief-related uncertainties affecting LCA results. Probability theory is well suited to represent precise results of mutually exclusive (independent) events. The uncertainty on the trueness of LCI emissions depends on belief in the methodological choices behind their calculation and the interdependency of such events is more difficult to be proven. <u>[3] Huijbregts M et al.</u> The authors proposed a methodology that quantifies parameter, model and scenario uncertainty simultaneously. Parameter uncertainty was quantified by means of Monte Carlo simulation; scenario and model uncertainty by resampling different decision scenarios and model formulations. The procedure developed to quantify scenario uncertainty foresees the identification of the potential sources of scenario uncertainty, and then a non

parametric bootstrapping procedure is proposed to quantify the resulting output uncertainty. First, for each normative choice two or more alternatives are formulated; second, a probability is assigned to each alternative, reflecting the preference of the decision maker for this alternative. For each normative choice, the sum of probabilities assigned to the various alternatives must equal 1. Finally, per bootstrap iteration, an alternative is chosen randomly for each normative choice, based on the defined probabilities for the various alternatives. The resulting output distribution reflects the uncertainty of the decision-maker regarding the normative choices involved. The results show the overall uncertainty, based on the combination of the three uncertainties.

The proposed approach derived from (Huijbregts, 1998, Part II) in which the author evaluated parameter and scenario uncertainty at the same time by using the Latin Hypercube sampling in the matrix method, and the scenario analysis respectively. Furthermore, he couples the uncertainty analysis with an uncertainty importance analysis, which verifies the parameters that introduce the largest uncertainty in model outcomes. The author suggested also a procedure in order to decrease the number of choice combinations in LCA case studies: i) formulate several options for every LCA choice; ii) find the two "extreme" options for every choice"; iii) construct two "extreme" combinations of options and compute the effect of the two combinations on the LCA outcomes

[5] Benetto et al.

The authors describe a tentative possibilistic approach based on the evaluation of a posteriori possibilities of final LCA results depending on a priori possibilities of the methodological choices behind the calculations. The method proposed is in complement of classical methods of uncertainty analysis.

The need for invoking a complementary approach could exist due to the axiomatic limitations of probabilities in belief-related calculations and uncertainties.

Possibilities measures: given the non-additivity of measures on a union of non-intersected events, a possibility distribution y = r(x) on (X,Y)(usually Yε [0;1]) looks like a probability one, but any addition in probability theory can be replaced, in possibility theory, by a maximum and any product by a minimum (Dubois et al. 1988). Also, two dual measures (instead of one) are considered to represent the belief: possibility (Pos) and necessity (Nec). Pos equals the maximum of the possibility distribution, i.e. Pos = max[r(x)] and Nec = 1-max[1-r(x)].

The rules of Pos calculation state that, in order to obtain the union of two events, it is enough to obtain the simpler between the two, that is coherent with the meaning of 'possible'. Also, the axiomatic defines that, if an event is certain, then it is also necessarily true and an event is necessary when the opposite is impossible. Two measures (Pos and Nec), instead of only one (probability), are supposed to be more informative about the belief, for the interpretation of results and for decision-making. Nevertheless, the elicitation of possibility values from practitioner knowledge could be difficult due to the novelty of the axiomatic. To simplify the elicitation, subjective probability density functions can be considered to represent a practitioner's belief in methodological choices and then transformed in possibility distributions for calculation (e.g. Geer et al. 1992). Actually, representing beliefs by means of subjective probabilities is fully pertinent, only their aggregation and propagation present the aforementioned limitations.

[6] Hellweg S et al

They assessed parameter and scenario uncertainty comparing two plan-protection products: parameter uncertainty by means of Monte Carlo simulation, and scenario uncertainty by calculating one Monte Carlo simulation for each scenario.
Also that it is impossible to fully predict uncertainty in LCA results without conducting a quantitative uncertainty analysis, the authors proposed a rule of thumb method to evaluate significance of LCA results. To this end, they considered inherent characteristics of impact categories influencing uncertainty in impact scores. The results suggest that a median quotient of impact scores larger than two may be considered on the safe side of being significant, concerning the impact categories global warming, acidification, eutrophication and photo-oxidant creation. This rule of thumb is supported by the similar inherent characteristics of these impact categories regarding uncertainty . Case study results exhibiting smaller differences should be evaluated for significance with a full uncertainty analysis. Regarding toxicity impact-categories, no rule of thumb is proposed, because large dispersion factors of individual parameters cause highly varying uncertainty in individual toxicity impact-scores. A detailed uncertainty analysis seems indispensable for reliable decision support concerning toxicity impacts assessed by the CML-baseline method We conclude that in the absence of better data, the rule of thumb may be used in LCA if a full uncertainty analysis is out of the scope of the study. The authors think that this rule of thumb is a more qualified value than common expert judgment, as it is based on a thorough uncertainty analysis. It should be born in mind, however, that the rule of thumb proposed here has not been verified for products with very different life-cycles yet (e.g. mechanical compared to chemical weed control). Moreover, for toxicity categories they are not able to propose a rule of thumb. Probably few case studies will actually have significant results in these categories due to the high uncertainties of characterization factors and sum parameters. In order to enable a meaningful application of toxicity impact categories in LCA, these uncertainties need to be reduced in future research.

<u>[7] Basson L et al.</u>
This paper presents a comprehensive and efficient approach for the integrated consideration of both technical and valuation uncertainties (uncertainties that affect the estimation of the potential consequences of the activities under consideration and those that pertain to uncertainties in variables which are used for the evaluation of these consequences) during decision making supported by LCA-based environmental performance information. The approach is illustrated in the context of a technology selection decision for the recommissioning of a coal-based power station. Key elements of this approach include ‘‘<u>distinguishability analysis</u>’’ to determine whether the uncertainty in the performance information is likely to make it impossible to distinguish between the activities under consideration; and the use of a multivariate statistical analysis approach, called <u>principal components analysis (PCA)</u>, which facilitates the rapid analysis of large numbers of parallel sets of results, and enables the identification of choices that lead to similar and/or opposite evaluations of activities. The results of the case study decision suggest that stakeholder involvement in preference modelling is important, and that the ‘‘encoding’’ of value judgements and preferences into LCA environmental performance information is to be avoided. The integrated approach presented for the consideration of uncertainty in decision making has been developed to be used in conjunction with an approach to decision support based on multiple criteria decision analysis (MCDA).
Three different strategies are used in the proposed integrated approach for the consideration of uncertainty in decision making:
(a) placing appropriate bounds on particular aspects, (b) ensuring that the quality of information is such that the alternatives are ‘‘adequately distinguishable’’ from one another before commencing with detailed preference modelling (i.e. performing ‘‘distinguishability analysis’’), and (c) propagating technical uncertainties and performing sensitivity analyses for valuation uncertainties.

Main advantages
[3] Huijbregts M et al. With this approach the different types of uncertainty are treated simultaneously, and the methodology helps to identify the most important sources of uncertainty. The analysis indicates the great influence of scenario and model uncertainty, although they were not quantified comprehensively. The results of the case study are not generalizable to other problems and applications. It seems that parameter uncertainty is the main type of uncertainty and that model and scenario are only of minor importance, but the case study results strongly depend on the case study setting. [5] Benetto et al. The approach is time and resources consuming, as Monte Carlo simulation is, but could be worth applied in specific situations when stakes are high and it is difficult to make methodological choices. The conclusion is that possibility theory seems to offer pertinent principles to model a practitioner's belief in LCA results, i.e. uncertainties due to methodological choices. Probability theory can be better suited to model uncertainties on the values of LCA results. The two formalisms complement each other and could be considered simultaneously. [6] Hellweg S et al The proposed rule of thumb for scenario uncertainty is a more qualified value than common expert judgment, as it is based on a thorough uncertainty analysis. Analysis of choice and model uncertainty is important to guide LCA research and model development [7] Basson L et al. The approach presented in this paper provides a foundation for the consideration of the implications of diversity in values and preferences as part of an overall approach to promote effective decision making based on LCA environmental performance information. However, the approach is more universally applicable and it can be used wherever multiple criteria decision analysis is used to assist in the resolution of complex decision situations.
Open questions
[3] Huijbregts M et al. Scenario and model uncertainty were not quantified comprehensively. The authors suggest the following improvements in the application of the methodology: the development of a life cycle inventory database with spatial and uncertainty information; the further development of spatial and temporal explicit impact assessment models for a more systematic analysis of scenario and model uncertainty.

[5] Benetto et al.
N.a.

[6] Hellweg S et al
The rule of thumb proposed has not been verified for products with very different life-cycles yet (e.g. mechanical compared to chemical weed control). Moreover, for toxicity categories a rule of thumb does not apply.

[7] Basson L et al.
N.a.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach.

[1] Huijbregts M
Crystal Ball has been used in performing sensitivity analysis, Monte Carlo simulation and bootstrapping. The software is also equipped with a tool which calculates the uncertainty importance of each parameter by computing rank correlation coefficients between every parameter uncertainty and every model outcome during the simulation.

[7] Basson L et al.
The approach for the consideration of uncertainty requires the capacity to propagate uncertainties through models using random sampling techniques (i.e. Monte Carlo simulation) and to perform principal components analysis (PCA). This can be done in an Excel spreadsheet environment using e.g. Crystal Ball (www.crystalball.com) or @Risk (www.palisade.com) (for Monte Carlo simulation), and a combination of Data Analysis and Matrix and Linear Algebra add-ins. However, several stand-alone software packages provide the necessary functionality.

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

[3] Huijbregts M et al.
The scenario uncertainty addressed concerned the allocation of environmental burdens in recycling processes, future waste scenarios and the timing, geographical scale and definition of environmental impacts.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. Few case studies will actually have significant results in these categories due to the high uncertainties of characterization factors and sum parameters. In order to enable a meaningful application of toxicity impact categories in LCA, these uncertainties need to be reduced in future research. A large variety of choices and sources of model uncertainty are less accessible to quantitative analysis. It is suggested that only choice and model uncertainty of specific interest for goals and scopes of case studies be modeled quantitatively. Choices and model uncertainty generally applying to LCA should be made transparent to decision makers in a more simple manner. This enables decision makers to explicitly accept choices and models employed as being an adequate basis for decision support [7]
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed. The majority of the papers selected tackle uncertainty scenario by means of scenario analysis and often they are more focused on identifying the source of uncertainty than in dealing with them. Where an approach is proposed, the relevance is given not on the approach itself but on the kind of source of uncertainty analysed (e.g. functional unit vs allocation vs etc.): quantitative evaluations are still rare. The approaches analysed could add significant sophistication to calculations; however quantitative approach to scenario uncertainty are not such a common practice.

Interpretation/Data Quality Assessment

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* There are two types of uncertainty on data: the basic uncertainty (typically measurement errors and normal fluctuations of the measured variable) and additional uncertainty [4]. Data Quality Assessment passes through two types of approaches: a "qualitative indicators" method and a "probability distribution function" method. Here the focus is on the first method; other sheets deal with the different statistical methods of uncertainty assessment. The survey report [1] in General References includes all relevant arguments of this topic and bibliography up to 1998. The overview intends to "illustrate the mainstream of the ongoing process" through a critical analysis of the development of data quality assessment models. The other two reviews are more recent and deal with the different aspects of uncertainty analysis and reliability of LCA. In Specific References the basic approach of the DQI Pedigree Matrix of Weidema has been considered and also some case studies, with different DQIs sets and applications.
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
1. Van den Berg N. W., Huppes G., Lindeijer E. W., van der Ven B.L., Wrisberg M.N., Quality Assessment for LCA, CML Report no.152, (1999)
2. Björklund, A.E., Survey of approaches to improve reliability in LCA, Int. J. LCA, Vol. 7, no.2, pp.64-72 (2002)
3. Lloyd, S.M and al. Characterizing, Propagating and Analysing uncertainty in Life-Cycle Assessment, J. of Ind. Ec. Vol.11, no. 1 pp. 161-179 (2007)
2. Specific references
4. Weidema B.P., Wesnaes M.S., Data quality management for life cycle inventories-an example of using data quality indicators, J. of Cleaner Production, Vol. 4, No. 3-4, pp. 177-174 (1996) 5. Weidema B.P., Multi-User Test of the Data Quality Matrix for Product Life Cycle Inventory Data, Int. J. of Life Cycle Assessment, Vol. 3, No. 5, pp. 259-265 (1998) 6. Maurice B., R. Frischknecht, V. Coelho-Schwirtz and K. Hungerbühler, Uncertainty analysis in life cycle inventory. Application to the production of electricity with French coal power plants, J. of Cleaner Production, Vol. 8, No.2, pp. 95-108 (2000)

7. Rousseaux, P., Labouze E., Suh Y-J., Blanc, I., Gaveglia, V., Navarro, A., An Overall Assessment of Life Cycle Inventory Quality. Application to the Production of Polyethylene Bottles, Int. J. of Life Cycle Assessment, Vol. 6, No.5, pp. 299-306 (2001)
8. May, J.R., Brennan, D.J., Application of data quality assessment methods to an LCA of electricity generation, Int. J. of Life Cycle Assessment, Vol. 8, No.4, pp. 215-225 (2003)
9. Lewandowska A., Foltynowicz Z., Podlesny A., Comparative LCA of Industrial Objects: Part 1: LCA Data Quality Assurance - Sensitivity Analysis and Pedigree Matrix, Int. J. of Life Cycle Assessment, Vol. 9, No.2, pp.86-89 (2004)

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

Including uncertainty information into LCA adds reliability to the LCA studies. Two main approaches can be identified: the use of data quality indicators and the use of statistical measures of dispersion [1]. The use of both of them is suggested to evaluate uncertainty in LCI.
A qualitative indicator method consists of defining the attributes of the data in question and assigning a score to them. To do this, a Pedigree Matrix must be defined, where each row corresponds to an attribute of the data and each column to a score ranging from good to poor. The DQIs represent data quality and are used to manage data quality and identify sources of data uncertainty (see for example [6]). Different sets have been proposed through the case studies and different uses of the scores can be recorded. Sometimes DQIs are aggregated [6] or translated into distributions for propagating uncertainty [7, 8, 9].

Main advantages

An advantage of using DQIs is the possibility to capture uncertainty-related information that is difficult to quantify. The data quality assessment through DQI matrix has an irreducible amount of subjectivity (scoring cannot be seen as objective). Nevertheless it does not compromise the utility of the method for data quality management and communication of data quality in a simple way.

Open questions

The validity of DQIs aggregation and of translating DQIs into distributions for propagating uncertainty is under discussion. In the first case it was observed that the score does not represent an ‘amount’ of data quality (e.g. a score of 4 for an indicator is not necessarily twice as problematic as a score of 2) [5]. Several authors say that caution should be paid when numerical and qualitative uncertainties are combined. In [8] two different methods of combining uncertainty have been compared and the conclusions highlight the following points: the methods produced very different results; there was no evidence that either approach produced results that were more accurate, or more representative of qualitative uncertainty, than the other; it could not be demonstrated that either method produced a measure of uncertainty that was more relevant than that of the numerical uncertainty method alone. Other authors are more positive on the use of these methods.

Practicability aspects

Practicability aspects refer to the availability of tool and data in order to implement the analysed approach. A LCA data documentation format according to ISO 14048 makes it practicable to classify data in a Pedigree Matrix, even if with a certain amount of subjectivity. However in [3] it was observed that, if DQIs are used to evaluate the so called 'additional uncertainty', expert judgment is required and in this case it may be easier for experts to identify ranges of foreseeable values rather than more abstract DQIs.
Application fields
Describe the sector of application of the peoposed approach (if relevant) and the purpose. The sector of application is not relevant.

3rd Part: COMMENTS

R&D needs and trends
In [6] a generalisation of the uncertainty assessment on the basis of the experiences gained, including the use of DQIs, is recommended. Moreover the authors highlight that a simplified method for a reliable uncertainty assessment should be developed in order to use LCA in early phases of product development. The need of simplifications to reduce the need for detailed analysis of each datum and the time required for data quality analysis is also stressed in [8].
Comments
Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

CROSS ISSUES

LCC

SLCA

SIMPLIFIED LCA

[Economic Aspects]

LCC

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* There are economic methods that can be used that include environmental effects as well, such as cost–benefit analysis, or CBA. However, there are several characteristics with these methods that make them less suitable for a combination with LCA. CBA aims to cover all positive and negative impacts from a policy or project in monetary terms. It is thus a very ambitious method, but it also lacks in transparency, as the result is a single figure: whether the policy or project is a net benefit or a net cost to the system studied. The aggregation of data in a CBA is normally only done with monetary terms, which can be problematic to combine with the system extensions often used in LCAs. A strict CBA could be seen as an overlapping method to LCA, but a CBA could also be "modified" and made to fit an LCA, and one such example would be the welfare economic analysis. However, in order to avoid too much overlapping of method descriptions and to keep the meaning of the term CBA where it usually is used, i.e. strictly economic analyses, the term CBA is for the purpose of this paper used only in its stricter sense. Another common economic method is cost–effectiveness analysis, or CEA. This is usually a more narrow method than CBA. CEA aims to determine the least cost option of a predetermined target. Thus, there is no need to measure benefits or compare and weight different benefits and costs, as this trade-off is already defined before a CEA is performed. A CEA is therefore a more narrow method than required, as it does not have any specific tools for multidimensional analysis. Therefore, a method that combines the formalised framework of LCA with economic theory is needed. (2) Life-cycle costing (LCC) is a tool to assess the cost of a product over its entire life cycle, and can be regarded as an economic counterpart of LCA. A combined use of LCA and LCC would be imperative for assessing the sustainability of a product or product systems in the economy. However excellent a product is with regard to environmental load, however, its wide introduction into the economy would not follow unless it is also economically affordable. Without a wide-ranging introduction into the economy, its potential to reduce environmental load remains unexploited. (7)
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
2. Specific references

1. Assefa G., O. Eriksson and B. Frostell, Technology assessment of thermal treatment technologies using ORWARE, Energy Conversion and Management, Vol. 46, 2005, pp 797-819
2. Carlson Reich, M., Economic assessment of municipal waste management systems - case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC), Journal of Cleaner Production, Vol. 13, 2005, pp 253-263
3. Ekvall T, Assefa G, Björklund A, Eriksson O, Finnveden G, What life-cycle assessment does and does not do in assessments of waste management, Waste Management, Vol. 27, 2007, pp 989-996
4. Hondo Hiroki, Moriizumi Yue, Sakao Tomohiko, A Method for Technology Selection Considering Environmental and Socio-Economic Impacts, International Journal of LCA, Vol. 11 (6), 2006, pp 383-393
5. Raadal HL, Cecilia Askham-Nyland, Ole Jørgen Hanssen, Life Cycle Assessment (LCA) and Socio-Economic Cost Benefit Analyses based on LCA for Treatment of Plastic Packaging Waste, International Journal of Life Cycle Assessment, Online First, 2007
6. Nakamura S., Kondo Y., A waste input–output life-cycle cost analysis of the recycling of end-of-life electrical home appliances, Ecological Economics Vol 57, pp 494–506, 2006
7. Ciroth, A. et al. Environmental Life Cycle Costing. Edited by Hunkeler, D.; Lichtenvort, K.; Rebitzer, G. SETAC book, draft in press
8. Rebitzer, G.; Seuring, S. Methodology and Application of Life Cycle Costing. Int J LCA 8 (2) 110-111 (2003)
9. Hunkeler, D. (2006). Societal LCA Methodology and Case Study. International Journal of Life Cycle Assessment, 11, 6, 371-382.

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. Environmental Life Cycle Costing (LCC) differs from conventional Life Cycle Costing because of the following main elements: product system modelled, system boundaries, actors involved, reference unit, cost categories and cost model. A sound survey on environmental LCC has been performed by (7), as a result of the activity performed by the SETAC Working Group on Life Cycle Costing. The authors define LCC as a technique that considers "[…] all costs associated with the life cycle of a product that are directly covered by one or more actors in that life cycle […]. Externalities that are expected to be internalised in the decision-relevant future comprise real money flows as well, and they must also be included". One of the main features of LCC is that it shares the same LCA structure, i.e. they have equivalent system boundaries and functional units, because they are built upon the same product system providing the same function, and have a steady-state nature. Indeed, the framework developed can be easily linked together with an LCA, without generating overlaps, because impact assessment indicators deriving from LCA are not translated into monetary terms but are kept separate. The work performed by (7), whose publication is forthcoming, represents a fundamental step in the LCC development, since it addresses the question of how costs and environmental aspects can be combined and provides a clear guidance for performing LCC studies. The approach, which represents the evolution and the completion of those presented by the same authors like (8) and (9), just to mention some, contributes to the

development of a code of practice for LCC and leads to a potential standardisation in analogy to ISO 14040 series.
Not all previous works are aligned to this statement, starting from a different use of the terminology. For example, Reich (2005) proposed a terminology and methodology for the economic assessment of municipal waste management systems, which include financial LCC, life cycle costing (which is used in parallel with an LCA) and environmental LCC. The last is intended as the weighting of environmental impacts of an LCA system in monetary terms; in particular, it makes use of three different weighting methods to monetarise environmental effects such as emissions and resources. The results from financial LCC and environmental LCC are thus combined in order to provide an economic methodology useful to make environmental aspects directly comparable to the economy of the studied options. This approach has been tested through a case study, by using the ORWARE model (1). Some open questions emerged, in particular with reference to comprehensiveness and consistency in both theory (how to deal with timing of emissions and economic activities, and system boundaries) and data, together with a difficulty in communicating results to the actors of the waste management sector.
A different approach has been proposed by (6): they developed a hybrid LCC methodology, called WIO price model, which builds upon the hybrid method of LCA based on WIO (Kondo & Nakamura, 2004; 2005), and illustrated it by a case study of electrical home appliance under alternative end-of-life scenarios.

Beyond conventional and environmental LCC, also societal LCC should be mentioned, introduced by (7) as the third type of LCC. Societal LCC takes a society perspective, and includes all of the environmental LCC plus additional assessment of further external costs: it means that it should include the monetisation of externalities. The use of "should" is mandatory as the identification and quantification of externalities is strongly affected by high uncertainties, and thus their inclusion represents a great challenge for the methodological development. The approach is still under development, and it is suggested to deepen its relation with SLCA: indeed, as societal LCC is used to quantify environmental effects on society in monetary terms, it is considered an important ingredient for performing "sustainability" evaluation.
But social aspects are not simply a quantification of environmental effects on society in monetary terms: more complexities exist, more interrelations that need to be accounted for. Perhaps, the possibility of finding a point of contact between two approaches should be investigated, in order to avoid spending too much efforts in developing methodologies that could have a limited application.

Main advantages

Due to dynamic socio-economic conditions, it is not always feasible or not necessarily optimal to introduce only a technology that is best evaluated with conventional LCA. It is likely that the minimization of environmental burden on a social scale requires the mix of two or more technologies including those that are inferior based on the conventional LCA results. This implies that the conventional LCA methodology may lead to potentially misleading results when examining the technology selection for the long-term reduction of environmental burden on a social scale. The conventional LCA methodology assesses which technology is superior or inferior based on a functional unit. Although such an assessment is useful information to some extent, real policymaking often requires information on the role that each technology can play to reduce the environmental burden on a social scale under various socio-economic conditions. The newly developed methodology can determine the optimal mix of technologies over time. (4)

Open questions
Several of the possible additions to LCA methodology require different types of economic data in addition to technological and environmental data. This means that economists ought to be involved in the study. Otherwise, the risk for mistakes increases. The data required to model the additional aspects are also often associated with a high degree of uncertainty. As a result, the uncertainty in the results of the study increases. (3) Furthermore, there have been some attempts to integrate the economic and environmental aspects; for example, the monetary valuation of environmental externalities across the entire life cycle of a technology/product. These studies address the impact of a technology/product from both environmental and socio-economic viewpoints, while not considering temporal information sufficiently. (4)
Practicability aspects
Practicability aspects refer to the availability of tool and data in order to implement the analysed approach The ORWARE tool carries with it the concepts of systems analysis, material flow analysis (MFA), substance flow analysis (SFA), life cycle assessment (LCA) and life cycle cost (LCC). (1)
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose.

3rd Part: COMMENTS

R&D needs and trends
Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends. Economic methodology may provide a useful tool for tweighting, a tool that also may make environmental aspects directly comparable to the economy of the studied options. Further research should be directed into the possibility of elaborating a consistent methodology for the entire chain of economic assessment of LCA systems. The inconsistencies that need to be overcome are mainly concerning the timing of emissions and economic activities, and concerning system boundaries. As basically all LCA results sooner or later are compared to economic results in a decision process, guidelines for this step of LCA interpretation could be relevant, for example, the ISO 14000 series. (2) The decision-making with regard to the selection of a technology/product for addressing environmental issues often requires a methodology to explicitly and simultaneously deal with three points that are usually ignored by the conventional LCA: 1) consideration of socio-economic aspects, 2) introduction of time as a parameter, and 3) treatment of the impact on a social scale. (4)
Comments
Comments of the person who fill in the scheme in order to understand the “importance” of the approach analysed.

[Phase/Topic/Approach]
LCS

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approach(es). *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* The development of a Social Life Cycle Assessment (SLCA) that includes the assessment of social aspects related to the life cycle of a product can give a contribution to the interpretation of its sustainability by stakeholders and decision makers. Even if in its infancy, SLCA is object of an increasing number of published papers, thus demonstrating the existing interest about the methodology and its application. Recently a comprehensive review has been published (Jørgensen et al., 2008), where the existing methodology and proposals are presented and discussed. The methodological framework adopted, based on the ISO-LCA structure, was proposed by the taskforce "Integration of social aspects in LCA", nominated in the context of the UNEP-SETAC Life Cycle Initiative (Grießhammer et al., 2006).
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
- (1) Grießhammer, R., C. Benoît, L.C. Dreyer, A. Flysjö, A. Manhart, B. Mazijn, A.-L. Méthot & B.P. Weidema (2006). Feasibility Study: Integration of social aspects into LCA.
2. Specific references
- (2) Dreyer, Louise; Hauschild, Michael; Schierbeck, Jens (2006). A Framework for Social Life Cycle Impact Assessment. International Journal of Life Cycle Assessment, 11, 2, 88-97.
- (3) Norris, Gregory A. (2006). Social Impacts in Product Life Cycles - Towards Life Cycle Attribute Assessment. International Journal of Life Cycle Assessment, 11, Special Issue 1, 97-104.
- (4) Weidema, Bo Pedersen (2006). The Integration of Economic and Social Aspects in Life Cycle Impact Assessment. International Journal of Life Cycle Assessment, 11, Special Issue 1, 89-96. - (5) Jørgensen A., Le Bocq A., Nazarkina l., Hauschild M., (2008). Methodologies for Social Life Cycle Assessment, International Journal of Life Cycle Assessment, 8, (Online First), 1-8. - (6) Hunkeler, D. (2006). Societal LCA Methodology and Case Study. International Journal of Life Cycle Assessment, 11, 6, 371-382.

2nd Part: ANALYSIS

Rationale

Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc.

In the context of the document "Integration of social aspects in LCA" mentioned above, several aspects have been discussed, both related to the methodology and to the **scope of the analysis**. The first aspect under discussion is if social impacts are related to processes or to the conduct of companies carrying out those processes, as (2) suggest. In this latter case, where the causal link is different than the one of an environmental LCA, more problems of allocation arise, which introduce bias in the assessment. To face them under this approach, (2) propose that the allocation principle should reflect the company's importance in the overall life cycle and could be based on:

i) value creation, which would require that monetary input and output for each company or for each life cycle stage be used;
ii) number of hours spent at the company for functional unit;
iii) material costs and product price for the company in the product chain.

The definition of the **system boundaries** in SLCA is also matter of discussion in the scientific community. Some authors point out that the choice depends on the goal of the study: if the focus is on product comparison, a full assessment is necessary; for supporting management decisions it could be enough to include only those part of the life cycle which can be directly influenced by the company. In (2) some general criteria for setting system boundaries are presented and discussed. If compliance with ISO 14044 is recommended, as in Weidema (2005), exclusion of life cycle stages indeed should be accepted only if it does not significantly change the overall results of the study.

Another important aspect to consider is the **selection of indicators**. A good indicator, in agrement with (4), allows 'quantification of the extent, the duration and the severity of the considered aspect'. Some SLCA approaches use inventory results, other midpoints or endpoint indicators: attempts of separating them are often confused and in some cases it is difficult to express the cause–effect relationship between midpoint and endpoint. Which type of indicators to use is under discussion: endpoint indicators have the advantage that no subjective weighting is needed, but require the impact pathway be known; midpoint indicators are closer to the activities and for this reason more understandable for decision-makers. The UNEP-SETAC task force recommends to combine inventory, midpoint and endpoint indicators, starting with the first two types of indicators and thinking about adding the third ones later on. They also stress the need for well discussed indicators and indicator-sets for SLCA (1).

Two types of questions have been raised concerning **formulation of indicators** (Jørgensen et al., 2008):

- should indicators be formulated in quantitative, semi-quantitative (scoring systems) or qualitative terms?
- should the indicators measure the impact directly or based on indirect indication/proxy measurements?

The latter aspect relates to the problem that sometimes the direct measurement does not reflect the actual problem (see for example (2) or to the problem of data availability. For the first question, the UNEP-SETAC task force suggests a combination of quantitative, semi-quantitative and qualitative indicators in order to produce the most accurate and relevant assessment possible.

Some **example of social indicators** proposed for SLCA studies are here given.

- (6) suggested the use of a methodology, which focuses on the work hours required to meet basic needs, transforming the life cycle inventory into labour units, a unique indicator that can be used to compare different solutions.
- (3) proposed the use of human health as indicator of socio-economic status: he suggested that they are directly linked as the grown in well-being is followed by a grown in the economy and used the Eco Indicator 99 methodology to evaluate health impacts in terms of life years lost, measured in disability-adjusted life-years (DALYs).
- (4) proposed the QALY (Quality Adjusted Life Years) indicator, deriving from aspects linked to the human life intrinsic values like: life and longevity; health; autonomy; safety, security and tranquillity; equal opportunities; participation and influence. This last procedure measures the well-being in a single value that could be compared to the monetary index of other procedures like for example Cost Benefit Analysis or Life Cycle Costing.
- (2) observed that there are two layers of SLCA, a mandatory one, driven by normative, and an optional one, that respects specific interests. They focussed their work on the development of a methodology for the mandatory part of the SLCA, which includes the minimum expectations for a social responsible company.

Besides the selection of indicators, another challenging aspect of SLCA is **data collection**. Some authors claim that the use of generic process data, as in environmental LCA, is irrelevant because social impacts have to deal with the behaviour of each company (2). However, using generic data can give an estimate for a certain number of social impacts, while collecting site-specific data is a very demanding task and guidelines on monitoring approaches would be necessary. In general, a problem of data availability and reliability exists. It seems that further discussion and case studies are needed in order to reach a common position on this subject and develop agreed guidelines.
The impact assessment phase of SLCA can be analysed following the steps of ISO 14044 for environmental LCA. In the classification step the indicators are arranged in impact categories, but also another type of classification, the ‘stakeholder approach’, has been proposed. The UNEP-SETAC task force has agreed that the two approaches are not incompatible and that four main stakeholder categories can be identified: workforce, local community, consumers (for the use stage), society (national and/or global). The review of (5) presents a certain number of approaches to the characterisation of social indicators, but concludes that the trend seems more oriented towards simplification of inventory results than towards a characterisation in line with the environmental LCA methodology.

Several authors suggest normalisation and valuation in SLCA, but very little work has been done on this subject (5).

The UNEP-SETAC task force has also pointed out some aspects of the interpretation phase of SLCA. It should include checks of completeness and consistency, but also on the relevance of information provided and on the engagement of stakeholders. Moreover, they consider that the process of evaluation of SLCA is fundamentally subjective, so that a plurality of evaluation and of weighting methods can be accepted.
The conclusions of the feasibility study (1) are topical issues up to now and can be summarised in the necessity of:
a) conducting case studies with the key elements that have been discussed above in order to find a solution to the numerous open questions and
b) composing a ‘Code of Practice’ for SLCA.

Main advantages
The integration of stakeholders bases the indicators and judgments on a broader discussion and helps to collect data. (1) Social LCA should embrace a broader understanding of human life, encompassing the value of a good and decent life, to be able to truly consider social impacts and damage to people. (2) In addition, it may also make LCA a more interesting and relevant tool for companies in developing economies by supporting inclusion of the beneficial sides of economic development, where Environmental LCA focuses on the damages which the development typically causes to the environment. (2)
Open questions
Practicability aspects
Practicability aspects refer to the availability of tool and data in order to implement the analysed approach. See rationale.
Application fields
Describe the sector of application of the proposed approach (if relevant) and the purpose.

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

Social impacts or benefits on the consumer should be described as part of the product utility. Social impacts on the society correspond with common or internationally accepted values and should be described as other social impacts along the life cycle. (1)
To carry out SLCA (Social LCA) studies, it would be useful to have a universal set of indicator classified after stakeholder groups and impact categories. Indicators can then be selected that are appropriate to the study's goal and to the capacity available. (1)
The evaluation of the Social Assessment is performed within a setting determined by actor-specific and individual interests and values, and is thus fundamentally subjective. For this reason alone there must be a plurality of evaluation and of weighting methods. (1)
It is quite probable that the very different appraisals of social aspects by different actors and in different countries, in combination with the process of interdisciplinary scientific discourse, will delay agreement for a longer time. For the further development process, there is an urgent need to carry out more case studies, improve the data situation, and create first module of datasets whether or not they are of input-output types. (1)
What is conceived as damaging or beneficial for the human dignity and well-being in a society is also influenced by its culture, and political and socio-economic stage of development. (2)
Further work with the establishment of local and country norms is necessary for Social LCA to give a covering image of the social impacts through use in business decision-making and to help it to reflect impacts which raise living standard in some parts of the world and thereby promote human dignity and well-being. (2)

See also rationale.

Comments

Comments of the person who fill in the scheme in order to understand the "importance" of the approach analysed.

[Phase/Topic/Approach]

LCI/Simplification/

1st Part: GENERALITIES

General description
Describe the criteria for the literature selection and the analysed topic/approaches. *In the topic description, also deviations/development with respect to ISO standard should be reported if relevant.* In [1] different approaches for LCI are described. LCA can be of two types: detailed LCA and simplified (or streamlined) LCA. The main approaches of LCI simplification are three: direct simplification of process-oriented modelling; LCA based on economic input/output analysis; hybrid method. The topic here analysed focus on the first approach. The literature review refers to selected papers published after 2000. A simplified LCA is conducted not in full compliance with the ISO standards [3].
Relevant references *The relevant references should be organised along two lines:* - *General references (related to the topic addressed)* - *Specific references (related to the approach analysed)* *In this case, the list of references is not in its final version*
1. General references
1. Rebitzer G. et al. Life cycle assessment Part 1:Framework, goal and scope definition, inventory analysis, and applications, Env. Int. vol.30, pp. 701-720 (2004)
2. Specific references
2. Fleischer G; Karin Gerner; Heiko Kunst; Kerstin Lichtenvort; Gerald Rebitzer, A Semi-Quantitative Method for the Impact Assessment of Emissions Within a Simplified Life Cycle Assessment, Int. J. LCA, Vol.6, no.3, pp.149-156 (2001)
3. Hoschorner E, Finnveden G, Evaluation of Two Simplified Life Cycle Assessment Methods, Int. J. LCA, Vol. 8, no.3, pp. 119-128 (2003)
4. Mueller Karl; Lampérth Michael U.; Kimura Fumihiko, Parameterised Inventories for Life Cycle Assessment - Systematically Relating Design Parameters to the Life Cycle Inventory, Int. J. LCA, Vol. 9, no.4, pp. 227-235 (2004)
5. Park Pil-Ju; Lee Kun-Mo; Wimmer Wolfgang, Development of an Environmental Assessment Method for Consumer Electronics by combining Top-down and Bottom-up Approaches, Int. J. LCA, Vol.11, no.4, pp.254-264 (2006)
6. Rydh CJ, Mingbo Sun, Life cycle inventory data for materials grouped according to environmental and material properties, J. of Cleaner Production, Vol. 13, no.13-14, pp. 1258-1268 (2005)
7. Hur T, Jiyong Lee, Jiyeon Ryu and Eunsun Kwon, Simplified LCA and matrix methods in identifying the environmental aspects of a product system , Journal of Environmental Management, Vol.75, no. 3, pp.229-237 (2005)

2nd Part: ANALYSIS

Rationale
Describe the key principle of the approach analysed. Why the approach is implemented, which needs the author addresses, etc. The need for using simplified methods comes from considering that LCA can be time and resources consuming. Moreover early in the product design only a limited amount of information is available and it is difficult to assess the potential environmental impacts under these conditions [6]. The answer to these problems is on simplified LCA and on life cycle thinking approaches. We can distinguish three different types of approaches: qualitative (e.g. MET-Materials Energy and Toxicity- matrix, checklists [5], ABC hot spot screening, expert panels [1]); semi-quantitative (e.g. ERPA – Environmentally responsible product assessment- matrix [7], MECO chart [3], ABC/XYZ assessment [2], Environment-Failure Mode Effect Analysis [1]) and quantitative. A quantitative simplified LCA is obtained reducing the scope of the study/excluding some phases of the system (horizontal cut-off) and/or reducing data needs (vertical cut) through the use of surrogates, which can be already available, or generic databases for one or more steps of the life cycle [7]. In [1] a preference to the vertical cut is given, considering the horizontal cuts arbitrary and depending on the single application. The identification of relevant stages and stressors, for which primary data have to be collected, requires a screening step before a simplified inventory. The screening can use the above mentioned qualitative and semi-quantitative methods or other quantitative approaches (I/O LCA, calculation of the cumulative energy demand, assessment of single key substances)[1]. The choice between different methods depends on the intended application. If the use in ecodesign is taken into account, three applications can be identified: eco-redesign, new design/eco-innovation and ecological system innovation. If quantitative simplified methods are compared with the semi-quantitative ERPA matrix [7], it has been observed that the former are more suitable for new design and eco-innovation, while the latter is suggested for eco-redesign because it identifies areas where environmental improvements are needed and can be made. Generally the results generated from different methods give different types of information.
Main advantages
Using simplified LCAs allows: *introducing design changes at the early phases of the design process, where they are inexpensive [4]; *decreasing the requirements concerning data quality (accuracy) and data quantity (comprehensiveness of the inventory) [2]
Open questions
For quantitative simplified LCI, the simplification of the model of the product system after screening is the most critical but least developed step of the simplification process. No general methods can be recommended.
Practicability aspects
Practicability aspects refer to the availability of tool and data in order to implement the analysed approach. Lack of data availability and expensive manual collection are the main obstacles to the introduction of environmental considerations in early design phases. Moreover the data collection must take into account that some information is confidential [4]. Exchange of relevant data along the supply

chain and the possibility of having averaged data concerning a product range rather than specific products represent a solution to this problem. Different methods have been tested to obtain these generalised data [4, 6].

Application fields

Describe the sector of application of the proposed approach (if relevant) and the purpose.

Typical application fields of the simplified approach are product development, especially in the early design phases [4], and procurement [3]. As regards the quantitative simplified methods, there is no single method which is suitable for all product categories: in [7] 11 methods were evaluated to determine the best one for EEE sector, but the results obtained cannot be transferred to other product categories. In procurement simplified methods can be used to identify critical aspects of products and then criteria for procurement [3].

3rd Part: COMMENTS

R&D needs and trends

Describe the proposed (by the authors) R&D needs related to the approach(es) analysed and the development trends.

In [4] the need for a methodology which makes LCA a more accessible tool for SMEs is highlighted.

As regards the simplification of the model of the product system, in [1] a trend is identified in the use of hybrid methods to transfer cut off procedures from one specific product system to similar systems. Another trend is focused on methods for generating generalised data (ex. parameterised inventories [4], LCIs for groups of materials [6]).

Comments

Comments of the person who fill in the scheme in order to understand the “importance” of the approach analysed.