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

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Preface

Since the UNEP-EPA-CML workshop in 1999 in Brighton was held, a broad consensus has grown among LCA practitioners and methodology experts that it is desirable to combine methods for life cycle impact assessment (LCIA) using the so-called “midpoint” approach with the “endpoint” approach in a common framework, as both approaches have their specific strengths and weaknesses. This consensus can also be found in the results of the SETAC workgroups on impact assessment (WIA).

The figure below gives a simplified representation of some key differences between midpoint and endpoint methods for an overview of the main difference between these two methods.

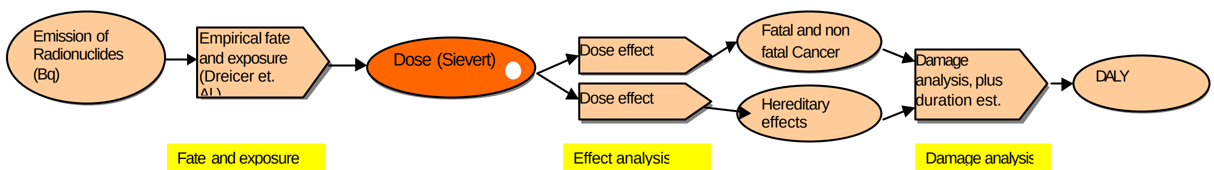

Figure 1 Simplified representation of the midpoint and endpoint approach for ionising radiation. The impact category indicator at the midpoint level could (for instance) be the dose, expressed as Sievert, while the impact category indicator at the endpoint level, could (for instance) be at the level of damage to human health expressed as DALY. The aim of this project is to have both indicators lie along the same environmental mechanism.

The present report is the result of the first phase of the project “Aligning Eco-indicator 99 and LCA Guide 2001” that was carried out by the National Institute of Public Health and the Environment (RIVM), the Centre of Environmental Science of Leiden University (CML) and PRé Consultants (independent consultancy). Funding took place by the Dutch Ministry for the Environment (VROM) and by RIVM itself. We thank Henk Strietman from VROM for his constructive role. The project started in the end of 2001, and was completed one year later. Steps are being undertaken to organise a second phase, aiming at the calculation of characterisation factors at the midpoint and the endpoint level.

A draft version of the present report was presented to and discussed by an international panel of LCA experts, during a meeting that was held at Schiphol Airport at 19 June 2002. Invited persons were

- Edgar Hertwich
- Mark Huijbregts
- Olivier Jolliet
- Göran Finnveden
- Erwin Lindeijer
- Ruedi Müller-Wenk
- José Potting
- Bengt Steen

Comments were received from:

- Jane Bare
- Thomas Köllner
- Michael Hauschild

In general, the comments were positive and stimulated us to expand on certain topics. We thank all reviewers for their valuable contribution.

Phase 1 of the project concentrates on an analysis of the differences and similarities of two main approaches for life cycle impact assessment, and in particular the first part of LCIA, in which impact categories and category indicators are chosen and characterisation models are selected or developed to convert LCI results into category indicator results. These two main approaches are:

- the one proposed as the baseline method for characterisation in the Handbook on LCA (Guinée et al., 2002); we will refer to this as the midpoint approach;
- the method advanced in the Eco-indicator 99 (Goedkoop & Spriensma, 1999); this will be referred to as the endpoint approach.

In addition to an analysis, phase 1 proposes a synthesis of these two approaches as well. The elaboration of the synthesis in the form of concrete methods is not part of phase 1, and is hence outside the scope of this report. Phase 2 will be devoted to this operationalisation.

The report is structured in two parts. The first (Chapters 1 and 2) is devoted to the synthesis: the design of a method for LCIA in which category indicators can be chosen at the midpoint level or at the endpoint level. As such it is a concrete proposal for the design of an improved method. The second part (Chapter 3) can be seen as the scientific argumentation of the design of the first part. It contains definitions, commentaries, literature references, and many more elements that seek to justify the design presented in the first part.

Summary

LCA, or quantitative environmental life cycle assessment of products, has undergone a large development during the nineties of the last century. Initially, meant to be used for the comparison of clearly-defined end product alternatives, such as various forms of milk packaging or baby diapers, it has been incorporated into the much broader decision-making at the firm level and the policy-making level. The use of LCA now ranges from ecolabeling to product design, and LCA has been applied to energy systems, food production and transportation alternatives; it now clearly extends beyond end products. The discourse around LCA has been tied to the involvement of stakeholders and the systematic use of quality assurance aspects, including peer review and uncertainty analyses. At an international level, the process of standardisation has yielded an ISO-standard (the 14040-series), and the establishment of working groups within the scientific community (SETAC) and within UNEP. Meanwhile, developments at the national level and within individual universities research centres and consultancy firms lead to a further development of the procedures and methods for LCA.

All these developments make clear that there is no single method that is to be preferred in al 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.

Samenvatting

LCA, de kwantitatieve milieugerichte levenscyclusanalyse van producten, heeft gedurende de het laatste decennium een grote ontwikkeling doorgemaakt. Oorspronkelijk was het bedoeld om helder gedefinieerde eindproducten, zoals alternatieve melkverpakkingen of luiers, te vergelijken, bijvoorbeeld vanuit een vraagstelling van ontwerpers of beleidsmakers. Maar gaandeweg is het een onderdeel gaan vormen van de veel bredere besluitvorming op bedrijfs- en beleidsniveau. Het gebruik van LCA reikt nu van milieukeur tot productontwerp, en het is toegepast op energiesystemen, voedselproductie en transportalternatieven; een uitbreiding waarbij LCA niet meer beperkt is tot eindproducten. Het debat rondom LCA heeft ertoe geleid dat belanghebbenden een rol hebben gekregen in het LCA-proces, en dat de kwaliteitsbewaking, inclusief een kritische externe beoordeling en onzekerheidsanalyses, een systematische plaats binnen het LCA-proces hebben verworven. Op het internationale niveau heeft een standaardisatieproces geleid tot een ISO-norm (de 14040-reeks), en zijn er voorts werkgroepen opgericht binnen de wetenschap (SETAC) en in UNEP. Ondertussen hebben ontwikkeling op het nationale niveau en binnen individuele universiteiten, onderzoeksinstituten en ingenieursbureaus geleid tot een verdere ontwikkeling van de procedures en methoden voor LCA.

Uit al deze ontwikkelingen blijkt dat geen enkele methode voor alle toepassingen de beste is. LCA wordt ook wel doel- en reikwijdte-afhankelijk genoemd, en dat is ook voor de methoden voor LCA het geval. Tegelijkertijd hebben de autonome ontwikkelingen geleid tot methoden die ook verschillen op punten waar dat niet strikt noodzakelijk is, en die vooral vanuit een historische context begrepen moeten worden.

Een voorbeeld hiervan is de ontwikkeling van middelpunts- en eindpuntsgeorienteerde methoden voor levenscycluseffectbeoordeling (LCIA). Er zijn methoden voor LCIA waarbij emissies van milieubezwaarlijke stoffen en onttrekkingen van grondstoffen worden vertaald in effectindicatoren op het middelpuntsniveau (ruwweg het themaniveau: verzuring, klimaatverandering, ecotoxiciteit, ...), en er zijn methoden met indicatoren op het eindpuntsniveau (zoals schade aan de volksgezondheid en schade aan ecosysteemkwaliteit). Het feit dat deze twee methoden naast elkaar bestaan is te rechtvaardigen vanuit specifieke gebruikersbehoeften. Dat wordt door een aantal interviews bevestigd. Maar er zijn ook verschillen in de onderliggende modellering die op zijn minst verwarrend zijn, en die wellicht onnodig zijn. Om een voorbeeld te geven, er is geen reden om aan te nemen dat de windsnelheid en temperatuur, die als milieuparameters in het lotgevallenmodel voorkomen, zouden moeten verschillen. Het is daarom wenselijk dat methoden voor LCA op het detailniveau geharmoniseerd moeten zijn, terwijl een zekere mate van vrijheid wat betreft de hoofdprincipes wel toelaatbaar is. In het onderhavige geval gaat het bij dit laatste aspect om de gerichtheid op middelpunts- of eindpuntsindicatoren.

Dit rapport beschrijft een studie naar het ontwerp van een methode voor LCIA die geharmoniseerd is wat betreft modelleerprincipes en –keuzes, maar waarbij resultaten beschikbaar zijn op middelpunts- of eindpuntsniveau. Het rapport geeft een basis voor het daadwerkelijk formuleren van geharmoniseerde modellen, waarna karakteriseringsfactoren op beide niveaus afgeleid kunnen worden.

Het rapport dient gezien te worden in een context van de beschikbaarheid van twee grote Nederlandse systemen voor LCIA, het middelpuntsgerichte Handbook LCA van Guineé en

collega's (CML, Universiteit Leiden) en de eindpuntsgerichte Eco-indicator 99 van Goedkoop en collega's (Pré Consultants, Amersfoort). Uitgebreide samenwerking met het RIVM garandeert in een mogelijke uitwerkingsfase de toegang tot de expertise en de modellen op een groot terrein van milieu-aspecten, van verzuring tot klimaatverandering.

Contents

1. General characteristics of the new method

This chapter describes some general characteristics of the designed method: the requirements and constraints with we had to deal, the overall structure in terms of the impact categories and the way space, time, uncertainties, etc. are dealt with.

1.1. Requirements and constraints to the new method

This section describes a number of requirements and constraints that define the position of the material that is described in the remaining text. It has been included to make clear that the text does not describe an ideal context-free method, but that different sorts of forces have limited our intellectual freedom. These forces include those exerted by the project purpose, by different user requirements, and by the overall LCA and LCIA field.

1.1.1. Background of the project

As noted in the preface, it is quite universally acknowledged that midpoint-oriented and endpoint-oriented methods for LCIA need to be integrated. Given the scope of the project, we have not made an overview of all or even the most important methods for impact assessment. Eco-indicator 99 (Goedkoop and Spriensma, 1999) and the Handbook LCA (Guinée et al., 2002) have at the outset been selected as providing the reference of an endpoint-oriented and a midpoint-oriented method respectively. Especially at the design-oriented phase 1 of the project, we have tried to design a framework that is capable of hosting a more general methodology. To that aim, selected elements of the recommendations from SETAC-WIA (Udo de Haes et al., 2002) have been followed.

The ambitions of the authors are therefore twofold:

- to integrate and harmonise the methods to create a common framework;
- to improve the method and to use the results of the consensus building process in the WIA working groups as far as practicable.

The proposals presented in this document are in our opinion feasible, provided sufficient budget is available in a next phase in 2003. At this stage the budget from the commissioner is still under discussion. Budget alone is not the only factor. In the future project we will need to establish links with many research groups in different fields, and to tie to the UNEP?-SETAC Life Cycle Initiative.

1.1.2. Formal purpose of the project

This report is the main results of the first phase of a project called "Aligning Ecoindicator 99 and LCA Guide 2001". The research has been made possible by funding by the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM). This phase of the project aims to describe how an integrated methodology for life cycle impact assessment (LCIA) can be developed, which can produce results at different steps in the effect chain, and hence at different levels of aggregation, as consistently as possible. In particular, it concentrates on the integration of the LCIA-methods in Eco-indicator 99 and the Handbook LCA.

1.1.3. Demands to the new method

When considering the demands that people have in mind for the new method, it is useful to distinguish user demands from scientific demands. We will first discuss the demands by users of LCA.

Within this first phase, four personal interviews were held with industry users of impact assessment methods. The users apply LCA for different industries, however with different purposes. In the Annexe a summary (in Dutch) of these interviews is given.

One of the main conclusions of these interviews is that users find it important that the method is standard and broadly accepted among policy makers, industry and scientists. A standard method will be more appreciated than a model with choices regarding for instance the geographical scale or time frame. Given a combined midpoint/endpoint method, the present midpoint users appear to keep on using midpoints, despite the fact that endpoint will be available within the same method and the other way around; endpoint users will keep on using endpoints or single score indicators. This is not surprising since the intended use differs from internal use to public disclosure. The goal of the LCA sets the preference for midpoint or endpoint, as it ought to.

The high relevance of being the standard and accepted method, seems in contrast with the requirements of scientists, for having a transparent and sophisticated model. However, we strongly believe that one of the most decisive factors for getting credits as an accepted "standard" method, is the acceptance by scientists. So our interpretation of the requirement to develop a well accepted standard method means that we have to invest enough energy in developing a consistent and widely accepted method, that may be complex on the inside, but is easy to use.

The interviews also support the concept of integrating the midpoint and endpoint systems, as we can now serve two user groups with one method, which will also increase acceptance

In general, it is in many cases desirable that LCA is a transparent procedure, i.e. that the results do not emerge in a miraculous way, but that a person with a sufficient training can understand how the results were obtained, and that they can be reproduced. It also means that methods (or software) for LCA should give not only final results, but that intermediate results can be made available on the user's request as well. Moreover, methods for LCA should not only produce a result, i.e. a number or a set of numbers, but also the possibility to explore these results along various ways, for instance by means of contribution analyses.

Another general requirement of an LCA method is flexibility: it should be possible to redo the calculations under slightly different assumptions. Furthermore, results of LCA should to a certain extent be robust, i.e. the answer should not be highly dependent on small changes of assumptions or variations of data.

This brings us immediately to the issue of uncertainties. It is well-known that the LCA deals with uncertain information at many different places and in many different forms. In many case studies, it is found that the conclusions are sensitive to at least some of the assumptions or data variations. In the course of years, different ways have been found to deal with the uncertainties. We may categorise these as follows:

- the scientific way: the divergence of results is concluded to be caused by imperfect knowledge, and no, or only provisional, conclusions are drawn; the recommendation is to carry out more research on acquiring better data and developing better models;
- the political way: the divergence of results is avoided by (s)electing one data source or model as the "best available" one, ruling out the validity of the other data sources or

models;
- the statistical way: the divergence of results is acknowledged to be caused by an intrinsic lack of knowledge or an intrinsic variability of results; this calls for ways of treating LCA as a stochastic instead of a deterministic model.

Although we agree to a certain extent with the need for acquiring better data and developing better models, and we agree as well with the usefulness of ranking some data sources and models as better than others, we believe that the conception of LCA as a stochastic model deserves more emphasis than it has received so far. This means, concrete, that it is for us a requirement of a method that it is capable of dealing with uncertain information in a stochastic way. Major methods of doing so include:

- the variation of the most crucial uncertain issues to calculate a number of results;
- the formulation of a number of more or less consistent scenarios (like business as usual, worst case, best case, etc.) or perspectives (like the hierachist, the individualist and the egalitarian in Eco-indicator 99) to calculate a discrete spectrum of results;
- the use of Monte Carlo analysis or other numerical ways of dealing with stochastic information to calculate a distribution of results;
- the use of the mathematical theory of error propagation to estimate standard deviations of results.

Given this project's focus on methods for LCIA, not on software or mathematics, this project will address the first two options only.

A requirement of a more practical kind is that methods for LCA should deliver fast answers, although the process of collecting data may be time-consuming.

LCA is accepted to be goal and scope driven. This implies that there is no universal method that can be used in all circumstances. For instance, some applications benefit from using a midpoint-oriented approach, while other will benefit from using an endpoint-oriented approach:

- A midpoint-oriented approach typically results in a dozen or so impact category indicator results that are expressed somewhere along the environmental mechanism that links an LCI result to an endpoint. These results refer to life-support functions (see §1.2.1): they represent conditions and the smooth performance of regulation functions that enable life and subsistence of a certain quality on earth.
- An endpoint-oriented approach gives results on the level of the endpoints (or damages). Usually the number of endpoints is two to four. They refer to areas of protection: classes of objects that are perceived to be of direct value to society.

Often, but not necessarily and certainly not entirely, the endpoint indicator results can be desegregated into a number of contributing midpoint indicator results. In both approaches normalisation, grouping and weighting can be applied to add a further interpretation and eventually to obtain a single weighted index. However, it is often claimed that weighting endpoint indicator results may be less difficult than weighting midpoint indicator results.

As to the meaning and use of midpoint and endpoint indicators, the situation is not entirely clear:

- Many claim that endpoint indicators are easier to understand and thus interpret, as they express issues of societal concern, such as human health damage or ecosystem quality damage. This means that the uncertainty in the interpretation can be potentially lower compared to a midpoint method, especially in decision making.
- Others claim, however, that midpoint indicators are easier to understand and thus interpret, as they relate to facts and phenomena, such as decrease of the ozone layer,

whereas endpoint indicators pertain to badly-defined and subjective intuitive notions, such as human health.

- Midpoint indicators are calculated using relatively robust environmental models, which may mean that the uncertainty in the indicator itself is lower. Often also the need to make value choices is lower than in the case of endpoint indicators.
- Often, the number of endpoint indicators is considered to be lower than the number of midpoint indicators. This may be seen as an advantage for endpoint indicators in use and in weighting. It may on the other hand be seen as an undesirable form of loss of information.
- Some people, however, think that the number of endpoint indicators is higher than the number of midpoint indicators, with exactly reversed consequences for interpretation, weighting and information loss.[1]
- As the models that calculate indicators at endpoint levels are more complex, it is not always possible to include all relevant environmental mechanisms. So endpoint methods may potentially be less complete.

Despite the fact that not all controversies on the facts and values are settled, we think that we can provide a solution for a wide range of applications, with an LCIA framework that can offer results on both levels; see Table 1.

Table 1. Schematic overview of the suitability of the midpoint- and endpoint-oriented approach. More +s means better suited. A single score (the weighted index) can be derived by weighting, either from indicators at the midpoint or the endpoint level.

Decision situation	Impact assessment result		
	separate midpoints	separate endpoints	weighted index
decision support involving many different stakeholders with a low level of environmental expertise		+++	+
decision support involving many different stakeholders with a high level of environmental expertise	+++	+++	
decision support in routine conditions (tools for designers)	+	+	+++
benchmarking on processes	+++	++	
benchmarking, external use i.e. compliance	++	++	
process monitoring and optimisation	+++		
environmental declarations	+	+	

1.1.4. Constraints put by LCA in general and by LCIA specifically

In designing an integrated method for LCIA one could start from scratch and design a visionary foundation and erect a scientifically consistent theory. We believe that this is a task that is more that of SETAC-WIA than that of this project of which the historical and existing constraints are part of a given and unalterable context. In this project, we must face certain limitations of LCA and LCIA that are perhaps not intrinsic limitations, but that at least the next few years will continue to be a typical hallmark of normal LCA, at least in the Netherlands and probably in Europe. We think that these limitations include the following:

- LCA is based on linear or at least linearised models, with a functional unit that is arbitrarily large;

[1] For instance, radiative forcing is a single midpoint, implying multiple endpoints like increase of malaria incidence, rise of sea level, and change of ecosystem composition.

- LCA to a large extent ignores spatial and temporal detail, although moderate forms of spatial differentiation are becoming common;
- LCA deals with many different processes, substances and impacts, and must be equipped with easy-to-use tables of process data and characterisation factors;
- LCA supports decisions that are taken by people and that affect people; there shall be room for the role of stakeholders in choosing models, data sources, scenarios, assumptions and so on, so that LCA is not a mechanical procedure.

Notice that this last constraint is to a certain degree in conflict with the previously mentioned requirement that LCA provides reproducible answers.

1.1.5. Constraints put by the project

Notice that, although the general purpose is perfectly general, the emphasis on two existing Dutch methods makes that the design of the project in terms of time and budget is primarily motivated by the desire to align these two existing methods, and not by the desire to broaden the framework for the introduction of aspects that are not covered by any of the two. Spatial differentiation, non-OECD impact categories (like erosion and salination), the average-marginal dichotomy, and new ideas on the role of areas of protection are just four examples of developments that can only superficially be covered by this project.

1.2. Overview of the new method

This section discusses the principal elements of the new method: the areas of protection, the environmental mechanisms, impact categories and category indicators, and main choices as to spatial and temporal detail and some other model-related features.

1.2.1. Areas of protection and life support functions

Although undefined in ISO 14042, areas of protection serve an important role in the current debate on the choice of impact categories and their category indicators, both at the midpoint and the endpoint level. An area of protection has been defined as a class of endpoints. There are two comments to be made on that. The first is: what are endpoints? We suggest: those elements in impact pathways which have an independent value for society. The second is: how are they selected? We suggest: in such a way that this class is clearly linked to a given societal value (like public health, nature conservation, etc.). So to our opinion this top-down aspect should also be included in the definition.

Traditional areas of protection are: human health, biodiversity (or ecosytem health) and natural resources. But also other classifications are possible, such as: human health, natural environment and man-made environment. In Eco-indicator 99, there are three endpoints: human health (with DALY as the indicator), ecosystem quality (with PAF as the indicator) and resources (with surplus energy as the indicator). Of course these classifications are connected. It is important that a default choice will be made here, but that is a point for later discussion.

A specific question is: are life support functions also an area of protection (or part of a larger one), as has been suggested a number of times? Then we must first answer the question what we mean with life support functions. Our interpretation is that these are regulation functions, supporting life on earth. Because “values” (in society) and “functions” (for society) are comparable entities, one can argue that life support functions are also (part of) an area of protection. Still, these functions are not so much of significance for society in themselves (i.e., they are not independent values in the above terminology), but they rather constitute fundamental conditions for the areas of protection. Therefore we propose to define life support functions as entities at the midpoint level. To put it more precisely: life support functions are classes of midpoints, just like areas of protection are classes of endpoints.

For the life support function, comparable to the areas of protection, we must add how these classes are selected. Starting from the above definition, we propose that the selection is guided by regulation functions linked to the functioning of environmental media and life supporting cycles of substances and materials. So a suggestion is (as a heuristic list and not as a priori list):

- climate regulation;
- hydrological cycles (flooding, availability of water);
- soil fertility (soil erosion, soil degradation, soil fertility);
- biogeochemical cycles (the main nutrients flows, like C, N, P, S, Ca and possibly others).

It is not imperative that all these function will become new impact categories in LCIA. Thus, soil erosion may be put under natural resources, and the material cycles may be out of the scope of LCA all together.

A next question is: do the life support functions include all midpoints? So, can every midpoint in all impact pathways be attributed to one or more life support function? This is a real point of choice. An argument in favour is that together all midpoints should be covered by the total of life support functions. An argument against is that it is a selection, related to regulation functions. So, concentrations of toxics can disturb the regulation functions, but are not necessarily to be regarded as part of them. This is an interesting point of choice.

In general, classes of objects are not approached in life cycle impact assessment: one does not calculate a numerical score for the areas of protection. Neither does one calculate a numerical score for the life support functions. One does calculate numerical scores for the chosen indicators: these are the category indicator results. These can reside at the beginning, at the midpoint or at the endpoint of the environmental mechanism. Eco-indicator 99 is a typical endpoint method, with three endpoint categories that coincide with the areas of protection. CML's Handbook LCA offers a typical midpoint method, with a larger number of midpoint categories that can be grouped into three or four life support functions. Finally, there exist a number of methods that operate at the beginning of the environmental mechanism, and that have category indicators related to total mass flow, total energy requirement, or total waste flow, and that could be grouped into a small number of stressor classes.

1.2.2. The environmental mechanisms, impact categories and their indicators

ISO 14042 rightly stresses the importance of the choice of the category indicators, that are assumed to be quantifiable representations of certain impact categories. A well-chosen category indicator provides an appropriate representation. Here, one must distinguish two meanings of the word appropriate:

- it must provide a quantitatively appropriate representation; that is to say, a lower category result should correspond to a lower environmental impact[2];

[2] This may sound trivial, but it is not. Consider, for instance, the case of an aggregated toxicity score on the basis of PEC/PNEC-values, where it is not obvious that a lower indicator result is indeed always preferable. This depends on background levels, combination toxicity, and other details that are ignored by the indicator, but that may be decisive in the end.

- it must provide a substantively appropriate representation; that is to say, the indicator should indicate something that has an environmental relevance.

Usually (but not necessarily), the first meaning is often interpreted as signifying that the category indicator should be chosen towards the intervention-side of the intervention-impact-damage chain. For instance, if the choice of a category indicator for the impact category of acidification is a battle between proton release and forest disappearance, the first choice requires less complex models, and is therefore said to be more robust to choices and uncertainties. The second choice, on the other hand, is closer to the perception of decision-makers, as it is directly coupled to entities that can be experienced in the environment. The second meaning is often (but again not exclusively) coupled to these damage-oriented category indicators.

From these considerations, the emergence of two competing or complimentary systems of category indicators can be understood:

- the midpoint category indicators, as an attempt to model the intervention-impact-damage chain to a point where knowledge is still fairly sure and complete, and where the remaining end of this chain is only conceptually or partially known;
- the endpoint category indicators, as an attempt to let decision-makers decide on what they can understand, and to use scientific knowledge, even if unsure and incomplete, to specify the category indicators at this comprehensible level.

Although the development described above is appealing in its simplicity, it is not entirely correct.

In the first place, although a category indicator near the intervention-side may need fewer assumptions and data, this does not make it more robust. The crucial assumption of a good indicator is what we shall refer to as the principle of correspondence: there should be a reasonable correlation between the indicator value and the indicated impact. The emitted mass of toxics is not a good indicator of the toxic impact, because the degree of correspondence between indicator and impact is low. Proponents of midpoint category indicators are of course aware of this, and move somewhat further towards the damage-side, including simple fate and effect models. Although the inclusion of damage models would possibly further increase the correspondence, this step is not taken by the proponents of midpoint indicators. The question that thus emerges is the following: what is a good criterion for selecting category indicators at the midpoint level? We will postpone an answer to this question for a while.

A second reason for rethinking the choice of category indicators is the challenging observation (see §1.1.3) that the number of endpoint indicators may be much higher than the number of midpoint indicators (depending on the level of aggregation at both levels), but that somehow current practice seems to be at variance with this. Indeed, the choice of endpoint indicators in Eco-indicator 99 may be described as the result of two forces: to move close to the damage level, and to express the indicators in compatible and additive units. In principle, the human health is an area of protection, not an endpoint indicator. It is a class with only conceptual meaning, capturing many concrete and measurable endpoints, such as lung disease, cancer and skin allergy. But the DALY-framework offered a way of treating human health not only as an area of protection, but also as a category indicator. The question that arises here is thus: what is a good criterion for selecting category indicators at the endpoint level? Answers to this question are also postponed for a while.

To complicate the analysis, there is a third force at work: the availability of models and data. Toxicity in the midpoint framework has been based on the PEC/PNEC-ratio, because it was available and was felt to be sufficiently appropriate. In the endpoint framework, ecosystem quality has been based on plant diversity, for the same reasons.

In conclusion, the choices of category indicators in the Handbook LCA and Eco-indicator 99 was not a pure balance of powers between robustness and environmental relevance. It is difficult and probably not constructive to analyse the historical backgrounds of the category indicators in both methods. Instead, we will focus on the development of criteria for choosing category indicators at both levels, and we will apply these criteria in due course. As the first two criteria, we repeat the ones directly derived from ISO's definition:

- it must provide a quantitatively appropriate representation;
- it must provide a substantively appropriate representation.

In addition to that, there are practical constraints:

- the number of category indicators must be limited;
- the category indicators must be accessible by existing models and data, that moreover can be attached to the inventory results of an LCA;
- the implementation of category indicators in the form of characterisation models should be feasible in a limited time.

From these principles, the development of consistent sets of category indicators may proceed. We will first discuss the endpoint indicators, and then move to the midpoint indicators.

For the endpoint level, the procedure is more straightforward than that for midpoints. For endpoints, the idea of basing the category indicators on the areas of protection is a good starting point for providing a high environmental relevance under a quite limited number of indicators. Thus, the areas of protection Human health, Ecosystem health, Resources and Man-made environment may directly be used for four category indicators with identical names (preceded by “damage to”). In Eco-indicator 99, some deviations can be noted: there is no category indicator for Man-made environment, and instead of Ecosystem health the term Ecosystem quality is used. This is more than a naming aspect: it can be seen as a sign that the health aspect is indicated by the quality aspect (although the term Ecosystem diversity would be even more appropriate for the indicator). It should be recognised that a diversity of endpoints fall under one area of protection, despite the fact that there is only one category indicator per area of protection. Thus, different types of human health problems (respiratory problems, cancer, etc.) are in principle addressed with different category indicators at the endpoint, but these category indicators in one area of protection have the same significance and unit, so that they can be added into one metric. This metric is DALY. For Ecosystem quality, it is PDF*time*area, and for Resources it is surplus energy.

In the second phase, we will certainly discuss the exact metrics used, but it seems wise to stick to the idea of basing the category indicators on the areas of protection for which they are supposed to reflect an environmental relevance, and to choose the indicators for the diverse endpoints within one area of protection as having commensurate metrics that allow for aggregation within the area of protection. Thus, we end up by the following endpoint category indicators with in parenthesis the area of protection and category endpoint indicated:

- damage to human health (human health);
- damage to ecosystem diversity (ecosystem quality);
- damage to resource availability (resources).

We have, mainly for reasons of budget and time restrictions, chosen not to elaborate the endpoint damage to man-made environment, although we think there is an interesting possibility for operationalising a category indicator in terms of monetary units.

For the midpoint level, the situation is more complicated. It is attractive to use the best compromise between robustness and environmental relevance as the guiding principle in selecting the category indicators at the midpoint level. However, here the ambiguous meaning of the term robustness creates problems. When is a category indicator robust? There seems to be at least three interpretations:

- a category indicator is robust when there are few debatable assumptions and choices involved;
- a category indicator is robust when variation of the debatable assumptions and choices does not significantly affect the conclusions;
- a category indicator is robust when it (always, in most cases, on the average, ...) points in the right direction (this is the aforementioned principle of correspondence).

We can illustrate this with an example. Suppose we wish to address the wealth of people, and consider the price of their car as an indicator. Clearly, there are not so many debatable assumptions and choices involved in the calculation of the indicator result. Perhaps we must make a few concerning how the price is measured and how the price of a car that is shared by several household members is distributed among these members. So, with respect to the first interpretation, this indicator is quite robust. For the second interpretation, we need to address questions like: if we change the method of distributing the price of a car among the several household members, how do the results change? And for the third interpretation, we need to address the question if the indicator car price is representative for the wealth of its owner.

For environmental impact categories, the situation is similar. We may wish to address climate change with the radiative forcing-based GWP, but are left with the question how robust this is. There are some debatable assumptions and choices, that moreover may affect the results. This suggests that radiative forcing is not a robust indicator, so that the category indicator should be placed more to the emission side. Mass of emitted greenhouse gases is definitely more robust in these first two interpretations, but it is less so in the third interpretation. In fact, it is the third interpretation of robustness that leads to a preference for radiative forcing over mass. Notice that it not necessarily suggests to model further to the damage side, e.g. to temperature increase, flooding, or human health. This depends on the degree of correspondence that is present between the indicator and the impact that is to be indicated. Radiative forcing may well be a sufficient indicator for climate change, and temperature increase may be hardly a better indicator while it involves more debatable assumptions and choices. Still, the environmental relevance of temperature increase is undeniably higher than that of radiative forcing. This clearly demonstrates that environmental relevance is not the same as correspondence.

We have also seen that environmental relevance often implies a prolongation of the modelled intervention-damage chain, thereby needing more debatable assumptions and choices. At the midpoint level, it suffices to demonstrate or assume a sufficient degree of correspondence between category indicator and indicated impact, whilst obviating the explicit and quantitative modelling of the environmental relevance. But an important question then is: when is a midpoint category indicator good enough? When is the degree of correspondence with the indicated impact sufficient to locate the category indicator at that point in the intervention-damage chain? Should there be correspondence on the average, in 95% of the cases, as a worst-case approximation? And, more philosophically, how can we demonstrate or measure the correspondence?

These questions cannot be answered, partly because the entire correspondence principle has, as far as we know, not been formulated before as a basis for deciding on category indicators. That we give it a prominent position here is mainly to give it a central role in future discussions on the choice of category indicators. For now, we have to rely on heuristical considerations. As a preliminary list, we have the following category indicators with the indicated impacts in parenthesis:

- photochemical ozone concentration (summer smog);
- potentially affected fraction of plant species (toxic stress);
- contaminated body mass (human toxicity);
- concentration of radionuclides/absorbed dose (radiation);
- pH change in water (aquatic acidification);
- pH change in soil (terrestrial acidification);
- nutrient availability in water (aquatic eutrophication);
- nutrient availability in soil (terrestrial eutrophication);
- affected fraction of plant species (ecotoxicity);
- use of agricultural land (land use impacts);
- use of urban land (land use impacts);
- radiative forcing/temperature increase (climate change);
- ozone concentration change (ozone layer depletion);
- decreased ore concentration (depletion of mineral ores);
- primary energy content (depletion of energy resources);
- use of water (depletion of water).

In Chapter 2, more extensive explanation of the meaning of these indicators, as well as visual designs of the intervention-damage chains with the category indicators at midpoint and endpoint will be shown.

1.2.3. The position and role of uncertainty

A model is by definition a simplified representation of the real world or an aspect thereof. This implies that some elements of the real world are represented in a crude way or ignored altogether. This may be done for reasons of data availability, but it may also be that the state of knowledge is insufficient or insufficiently agreed upon to be labelled as certain knowledge. A famous example is the effects of global warming: there is no scientific, let alone societal, consensus on the exact impacts of greenhouse gases on issues such as flooding, malaria incidence and crop yields.

This creates an uncertainty in the model outcome. The degree to which this is acceptable partly dictates the efforts that should be invested in the model. But uncertainties do not only rise from an incomplete understanding by scientists. Cultural and religious background and professional affiliation are just two factors that may affect the degree of belief that a person has in the existence, seriousness and inevitability of a certain effect. Such degrees of beliefs show up in many places in life cycle impact assessment. A few examples are:

- the effects of pseudo-estrogenic substances on ecosystems and man;
- the decline and importance of biodiversity;
- the degree to which ecosystems will destabilise as a result of global change;
- the importance of future generations in comparison with the present one;
- the development of mitigation and prevention technologies;
- the rights and duties of mankind with respect to the creation.

There are different options of dealing with these uncertainties, but given the time constraint the development of better models and the acquisition of more accurate data is not a solution. We are left with a number of options:

- specify every possible uncertainty as a probability distribution and perform a Monte

Carlo analysis to calculate a distribution of characterisation factors;
- specify for every possible uncertain parameter a highest and a lowest value, and calculate characterisation factors for every combination of possible choices;
- specify for every possible uncertain parameter a highest and a lowest value, group conceptually similar choices into a small number of scenarios, and calculate characterisation factors for every scenario.

The second option probably would lead to a few hundred or thousand parallel lists of characterisation factors, and is thereby not a feasible option. And although the first option is feasible, its practical usefulness is restricted by the fact that most software for supporting LCA cannot deal with probability distribution of characterisation factors. We are thus left with the third option.

Here, the central problem consists of the formulation of a small number of consistent scenarios or perspectives. In Eco-indicator 99, cultural theory was used to define a number of archetypal attitudes, or perspectives. There are five such perspectives, ranked according to two dimensions: the binding to the group and the binding to an external grid. The five perspectives are:
- the individualist, representing the archetype of a person with a weak binding to the group and a weak binding to the external grid;
- the egalitarian, representing the archetype of a person with a strong binding to the group and a weak binding to the external grid;
- the fatalist, representing the archetype of a person with a weak binding to the group and a strong binding to the external grid;
- the hierarchist, representing the archetype of a person with a strong binding to the group and a strong binding to the external grid;
- the autonomist, representing the archetype of a person that resists to be placed in a diagram with a group and an external grid.

From these five archetypes, three (the individualist, the egalitarian and the hierarchist) were selected as representing the main spectrum of attitudes towards the environment, risk and uncertainty, and the confidence in mankind's capacities to prevent damage. For instance, the individualist is assumed to give the present a higher priority than the future, while the egalitarian will assume an opposite view and the hierarchist will give them equal weight.

The use of cultural theory and the derivation of the three main attitudes from it spawned more discussion than the authors had foreseen and wanted. But it appears that this is more due to the background of the theory, the term perspective, and the names of the three perspectives distinguished. The core idea of grouping basic attitudes into a small number of consistent scenarios was in general felt to be a step forward.

In this project, we will stick to this idea without relying on cultural theory and the labels derived from this. Instead of perspectives, the term scenario will be used. And for the three archetypes, certain small adaptations will be made. We will distinguish:
- a scenario in which future emissions will be reduced, prevention technologies will be available, resources will be available in large quantities, still unknown effects of chemicals will prove to be etc. (largely corresponding with the egalitarian);
- a scenario in which environmental management and technology will fail, in which run-away effects will become manifest, etc. (largely corresponding with the individualist);
- a scenario in which the most realistic compromise between the two above-mentioned

scenarios is the starting point (largely corresponding with the hierarchist).

A definite name for the three scenarios has not yet been chosen.

In addition to the use of these scenarios for dealing with the model uncertainty, data uncertainty will, as far as possible, be treated with Monte Carlo analysis.

1.2.4. Dealing with spatial aspects

LCA has at the outset been conceived as a global assessment tool. Emissions of hazardous substances were aggregated along the entire life cycle regardless of their location. Thus, emissions of SO_2 during electricity production in France were added to emissions of SO_2 during ship transport across the Pacific. This was partly done for reasons of a lack of specific data, and to keep the calculation and interpretation feasible. But it was also justified on more fundamental grounds: a pollutant is a pollutant even if it is emitted at places where it will not do any harm. This principle has been referred to as the "less is better" principle, coining the concept of "potential" impacts as impacts that may be the result of the presence of a pollutant. The meaning, rationale and validity of this principle has been challenged ever since its conception. And, it has not been applied consistently, even by its strongest advocates. The distinction of a number of environmental compartments, assigning a different environmental significance to an emission to air, water or soil is a first sign of a more sophisticated approach towards incorporation of spatial details. A next natural step is to distinguish fresh water from sea water, urban areas from rural areas, agricultural soil form industrial soil, the arctic environment from the tropics, etc. Clearly, this soon leads to a situation that becomes unmanageable, in its data acquisition, in its data storage and calculation, and in its interpretation by environmental experts or decision makers.

In moving from midpoint to endpoint indicators, the issue of spatial differentiation must be considered again. Where a midpoint indicator is more naturally linked to hazardous potency (like photochemical ozone creation potential), the construction of an indicator at the damage level easily involves considerations on background levels, thresholds, and other concepts that seem to call for a regional differentiation. This argument is not correct, not for the midpoints nor for the endpoints. Regionally differentiated midpoints will perform better (in the sense of being a better indicator) than global ones, and non-differentiated endpoints may well be constructed. Moreover, if we wish to adhere to the idea that endpoint indicators represent a further modelling on the basis of the midpoint indicator results, it is clear that one cannot regain in this further modelling spatial details that have been lost during the inventory analysis or the midpoint modelling. And the principle of correspondence may be brought to mind at this stage: a potency-based midpoint that disregards spatial details that do matter at the endpoint level will not be a good indicator, as it will be more likely to point in the wrong direction.

What should be kept in mind, however, is that many existing damage-oriented models are based on national or continental data. Indeed, the fate and exposure, and sometimes the damage to human health and ecosystems, are very dependent on local factors, such as climate, soil type, population density, food consumption patterns and ecosystem types. In order to get the highest precision all modelling should be done site specific. This implies that these models can only be used when the inventory results or midpoint indicator results are available at that level. However, there are many practical obstacles to do so:

- It is very difficult to trace production sites of products that come from the world market, which makes it questionable, if a region specific impact category is useful.
- It is unclear how regions should be chosen in practicable terms if one tries to cover the whole world. Currently there are many proposals to define regions (50 by 50 km

grid, country level, State level in US, Prefecture level in Japan).

- Some damage models require a different type of spatial detail, for instance distinguishing high-stack chimneys from low-level emission sources, or moving from stationary sources.
- It is unclear if it is desirable that LCA gives better results if emissions occur in areas where background-levels and population densities are relatively low.

The simplest solution is of course to somehow "upscale" the models to a more abstract level, treating the world as a single region, and use world wide averages for the fate, exposure, effect and damage parameters, such as temperature, population density and vulnerability of ecosystems. However, it is clear that this will result in a relatively high level of uncertainty. Another problem with this approach can be that some impact categories are only relevant in parts of the world. For instance airborne nutrient dispersion is a problem in industrialised areas like Europe and parts of the US, but in many developing countries these emissions would have a positive effect, as it is not the saturation of nutrients, but the depletion of soils that is the relevant problem.

As inventory data are, for the purpose of this project, to be considered as given, it is inevitable that the degree of spatial detail of the damage models must be reduced in order to fit to the data that are available.

A compromise between a high level of spatial detail and a global average could be to distinguish continents or parts of continents only, and treat these as homogenous areas. A separate region could be the oceans, as the fate of substances emitted above the oceans can be very different from the fate of emissions over land, and as population density is extremely low. This approach will still result in quite uncertain characterisation factors, but the uncertainties are expected to be considerably lower compared to a "one world" solution. Other advantages of this approach are:

- it might be relatively easy to distinguish between commodities from different continents;
- differences between non-OECD and OECD regions can be taken into account (perhaps with some complications in Asia and Eastern Europe, as it has OECD and non OECD countries mixed);
- there seems to be a trend towards the development of impact assessment methods on a continent level (like there are several regional Eco-indicator varieties).

In developing a partially regionalised LCIA, it is useful to distinguish two different issues when discussing spatial differentiation:

- the emission or extraction region (where substances are emitted or extracted);
- the impact or damage region (where the impacts or damages occur).

This distinction has some important consequences

- For emissions with a short atmospheric residence time in air the difference between damage and emission region will be small, although sometimes not unimportant. For instance, hydrocarbons emitted in an urban region tend to create the highest summer smog peaks just outside the urban region.
- For airborne emissions with an atmospheric residence time of a year or more (climate gasses, HCFCs and persistent carcinogenic substances) the damage area will be the whole world.
- For waterborne emissions (and emissions to other compartments that transfer easily into water) the impact area will be confined to the hydraulic region of the river basin

for substances with short residence times, while the more persistent substances will have most impacts in seas and oceans.

- For soilborne emissions the damage and emission areas will be the same for substances that bind to soil particles, while other substances will be transferred to air and water, and will have an impact region as described above.
- For mineral and fossil resources with a market value that is sufficient to transport and trade it all over the world, the damage region for resources is the world.
- For mineral and fossil resources that do not have sufficient market value to transport over long distances (water, sand, gravel, peat etc.) the depletion of a resource in a region will affect the region only (often the price elasticity can compensate the effect to some extend, but for instance for water there can be very serious regional problems)
- For land use the impacts are on the regional or local level

One might be tempted to develop the new method with Europe as the emission or extraction region, and explicitly invite colleagues in other continents to develop an Asian, American, etc. method. A disadvantage is, that an LCI treated with a European LCIA implicitly supposes that all emissions and extractions take place in Europe, while a substantial part may in reality take place in quite remote areas.

In conclusion, we propose to two types of environmental models:

- with Europe as an emission or extraction region. Europe is defined as the EU, plus Switzerland and Norway, possibly with the inclusion of the candidate member countries and Turkey (as OECD country). The exact choice needs to be still determined. It means that for some resources and emissions, the world will be the impact region.
- with the world as an emission or extraction region. Such a model should be based on world representative parameters, as far as possible.

1.2.5. Dealing with temporal aspects

The discussion on time resembles in certain aspects that of space. LCA has been construed as a tool in which temporal detail is less important than completeness. Moreover, aggregation of SO_2 over different life cycle stages automatically implies aggregation of SO_2 over different moments in time.

Like for space, we may distinguish an emission or extraction time and an impact or damage time. And, whereas we may continue to assume an infinite integration for emission and extraction[3], there are certain aspects that seem to call for a more detailed view with respect to impact or damage time. For instance a heavy metal emission can potentially have toxic impacts over many thousand years, as the metal can remain bio-available over such a long time before it ends in deep and stable sinks like the deep oceans or sediments. It is questionable if it is relevant to stakeholders that interpret LCA results to integrate such toxic effects over such a long term without any discounting of future effects or without setting a fixed period after which effects are disregarded. Setting a time limit for integration will have the effect that images that occur now, or in the near future, such as seawater rise become more important than the damage caused by the release of persistent substances.

Setting time limits is typically a subjective issue. The value that can be associated with it is

[3] Especially for very long time frames in the inventory side, we may adopt a different view. For instance, the rate at which pollutants percolate from a well-controlled dump site to the groundwater may be extremely small, but on an infinite time frame this may still be a lot.

the importance of future generations over present generations. We think we cannot set the time frame for the users of our methodology. Therefore we propose to maintain three time frames for the modelling (provided that the future development budget allows for this):

- short: 20 years;
- medium:100 years;
- long: indefinite period.

The selection of 20 and 100 years is consistent with the choices of the IPCC, the indefinite period is not; IPCC uses 500 years as a maximum integration period.

In somewhat more detail we can list the most relevant implications:

- For metals the short and medium timeframe will result in very low to low impacts.
- For CFCs, most climate changing gasses we can use the IPCC equivalence factors. The damage calculation will be affected in the short and medium timeframe.
- For radionuclides and persistent carcinogenic substances the short timeframe will result in much lower health damages.
- Irreversible changes in land-use, like irrigating a swamp, causing erosion or salinating soil will be important in all time frames.
- The depletion of minerals is only relevant when using the long timeframe.
- The depletion of fossil fuels is relevant in all time frames.

Another aspect of time has to do with the discrepancy between models requiring an emission flux as an input and LCI supplying an emission pulse. In LCA, emissions are generally reported as mass loads (or Bequerel), while fate models are using a flux (mass per time) as inputs. Guinée et al. (1996) solve this incompatibility by assuming all mass flows were released during the same but unspecified time. This means that the results have no absolute meaning and that they only have a meaning in relation to a reference substance, in this case dichlorobenzene. To model further in the direction of damage, this is not a proper solution as it cannot deal with one reference substances, as this substance does not contribute to all disease types that are to be modelled (it is for instance not carcinogenic). Here, one needs information on the following parameters:

- the magnitude of the concentration increase due to a mass load;
- the duration of that increase;
- the area size in which the increase takes place (the larger the area, the smaller the increase); this information is necessary for the ecosystem damage modelling and for the exposure modelling.

It is not necessary (or even desirable) to use dynamic fate models (if they would be available), as in LCA we have no meaningful information over the actual emission flux duration or “shape” of the emission pulse. In fact it is not even necessary to have separate information on concentration increase and duration of the increase. It is sufficient to know the multiplication of emission increase, duration and surface area.

1.2.6. Dealing with the average-marginal dichotomy

An important characteristic of an LCA study lies in the application of the result. As we will see the type of application determines the choice for marginal, versus average modelling. Our proposal is to use marginal modelling consistently in the method. This means all models and steps – fate, exposure, effect, damage, normalisation, weighting – should be based on the marginal approach.

There are basically two types of applications:

- to assess the effect of changes in a product system (like in eco-design);
- to assess status quo (i.e. environmental product declarations).

If changes are to be assessed, there is a need to adopt a marginal approach in the modelling. This means we need to see what the environmental impacts are of producing or avoiding 1 kg CO_2 on the greenhouse effect. If a status quo is to be reported, one could use an average model. All contributions of CO_2 are treated equally. However, one can also assume that an environmental product declaration is often also used to assess improvement options, which indicates that a marginal approach is defendable also.

The differences between the approaches can be illustrated with a simple hypothetical graph (Figure 2) that plots the environmental impact against an emission (or resource use). In the marginal approach, the slope of the impact curve at the current emission level is used, in the average approach, the slope of the line through the current damage level and the origin is used.

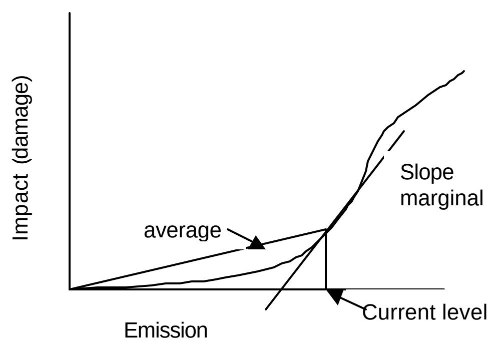

Figure 2. Illustration of the difference between average and marginal factors derived from a non-linear emission-impact curve.

It should be noted that some impact curves (like that of a PEC/PNEC-based toxicity indicator) are assumed to be of the non-threshold linear type, which means there is no difference between marginal and average.

The use of the slope of the impact function becomes complicated if we are modelling very large changes in the emission level, as in that case we cannot use a linear tangent of the slope; instead we would be forced to actually use the non linear impact curve. For LCA we do not need to consider non linearity as we can choose the functional unit freely, and usually we work with relatively small changes in emission levels.

We choose to develop a marginal approach for all impact categories, assuming the changes of the emission (or extraction) levels are small compared to the total level. This implies we can assume linearity of the marginal models.

Although outside the primary scope of the characterisation-oriented project, a special point of consideration is in the marginal normalisation and weighting. Traditionally normalisation values are computed by applying the impact assessment method on a reference set of emissions and extractions. The aforementioned choice has two consequences:

- the normalisation data set may not be the yearly emissions of a continent or the world, as we can no longer use the linear assumption;
- the normalisation values are also marginal.

The first point can easily be dealt with by dividing the yearly emissions from a region by the number of inhabitants, as is done by several authors. The second point is potentially more difficult to deal with, as it is difficult to explain to a panel that it is assumed to use the marginal impacts as a reference, instead of an average. The normalisation values show the impacts of "adding" the environmental load of a European to the total. Marginal normalisation values are difficult to explain to a panel, while we believe it is necessary that the panel indeed understands the implications of the use of a marginal reference.

2. Design of the new method

This chapter presents a graphical structure of an integrated midpoint-endpoint approach in a graphical format. The graphs use the following symbols:

- An ellipse represents a result, or a number of results. All results have a name and in most cases they have an SI unit. A white dot in an ellipse identifies a possible midpoint indicator; whether an ellipse can be an midpoint indicator depends on the question if an aggregation is possible; for instance it is possible to calculate results as environmental concentration of substances, but as all these concentrations for different substances are difficult to aggregate, they can not be used as a midpoint indicator. As far as possible, the SI units of the results are included in the ellipses.
- A block arrow identifies an operation, in which one result is transformed into another; very often the block contains a name of a model, or identifies the issue a not yet chosen model should address.
- Thin arrows identify a flow of information without an operation. They link operations and results.

Fur further clarification a set of colours is used. The colours have the following meaning:

- dark orange with light text: the models and results that can be used for the midpoint indicators, as well as the endpoint indicators;
- light orange: needed for the endpoint damage to human health;
- light green: needed for the endpoint damage to ecosystem diversity;
- light blue: needed for the endpoint damage to resource availability.

In a few cases the symbols have no colour. This identifies new operations to assess additional impacts that were not previously available. It is not always clear to what extent the inclusion of these new items is feasible, or which models shall be used.

As the design is rather complex, there are a number of separate sections:

- acidification, eutrophication and impacts of land use (§2.1);
- human toxicity, ecotoxicity, photochemical oxidant formation and radiation (§2.2);
- climate change and ozone layer depletion (§2.3);
- resources (§2.4).

Normalisation and weighting procedures have not been shown; the models end with an impact category indicator on the endpoint level, that is either:

- DALY (in yr), for the damage to human health;
- PDF*time*area (in m^2.yr) for the damage to ecosystem diversity;
- surplus energy (in MJ) for the damage to resource availability;

2.1. Human toxicity, ecotoxicity, photochemical oxidant formation and radiation

This part of the model deals with the following 4 types of substances:

- organic substances, specified as mass;
- inorganic substances, such as metals, specified as mass;
- fine dust, or substances that form aerosols, like NO_x, specified as mass. These are not judged on the chemical content, but on the physical properties. Note that dust can also contain toxic or radioactive substances, the toxicity of the substance is treated in the other categories.

- radioactive nuclides, specified per isotope, expressed in Becquerel.

2.1.1. Fate and exposure

The first step is the fate analysis. Exposure analysis is included in this section because some fate models include this step. Exposure modelling is only really relevant for human health-related indicators.

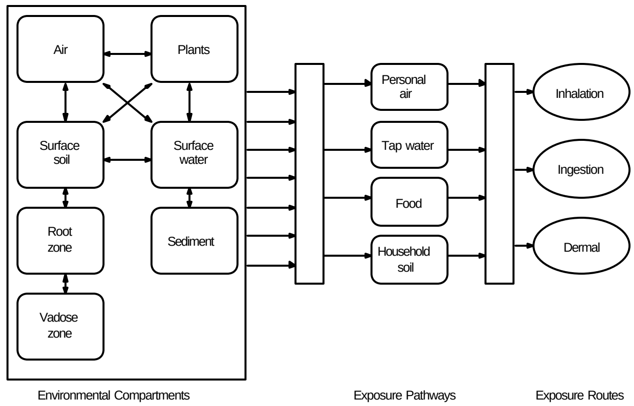

Figure 3. Structure of the roles of fate and exposure modelling.

WIA gives a generic scheme that represents most multi-media fate and exposure models, such as EUSES and Caltox. The WIA does not recommend a specific tool, but states that the ideal situation would be obtained if a site generic multi-media model and a site specific single media model is somehow combined. We propose not to develop a new combined tool, but to use both approaches where appropriate.

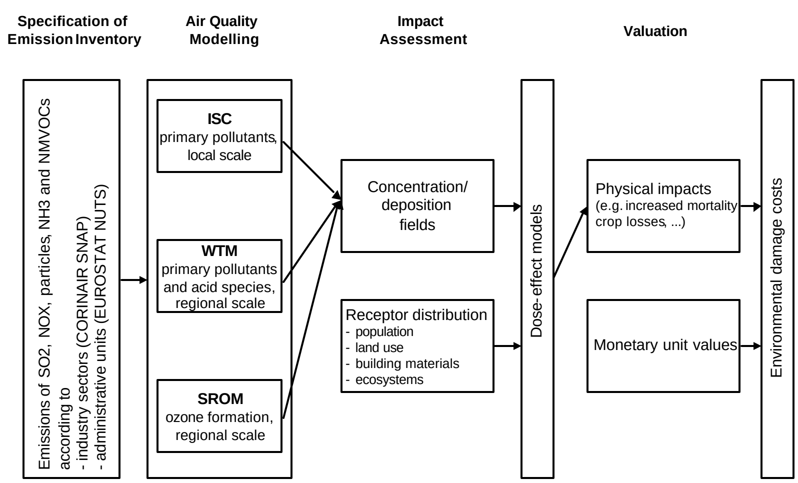

Figure 4. Schematic diagram of a single-media fate model, such as EcoSense.

The WIA also describes the GREAT-ER model; a single media model for water emissions in the major European river basins. It is in principle intended to be used for site specific modelling, but apparently it is possible to get generic factors, as the model allows for the modelling of non site specific (“down the drain”) emissions. For this project we see the major applications in the modelling of nutrients, acid and metal emissions (see below). Another interesting single media model is the EcoSense model, used for airborne emissions, like criteria air pollutants, fine dust etc. At RIVM the Deltawat is available for fate and damage modelling of water basins.

2.1.2. Fate and exposure for toxicity-related categories

For organic substances two environmental mechanisms are modelled:

- For the ozone formation potential of VOC, we can choose between the EUROS model of the RIVM, or the POCP equivalents by Derwent et al. The benefit of the EUROS model is that the damage to plants can be modelled as well. It works on an EU scale; we propose to use an average background NO_x concentration as parameter. The result is a midpoint indicator expressing the potential ozone formation from the VOC emissions, and an endpoint indicator relating VOC to ecosystem damage. Furthermore, a link can be made between the O_3 concentrations and the fine dust models, as O_3 can be treated as an aerosol-forming inorganic substance. For the endpoint approach this midpoint is used in an exposure model for the respiratory effects, as was done by Hofstetter and as it was applied in Eco-indicator 99. If EUROS is not available, we can fall back to the POCP model. In that case, for damage to ecosystem quality, we see opportunities to use the EcoSense model, as this contains a module to assess crop damage in monetary units, from which it may be possible to assess ecosystem damage.
- For all other effects of organic substances, the Simplebox, or EUSES-LCA model is used; both are available from the RIVM. This model includes exposure modelling, so in Figure 3 it is split up into two parts; the first part calculates the concentrations, the second part the dose.

EUSES or Simplebox, is a model that needs data on the climate, the soil properties and many other region specific parameters. We have not yet decided on which geographical scale such parameters will be entered. It is also not clear how (and if) the ocean compartment must be filled in.

For inorganic emissions three different approaches are used. Here, EUSES-LCA cannot be used without great care and comparison with empirical data. For the soil and water compartment the GREAT-ER model, and work of [Diamond et al.] can be useful. Other sources need to be identified, possibly the RIVM OPS model can be of use. The procedure we propose is as follows:

- use EUSES LCA carefully to obtain the first order results;
- compare the result with other (empirical or model) data;
- correct substance properties (and speciation) if necessary, in order to obtain a result that seems more in line with empirical data, and repeat cycle.

For fine dust (below PM10 and PM2.5) we will use the EcoSense model, in combination with empirical data such as was collected by Hofstetter, as was done in Eco-indicator 99, possibly the RIVM OPS model can be of use. Also emissions that form aerosols, like NO_x and SO_2 will be included, using the so-called umbrella mechanism, where the known damage of one or a few substances is extrapolated to all substances with the same damage mechanism.

For radionuclides the work of Dreicer et al. seems to be a good source, although we will also assess the applicability of the EcoSense model, or the RIVM NUCRED model. The model by Dreicer et al. has also been applied in Eco-indicator 99; also this step integrates exposure. It is at this stage not clear if this model can also be used for the other inorganic substances.

For LCA purposes, it is important to correct fate models, as they are intended to model worst case situations, like the use of maximum diets to calculate exposure through food, which would give an overestimation of the importance of this pathway (this overestimate has also been used sometimes in Eco-indicator 99). For the exposure calculations, a simple correction mechanism as proposed by Hofstetter will be used to take into account population density fluctuations as function of the atmospheric residence time[4] for all exposure calculations. For substances with an atmospheric residence time residence time of over a year, a world wide distribution and thus exposure will be used.

The fate modelling and most of the exposure modelling can be shared by midpoint and endpoint approaches.

2.1.3. Effect and damage modelling for human toxicity-related categories

WIA argues that methods should be developed that on the one hand cover a wide range of substances, while on the other hand there is a need to develop methods that indicate the severity. It is clear that there is some tension between those starting points, as severity based methods can potentially be limited in regards to the number of substances covered. In a combined midpoint-endpoint approach we propose to make the following combination:

- Fate and exposure models are combined. For the midpoint indicator, we do not use the ADI (as has been done so far), but we propose to use the slope factors, as proposed by [Crettaz et al 2002]. The advantage is the widely available data, while eliminating to a large extent, as WIA states, the inconsistency due to different levels of conservatism and political factors. An alternative would be to use acute toxicity data, as used by [Hauschild et al 1997]
- We propose to continue using different models for carcinogenic and respiratory diseases, as has been done in Eco-indicator 99. For carcinogenic effects it is possible to use the unit risk factors, which link the number of cancer cases per dose. These factors can be obtained form the IRIS database in the USA. A linear non threshold response is assumed. For respiratory effect a similar, but slightly different approach is used. Here we do not assume linear non threshold, but we use slope factors for the dose response curve, as was done in Eco-indicator 99.

For all other substances we propose to use the slope factor method also used for the midpoint. [Crettaz et al. 2002] has developed an estimation method, that can be used to estimate DALYs for several hundreds of substances using slope factors derived from the IRIS database. This approach has recently also been applied by PRé in a project for Philips in an effort to include all toxic effects from Metals[5]

WIA, in a chapter on human toxicity, has commented on the weighting of disabilities in the DALY approach. The alternative would be the use of YOLL, but the problem with this approach is that all non fatal outcomes are weighted with a weighting factor zero.

2.1.4. Effect and damage modelling for ecotoxicity-related categories

WIA basically compares two approaches:

- the use of the PEC/PNEC concentration ratio (predicted environmental concentration over predicted no-effect concentration);
- the PAF approach (potentially affected fraction of species).

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[4] Except for pesticides, all emissions are supposed to occur in urban areas. Substances with a short residence time will be in densily populated areas most of their lifetime, while substances with a long lifetime will be chemically active in less densely populated areas for most of the lifetime.

[5] This work was done in a relatively small LCA project on lead-free soldering. Soon a follow-up EU-Korea-Japan wide project EFSOT will continue this research.

The PEC/PNEC ratio is more widely accepted, but the level of environmental relevance is limited, while the PAF concept provides a much higher level of environmental relevance because it indicates the fraction of species that is not fully protected as a result of chronic exposure from a certain chemical.

The endpoint indicator is derived from this midpoint indicator by adding an (uncertain) conversion from affected (PAF) to disappeared (PDF) fraction of species.

For a mixture of toxic substances, more problems with regard to environmental relevance arise from the PEC/PNEC concept. Dimensionless hazard units may be calculated, which is comparable to the summation of PEC/PNEC, however the result is difficult to explain. If the chemicals have a similar mode of action, hazard units can also be used in a straightforward way to calculate ms-PAF (multi-substance PAF) or the fraction of species not fully affected due to chronic exposure to a mixture of toxic substances. If different modes of actions have to be taken into account, the approach by [Hamers et al. 1996] can be used to evaluate ms-PAF.

The PAF concept is suitable for the midpoint approach, also for complex mixture as it also uses the hazard unit or principle. Alternatively, the PAF concept can be understood in ecological terms and is therefore better suited for endpoint modelling. Hazard Units =1 corresponds with a Potentially Affected Fraction of 50%, meaning that 50% of the species may be under toxic stress.

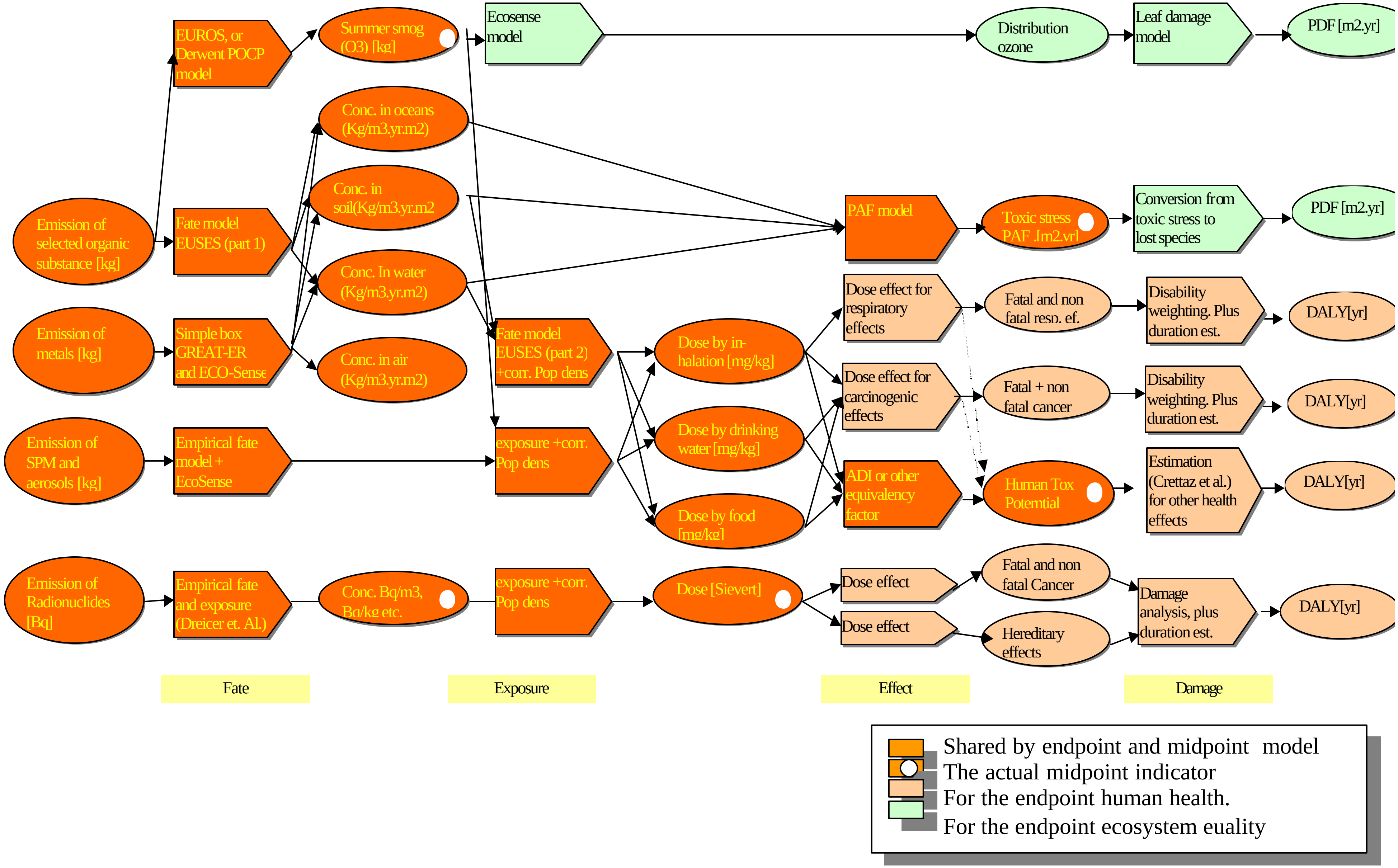
The marginal increase of the damage is determined by the background damage (=background PAF) in the area that is used to model the fate and damage. This results in the potentially affected fraction of species in a certain area during a certain period expressed as PAF.m^2.yr.

The unit PAF.m^2.yr, is not compatible with the unit of the endpoint category damage to ecosystem quality, which is in PDF.m^2.yr. PAF refers to potentially affected fraction of species, while PDF relates to potentially disappeared fraction of species. A conversion step is needed, and we will need the latest research results of RIVM to make this conversion.

Another possibility is to apply the same principle but to use chronic EC_{50} or LC_{50} data instead of the chronic NOEC. This could result in two other types of indicators:

- the affected fraction of species, as proposed by Jolliet, AF instead of PAF. AF fits better in the LCA since it is a measure for damage in stead of potential effect. AF should be calculated based on effect concentrations like EC_{50}, a concentration at which 50% of species is affected. The term “affected” can have different meanings, and does not necessarily relate to the disappearance of species.
- The potentially disappeared fraction of species (PDF), instead of the PAF. The benefit of this approach is the consistency with the other impact categories. PDFs can be calculated using the chronic LC_{50} figures, representing the concentration that is lethal for 50% of the population of a species.

An added advantage to these approaches is that more data are available on effect concentrations then on no-observed effect concentrations (NOEC) and the effect concentrations are less uncertain. However NOECs are based on long term experiments while effect concentrations are often based on acute data. The ideal would be to use EC_{50} or LC_{50} data for long term exposure.



EUROS, or Derwent POCP model
Summer smog (O3) [kg]
Ecosense model
Distribution ozone
Leaf damage model
PDF [m2.yr]
Conc. in oceans (Kg/m3.yr.m2)
Conc. in soil(Kg/m3.yr.m2
Emission of selected organic substance [kg]
Fate model EUSES (part 1)
PAF model
Toxic stress PAF [m2.yr]
Conversion from toxic stress to lost species
PDF [m2.yr]
Conc. In water (Kg/m3.yr.m2)
Dose effect for respiratory effects
Fatal and non fatal resp. ef.
Disability weighting. Plus duration est.
DALY[yr]
Emission of metals [kg]
Simple box GREAT-ER and ECO-Sense
Conc. in air (Kg/m3.yr.m2)
Fate model EUSES (part 2) +corr. Pop dens
Dose by in-halation [mg/kg]
Dose effect for carcinogenic effects
Fatal + non fatal cancer
Disability weighting. Plus duration est.
DALY[yr]
Emission of SPM and aerosols [kg]
Empirical fate model + EcoSense
exposure +corr. Pop dens
Dose by drinking water [mg/kg]
ADI or other equivalency factor
Human Tox Potential
Estimation (Crettaz et al.) for other health effects
DALY[yr]
Dose by food [mg/kg]
Emission of Radionuclides [Bq]
Empirical fate and exposure (Dreicer et. Al.)
Conc. Bq/m3, Bq/kg etc.
exposure +corr. Pop dens
Dose [Sievert]
Dose effect
Fatal and non fatal Cancer
Dose effect
Hereditary effects
Damage analysis, plus duration est.
DALY[yr]
Fate
Exposure
Effect
Damage
Shared by endpoint and midpoint model
The actual midpoint indicator
For the endpoint human health.
For the endpoint ecosystem euality

2.2. Acidification, eutrophication and impacts of land use

This section deals with elements that change the nutrient availability and the acidity of freshwater and soil, as well as land-use. The combination may seem odd from a midpoint-perspective, but it is relevant from an endpoint-perspective as these impacts all relate to the endpoint ecosystem quality.

WIA treats acidification and eutrophication in the same chapter. For acidification, the authors discuss a number of approaches:

- Hydrogen release potentials based on stoichiometric coefficients that express the amount of H^+ that can potentially become available, as is used by Heijungs et al. (1992). The main comments are that this method overestimate the importance of nitrogen, relative to sulphur, since nitrogen is more easily assimilated by ecosystems. Furthermore there is a very large regional difference, as to the actual release of H^+.
- Exceedence of thresholds, using single-media regional differentiated models such as Rains and EcoSense, as proposed by [Potting et al 1998] and [Krewitt et al. 2001]. Both authors arrive to significant different outcomes. The main comment is that emissions in area with acidification levels below thresholds are ignored. This shortcoming has been solved to a large extent in later work by [Huijbregts et al., 2000], using slope factors, expressing marginal damage.

For the endpoint indicator, we need to model further to the ecosystem endpoint. The marginal slope factors approach comes closest to this indicator, but is not applicable. However we do propose to use a single-media regional differentiated fate model, such as EcoSense or Rains, or the terrestrial fate, while using RIVM's Deltawat or the GREAT-ER model for aquatic fate. We do not yet know if we will calculate different factors for different regions, or an average factor. Another key difference with WIA's recommendation is the integration of eutrophication and acidification into a single model for the endpoint level (see below).

For terrestrial eutrophication WIA states that the frequently used Redfield ratio is not really applicable to terrestrial systems, as the ratio between phosphate and nitrogen is quite different in plants compared to aquatic systems (on which the Redfield ratio is based). The authors states phosphor limitation is rarely found in terrestrial ecosystem, which means they recommend to concentrate on nitrogen. Another remark is that there is an interrelation with acidification due to the absorption of nitrogen. The approach proposed, is very similar to the approach for acidification, using single medium regional specific fate models as Rains or EcoSense.

For aquatic eutrophication WIA describes (but does not recommend to use) the Redfield ratio as a baseline approach, knowing that it is suffering from a number of shortcomings. One of these is the fact that phytoplancton growth is limited by either phosphates or nitrates, and not by the ratio. An alternative approach is the oxygen consumption from the oxidation of nutrients. This however, relates to a completely different aspect, as COD or BOD does not reflect the phytoplancton growth. Another problem is the double counting, as in most LCAs both BOD/COD and organics are reported.

A more advanced approach is recommended for waterborne emissions, in which a region specific "transport factor" is combined with the Redfield ratio. The transport factor expresses the fraction of the nutrient that reaches a water body in which this nutrient is the limiting substance. Only a limited fraction of airborne emissions will cause aquatic eutrophication. The EMEP model is mentioned as the basis for several authors who have calculated country specific fate factors for direct deposition into water. However, run-off and leaching have not been included, until recent work by [Seppälä, Potting, Bare and Norris]. Another important issue is the bioavailability of the nutrients. Although it is plausible that ultimately all nutrients can become bio-available, this is not a useful assumption for endpoint modelling. Seppälä 1997 and 1999 is quoted to have provided a solution for emissions form pulp and paper industries.

2.2.1. Terrestrial acidification and eutrophication

New ideas are being developed to get a truly European model for terrestrial damages, by combining the following models:

- A single-media region specific model, like the EcoSense or Rains model is used as a fate model, resulting in changes in acidity and nutrient availability, as well as an estimate of the deposition in aquatic bodies (see below). Using the aforementioned slope factors approach we will determine the marginal changes in acidity and nutrient availability levels, as well as the background levels. These changes can be converted to a midpoint indicator, using the H^+-equivalency principle for acidification and the terrestrial Redfield ratio for eutrophication.
- Instead of using a geographical model such as RIVM's Smart model, we would like to use the Ellenberg curves[6] for plants that can be expected on different soil types to model the disappearance of plants at an increased level of acidity and nutrients. First indications suggest that this not regional specified approach does give quite consistent results compared to the very complex (Dutch only) Smart model.

A problem to be solved is that not all plant species are equally desirable in all regions. In Eco-indicator 99, the concept of target species was used for about 45 different ecosystem types.

2.2.2. Aquatic acidification and eutrophication

For damages to aquatic ecosystems we are faced with a number of problems:

- There is not a uniform world-wide or European aquatic system. Instead, there are “flow regions”. The GREAT-ER model described in the previous chapter, and the EMEP model are however candidates to model flow regions. We will study the applicability of the work of Seppälä and Huijbregts as a basis for the fate modelling, including the transport factor used for nutrients in P- or N-limited waterbodies. If possible we intend to use a correction factor for the bio-availability as has been done by Seppälä. The outcomes can be converted to a midpoint indicator, using the H^+-equivalency principle for acidification and the Redfield ratio for eutrophication.
- For terrestrial systems the damage is calculated per unit of surface area. For water systems surface area is not a good measure, or at least not a measure that can be directly compared with land surface. This means that there is a problem of converting the indicator to the damage category.
- It is not clear whether and how damage from COD and BOD emissions can be included. We propose to leave these out, as also suggested by WIA.

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[6] Ellenberg curves provide the relation between the chance of occurrence of a plant specie in relation to nutrient availability, acidity and humidity. In general they show every plant has its optimum combination, which means it is not true that less is better, as often assumed in LCA.

2.2.3. Impacts of land use

WIA distinguishes four types of land use impacts:

- increase of land competition, which expresses that the usable surface area on earth is limited and that different functions compete. This is also reflected in the economic system.
- degradation of biodiversity, which expresses that many non-natural uses of land results in lower or zero biodiversity.
- degradation of life support functions, often expressed as the net free productivity. This is a measure of the biomass production on land without human intervention.
- degradation of cultural values, which expresses that there are cultural values, and archeologic values in old landscapes.

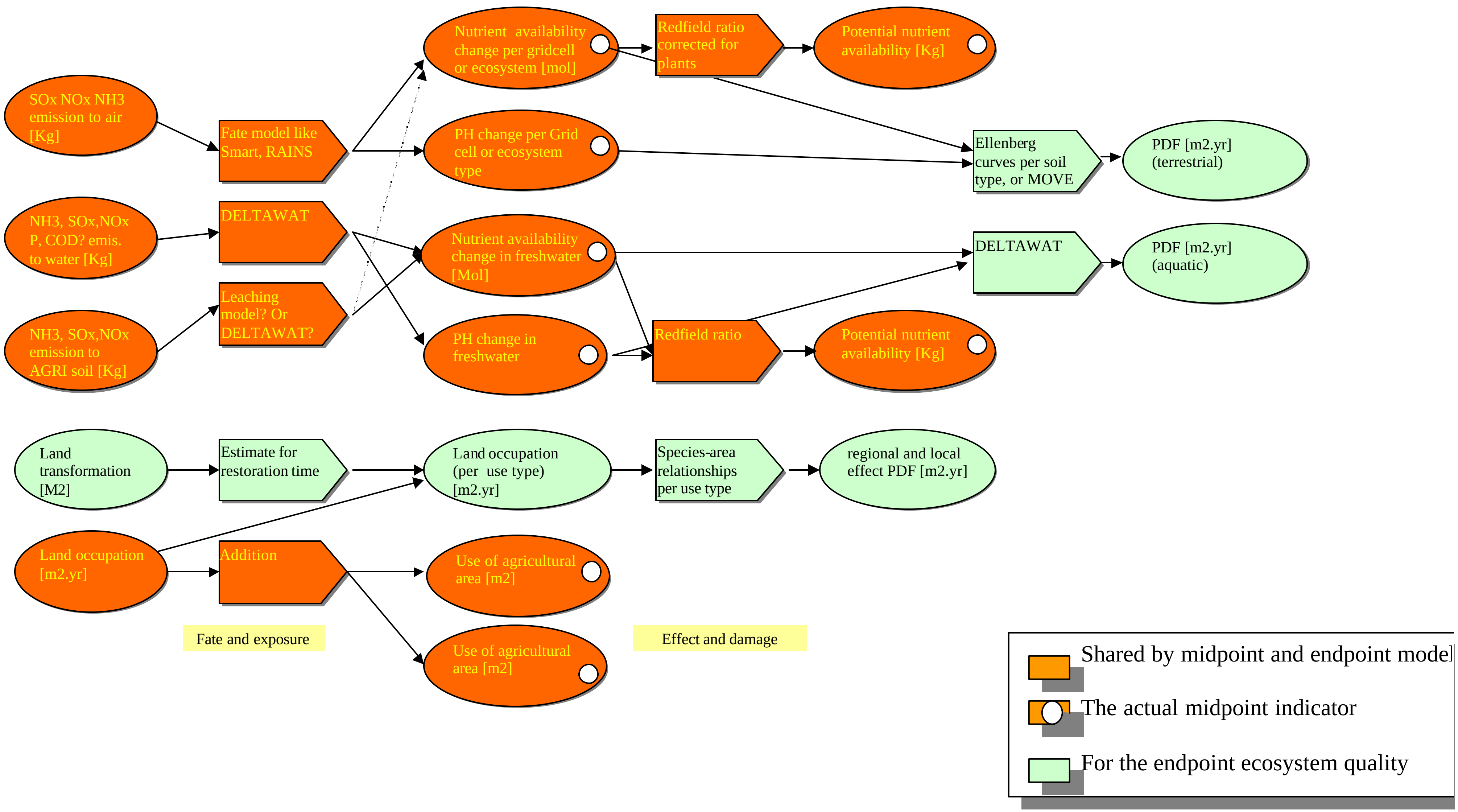
WIA finds it hard to recommend any particular approach, although it does not seem to favour the land competition approach, as competition is so closely related to economic aspects. It also has the rather strange consequence that conversion of natural areas reduces the competition in other areas.

For the midpoint indicator we propose the competition approach, as is currently used in the Handbook LCA; however as this approach all different type of land uses are simply added the environmental relevance is low. Therefore we propose to have two midpoints:

- competition in agricultural area;
- competition in urban area.

These midpoints only include LCI parameters defined as occupation, and not transformation. It is not useful to include a midpoint for competition in natural areas as in general natural areas are no longer natural when they become used.

For endpoints a similar model as the Eco-indicator 99 model that relates to biodiversity, can be used, preferably incorporating as much as possible the recent work of Köllner and Lindeijer. We propose to distinguish land occupation and land transformation as two different variables. Transformation can be converted to occupation if we multiply the transformed area with the average restoration time. This restoration time is then defined as the time it takes to get an ecosystem with a similar quality as the original. We propose to set default restoration period periods per type of transformation.


SOx NOx NH3 emission to air [Kg]
Fate model like Smart, RAINS
Nutrient availability change per gridcell or ecosystem [mol]
Redfield ratio corrected for plants
Potential nutrient availability [Kg]
PH change per Grid cell or ecosystem type
Ellenberg curves per soil type, or MOVE
PDF [m2.yr] (terrestrial)
NH3, SOx,NOx P, COD? emis. to water [Kg]
DELTAWAT
Nutrient availability change in freshwater [Mol]
DELTAWAT
PDF [m2.yr] (aquatic)
NH3, SOx,NOx emission to AGRI soil [Kg]
Leaching model? Or DELTAWAT?
PH change in freshwater
Redfield ratio
Potential nutrient availability [Kg]
Land transformation [M2]
Estimate for restoration time
Land occupation (per use type) [m2.yr]
Species-area relationships per use type
regional and local effect PDF [m2.yr]
Land occupation [m2.yr]
Addition
Use of agricultural area [m2]
Use of agricultural area [m2]
Fate and exposure
Effect and damage
Shared by midpoint and endpoint model
The actual midpoint indicator
For the endpoint ecosystem quality

2.3. Climate change and ozone layer depletion

WIA concentrates on a midpoint approach for these categories, and does not provide much new insights other then the recommendation to use only the direct greenhouse gas GWP values defined by the IPCC (Houghton, 2001), or the latest WMO ODP values. A further recommendation is to include NO_x emitted at high altitudes in the ozone depletion model.

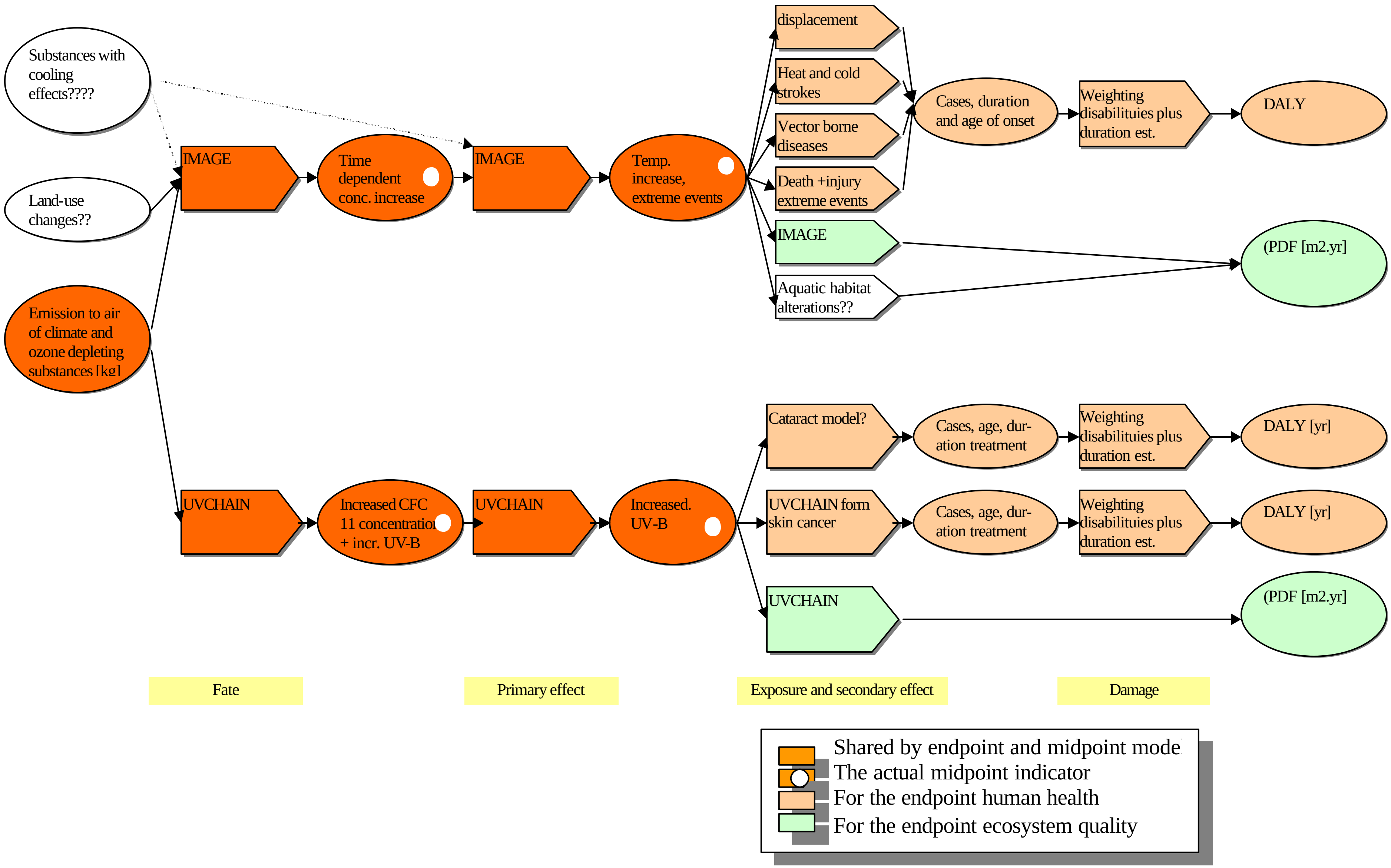
We propose to use some of the models that have been used by RIVM to contribute to the IPCC work. For climate change this is the IMAGE model, for ozone layer depletion this is the UV Chain model.

2.3.1. Climate change

The IMAGE model can produce temperature change calculation as result of a certain emission scenario and of land use changes. It is not yet sure if we should also take into account the land-use impact. Temperature change seems to be a good midpoint indicator. The IMAGE model can furthermore also compute damages to ecosystems (in terms of PDF) and some human health impacts, although it is not yet clear how.

2.3.2. Ozone layer depletion

The UV chain model can compute the UV increase as result of a certain emission scenario. This seems to be a good midpoint indicator. The model is also able to compute human health effects (although cataract is still missing), and ecosystem damage in terms of PDF.



Substances with cooling effects????
Land-use changes??
Emission to air of climate and ozone depleting substances [kg]
IMAGE
Time dependent conc. increase
IMAGE
Temp. increase, extreme events
displacement
Heat and cold strokes
Vector borne diseases
Death +injury extreme events
IMAGE
Aquatic habitat alterations??
Cases, duration and age of onset
Weighting disabilituies plus duration est.
DALY
(PDF [m2.yr]
UVCHAIN
Increased CFC 11 concentration + incr. UV-B
UVCHAIN
Increased. UV-B
Cataract model?
UVCHAIN form skin cancer
UVCHAIN
Cases, age, duration treatment
Cases, age, duration treatment
Weighting disabilituies plus duration est.
Weighting disabilituies plus duration est.
DALY [yr]
DALY [yr]
(PDF [m2.yr]
Fate
Primary effect
Exposure and secondary effect
Damage
Shared by endpoint and midpoint mode
The actual midpoint indicator
For the endpoint human health
For the endpoint ecosystem quality

2.4. Resources

The choice of impact categories and characterisation models for resource-related impact categories is less clear than for most other categories and models. Therefore, a larger discussion is required.

2.4.1. The nature of the problem

This chapter starts with the question what and why we would like to include in the resources-related impact categories. First, three points of view are described, and afterwards some proposals are made.

The user point of view

The risk that mankind will run out of resources for future generations, is often quoted as an important issue. Some groups take resource depletion as the only issue that is monitored. For instance in material flow accounting (MFA) all product systems are assessed by the amount of resources that are displaced, as a proxy for other environmental impacts. Others maintain that not the resources, but the emissions or waste (the sinc side of the resources) are the main problem.

As model developers we need to serve both views, and we cannot decide to leave resources out. The weighting procedure allows users to express their opinion. Having said this, we need to understand exactly why people consider resource depletion to be relevant. The most commonly heard opinion is that future generations need to have the same, or at least as good access to the resources as we have. This means we have to understand (or speculate on) the future resource needs, as that is apparently the thing we want to protect.

To understand resource needs we need to distinguish between a material and the function it can provide, or as Müller-Wenk states, the essential property of the material that is used to serve a certain purpose. Table 2 below provides an overview of the functions and essential properties some types of resources can provide.

Table 2. Main types of resources and some of their characteristics.

Resource	Subcategory	type	Essential property lost?	Recycling possible?	Main function(s)	Time after which shortages can occur	Alternatives
minerals	metals	stock	–	+	construction	centuries	many, also wood, etc.
	uranium	stock	+	–[7]	electricity	centuries	no (fission?)
fossil fuel		stock	+	–	all energy	decades	within the group
wind, water, solar flux		flow	+	–	electricity	unlimited	within the group
energy crops	(see also agriculture)	flow	+	–	all energy	see agriculture	other energy

[7] A breeder reactor can in principle generate plutonium, form the large stock of U238 as alternative fuels, with the same or higher rate than the depletion of the scarce U235.

water		fund/ flow	–	+	agriculture, humans, ecosystems	present	none
land (surface)	for urban use	fund/ flow	sometimes	sometimes	living, transport, working	present	intensify use
	for agricultural use	fund/ flow	sometimes	sometimes	feeding, energy crops	present	intensify use
	for natural area's	fund/ flow	sometimes	sometimes	recreation, "sustainability"[8]	present	none
	water surface	fund/ flow	sometimes	sometimes	recreation, transport	present	intensify use
silvicultural resources	hunting, fishing, herb collection	fund/ flow	+	–	feeding, medicines, energy (in 3rd world)	present	agriculture
	wood for construction	flow	+	sometimes	housing, furniture	present	metals, bulk resources
bulk resources		fund	sometimes	sometimes	infrastructure, housing	centuries or longer	within group

The table shows that there are many different types of resources, and that there is quite a range of possibilities to substitute or recycle the resource. Furthermore it shows that there is quite a range in the time frame within which the resource shortage can become problematic.

We can also use the table the other way around, and take the basic needs of future societies as a starting point, and see if we can have sufficient resources in future. However, such an analysis is quite complex, and is hampered by a set of fundamental but interrelated problems:

- How technology, and especially the requirements for materials change over time. "The stone age did not end due to a lack of stones"
- Most resources can be substituted by another. The reason for using a certain resource is often found in the market prices. Copper is not the best material to conduct electricity; gold is. However, copper is used most because of the ratio of resistance to price. In the last decades we can already observe a shift from copper to aluminium for electricity conduction. If ever super conducting cables will become a commercial reality the use of copper will of course decrease for this application. Substitution does not only occur within a resource group. For instance bio plastics can replace steel. In fact there are only very few resources that cannot be replaced by others. These are: water and space, especially natural area's.
- The "size" of the fund very much depends on the willingness to pay for the use of low grade or low quality resources, and of the efficiency improvements that are still possible for the mining of these low grade stocks.

In many cases resource depletion and shifts in material demand will have an impact on market prices. Often this means prices will go up, which could also negatively affect the ability to maintain and expand manmade environment.

[8] Sustainability refers to a wide range of functions, like climate regulation, metabolism, gene pool preservation, etc.

The geological experts point of view for minerals and resources[9]

a) Minerals

In geostatistical models for minerals, it is generally accepted that the distribution of concentrations of mineral resources is lognormal if we plot quantities against grade. This phenomenon has been described, for single deposits, as Laski's law [Deyoung 1981]. There is a wide agreement amongst resource geologists that the lognormal ore grade distribution is a reasonable approximation also for the world-wide ore occurrences of a large part of minerals. Although real proof for this relation is not easy to provide, an illustrative example for the case of uranium is available from Deffeyes [Deffeyes, 1964].

Deffeyes has determined the average concentrations of uranium in different types of rock and in water. This data, combined with data on the world distribution of rock types has been combined in Figure 6. The grade varies in this graph from 50000 to 0.0005 parts per million. From this graph we can see that the size of the resource stock is completely dependent on the grade we are willing to mine. So in fact we cannot speak about resource quantities without defining the resource quality. This makes it difficult to use the reserve to use ratio to describe scarcity.

For assessments in the not too distant future, we do not have to take the full distribution into account, and we can use only the first part of the slope; this allows us to make a real marginal assessment, like in the case of emissions. The slope of the damage curve is needed, at the present average concentration. This is at the far left-hand side of the curve.

In the same report Deffeyes also presents data on the distribution of other resources. [Chapman and Roberts 1983] refers to the work of Deffeyes and bases his analysis of the seriousness of mineral extraction on data from Deffeyes. Figure 7 (taken from Chapman) shows the relation between resource availability and the concentrations. If the slope is steep, the resource availability increases sharply as the concentration decreases slowly. The quality of minerals with a steep slope decreases relatively slowly when the extraction continues. Chapman refers to the slopes as the M values.

[9] Largely taken from the Eco-indicator 99 methodology report chapter 6, with some changes.

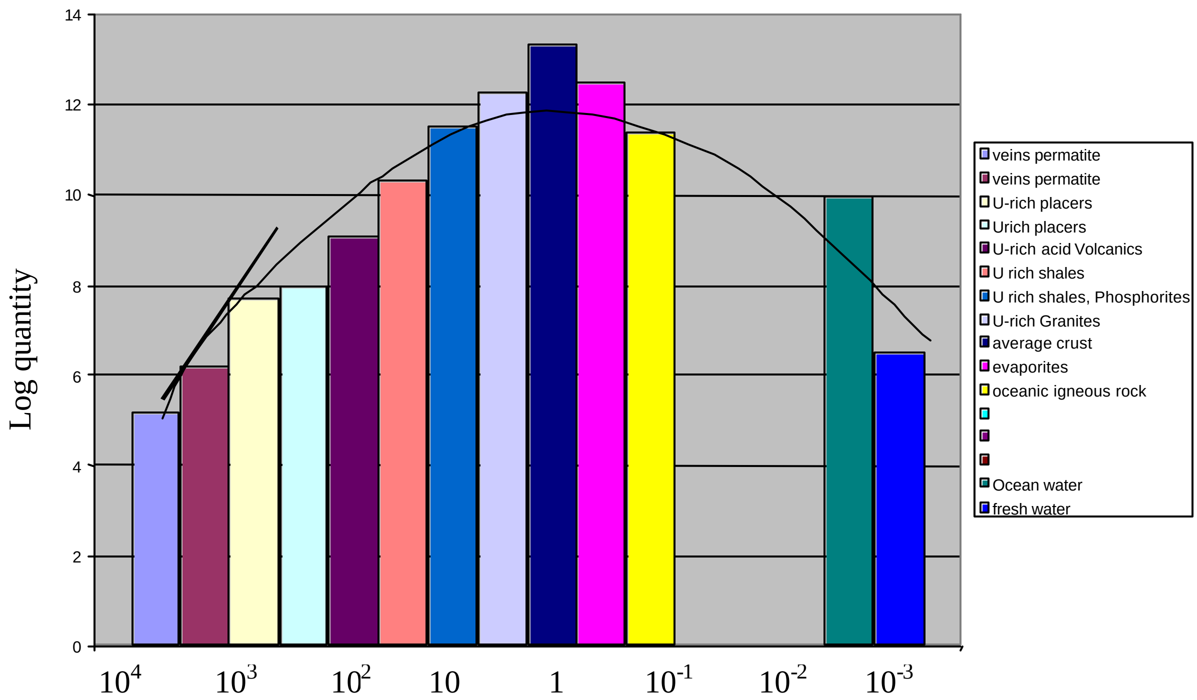


Figure 5. Distribution of the Uranium over the worlds crust, measured data according to [Deffeyes 1964]. The grade on the horizontal axis ranges from 50000 to 0.0005 parts per million; every two bars is one order of magnitude.

Box: Unclear data references

Unfortunately the source of the data used by Chapman is not clear. His only reference seems to be [DEFFEYES, 1964] ,and in this report we only find a graph, without a table and any reference to the origin of the data. An extensive literature search and attempts to contact the authors did not yield any results. [MÜLLER-WENK 98-1] Has critically analysed Chapman's and Deffeyes' data and compared it with another independent source [DE VRIES 1988].

Table 6.1 shows the differences in the slopes of the distributions according to Deffeyes and de Vries. The table uses the M values, which are defined as the slope of the quantity/quality relation.

For some minerals the data show good correspondence, while in the case of Chromium and Copper the correspondence is bad. We follow Müller-Wenk and use the Chapman data, plus the data for Tin and Iron from de Vries. .

Table 3 Comparison of the calculated slopes according to Deffeyes and de Vries; taken from [MÜLLER-WENK 1998-1]

	M according to Chapman	M according to de Vries	Accordance
Aluminium	25	22	good
Chromium	17	4	bad
Copper	1.6	5	bad
Lead	3.4	3	good
Manganese	19	7	medium
Mercury	2	3	good
Nickel	2.9	6	medium
Tungsten	6	3	medium
Zinc	7.3	5	good
Tin		1	
Iron		18	

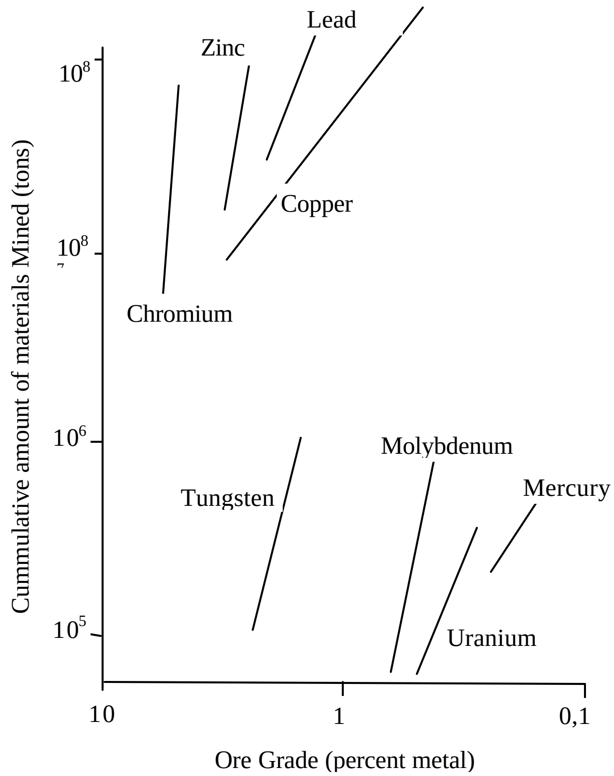


Figure 6. Slope of the availability against grade. Curve taken from [Chapman and roberts 1983].

b) Fossil fuels

The formation of fossil resources has occurred on a completely different time scale, trough completely different processes. A brief description of these processes can be found in box 2.2. and 2.3.

For fossil fuels the term “concentration” is not a very good indicator for the resource quality. The processes that have produced and distributed the fossil fuels are quite different from the processes that have caused the lognormal distribution in the earth crust. This means that the log normal distribution of resource concentration is not directly applicable to fossil fuels.

Basically we can distinguish three types of fossil fuels. These three types can be distinguished in a number of sub categories:

Table 4. Overview of fossil resources.

	sub category	
1 Oil	1.1 Conventional oil 1.2 Unconventional oil	1.1.1 All currently produced oil, that easily flows out of large wells 1.2.1 Tar sands 1.2.2 Shale 1.2.3 Secondary oil (produced from existing wells with steam injection) 1.2.4 Tertiary oil (oil from infill drilling, reaching pockets that were originally bypassed)
2 Gas	2.1 Conventional gas 2.2 Unconventional gas	2.1.1 Wet gas, associated with an oil accumulation 2.1.2 Dry gas, unrelated to oil fields 2.2.1 Natural gas liquids (condensed gas) 2.2.2 Gas from coal-beds 2.2.3 Gas from tight reservoirs 2.2.4 Others, like mantle gas from deep in the earth crust 2.2.5 Hydrates: Gas in ice-like solid concentrations in oceans and polar regions
3 Coal	3.1 Conventional coal	3.1.1 Open pit mining (Hard coal or Lignite) 3.1.1 Underground mining

This brief overview demonstrates that apart from the conventional sources there are several alternative (unconventional) sources for oil and gas. Like in the case of the minerals, until now only the conventional sources are used, as these can be extracted with the least effort.

Quite unlike in the case of minerals, the effort of exploiting a resource does not decrease gradually when the resource is extracted. As long as sufficient conventional oil can be found, the effort to extract the resource does not increase significantly, as long as the oil keeps flowing.

Only when conventional resources become really scarce, mankind will have to start to explore unconventional resources. In this case the effort to extract the resource does increase. In the example of oil this could mean that additional drilling and pumping or even steam injection is needed.

So instead of a continuous decrease of the resource quality, we can observe a stepwise resource decrease, while between these steps the effort to extract is basically constant.

Box: Conventional oil and gas

Conventional oil (and gas) has been formed during certain distinct periods in distinct places. For instance the huge oil resources in the Middle East, the North Sea and Siberia were formed in the late Jurassic, some 150 million years ago. Another period was the Cretaceous, some 90 million years ago, which was responsible for the formation of oil in Northern South America. The Oil in North America dates from the Permian, some 230 million years ago. Oil and gas usually formed in shallow seas or lakes in areas around the tropics. Stagnant sinkholes and lagoons where perfect places to preserve organic material. Later, When such sinks were covered by a layer of sediment or salt and the temperature and pressure had increased sufficiently, all the conditions to form deposits were present.

During the formation of oil and gas, the pressure increases and usually the oil migrates upwards through the pores in the sediment into porous and permeable layers until it encounters a non permeable layer, under which it is trapped. According to [CAMPBELL 1998], only a fraction (about 1%) of the oil is trapped in oilfields that are large enough to exploit. The older the deposit the more has leaked. Especially gas will get lost through leaking very easily.

Unlike the formation of minerals, the formation of fossil resources can be deducted from our knowledge of the plate tectonics the climate changes and other processes that occurred the last half a billion years of the earth history. In global terms the bulk of oil and gas occurs in a geological "province" called the Thetys; a zone of rifting between the southern and the Northern continents, of which the Middle East, the Mediterranean and Mexico are remnants.
The detailed geological mapping has revealed where suitable formations, under which oil could have been trapped, are located. Because of this understanding, we can conclude that the world has now been so extensively explored, that all the large oil resources have been found and the scope for finding an entirely new one of any size is now greatly reduced, if not entirely removed [CAMPBELL 1998]. This can also be demonstrated by the next two figures:

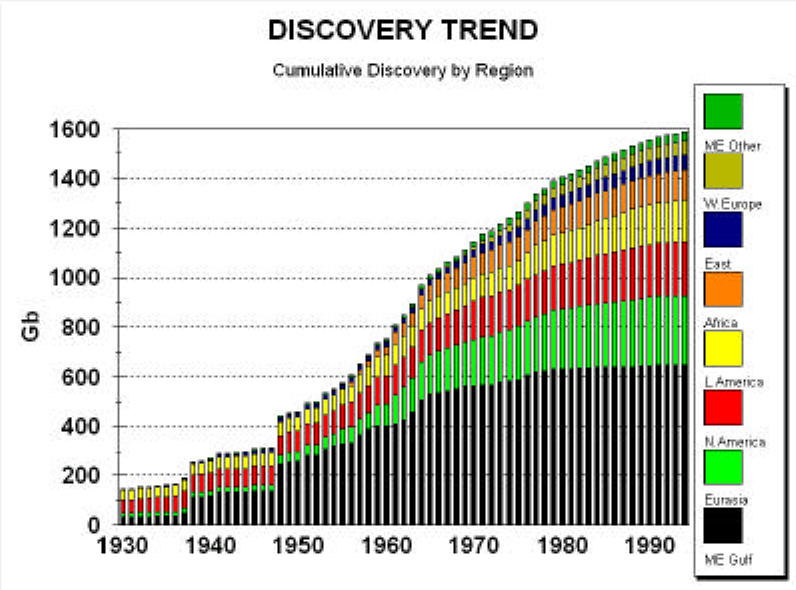


Figure 7: Cumulative discovery trend for oil. Clearly the discoveries are gradually becoming smaller, and the availability is reaching its maximum. [CAMPBELL 1998]

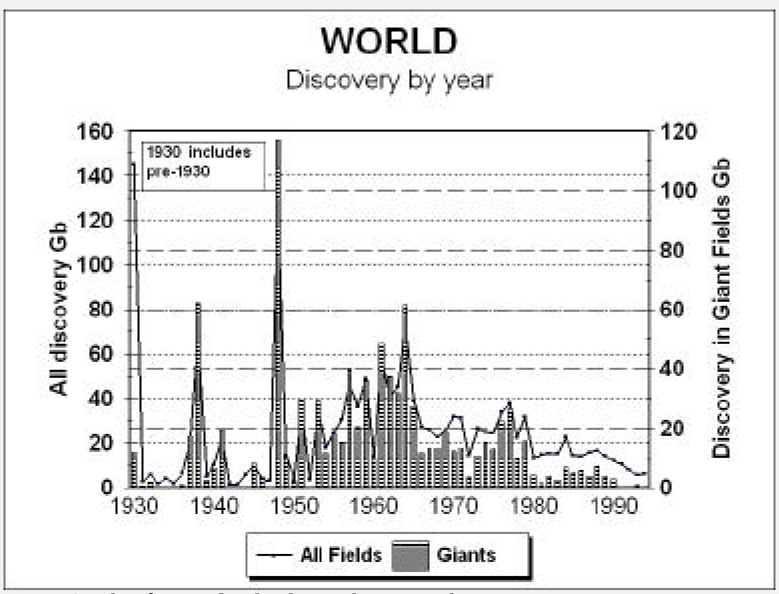


Figure 8: This figure clearly shows that since the seventies no new major recoveries were made. At present the discovery rate is about 6 Gigabarrel, while the production rate is about tenfold. [CAMPBELL 1998].

Figure 7 and Figure 8 show the problem with conventional oil in a nutshell. The last two decades the discovery rate is 6 to 10 Gigabarrel, while the consumption is in the order of 60 to 70 Gigabarrel.

In 1956 Hubbert proposed a prediction technique that is based on the observation that in any region, the unrestrained extraction of a finite resource rises along a bell shaped curve, that peaks when about half the resource has gone [CAMPBELL and LAHERRÈRE, 1998] and [KESSLER 1994]. With this model Campbell has surprisingly accurate modelled the increase and decline of the US oil production and to some extent also the world oil production, as can be observed from figure 6.4. According to Campbell this means that the peak in the world oil production may be expected around 2010. Also the International Energy Agency has adopted this view as can be seen from figure 6.5. [IEA 1998]

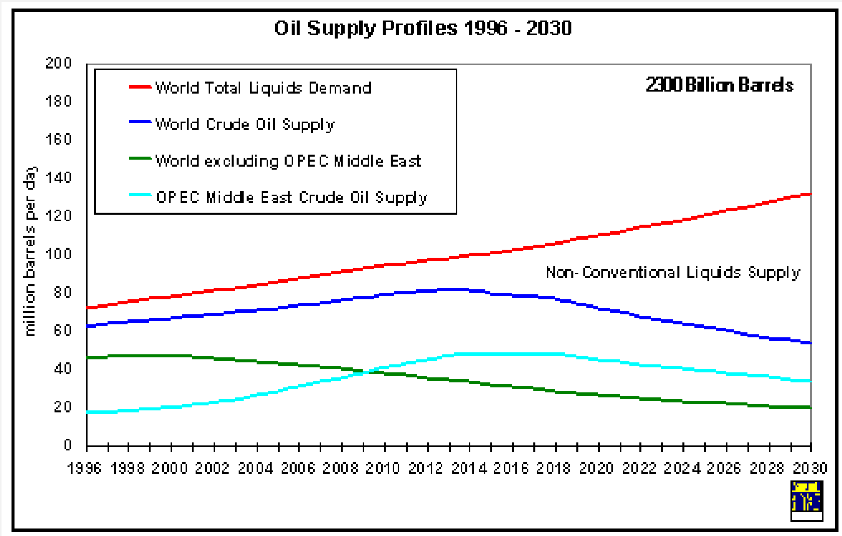


Figure 9: International Energy Agency projections for the future oil supply for the G8 countries. This graph clearly shows that the conventional oil supply will reach its peak around 2013, as around that time the OPEC production capacity will start to decrease. [IEA 1998]

As *Figure 9* shows, the transition from conventional to unconventional oil will be a gradual transition. However, the International Energy Agency recognises that around the peak of the conventional oil production, there will be a big shift in market prices, as from that time on the marginal oil production will be the unconventional oil. Also we will assume that at that moment we will assume oil is extracted from the unconventional sources.

Box: Coal

The biologic and geologic processes that produced coal resources are different from the processes that were responsible for the formation of oil and gas. In the first place, coal was not mainly formed from biological processes in aquatic conditions, such as in the case of oil and gas. Coal formation started with the build up of peat layers mainly from land-based vegetation such as woods, reeds and other plants. These formations occurred in a period between 250 and 50 million years ago in a much wider geographical area than the Thetys area that was the main place for oil and gas formation. This is one reason why coal resources are spread over a wider region than oil, although most coal is found in Europe, North America, the former USSR and China.

During the formation of the coal or lignite layer light hydrogen rich substances escaped from the layers and sometimes created gas deposits. As a result, coal has a high carbon content. In general the older layers have the highest carbon contents. Lignite is usually a relative young deposit with a carbon content of around 60 to 70%.

The resource availability for coal is much higher than for conventional oil or gas. The proven resources should be sufficient for about 200 to 300 years, if the present extraction rate is sustained, and if no major discoveries are made.

The LCA specialist point of view

In the WIA book Resources some important questions are raised:

- Is resource extraction limited by source or sink? For instance will the CO_2 related problems become so large that fossil fuel extraction is halted long before it is depleted?
- What to do with possibilities for substitution between resources, and the fact that resource uses change due to innovation? Remember: he stone age did not end because mankind ran out of stones, the iron age did not stop because iron became scarce.
- There are a number of different resource characteristics. Some are deposits, others are funds and again others are flows.

Table 5. Overview of the LCI results and the category indicators at the three levels, as far as they relate to Resources.

Elementary flow (LCI result)	Midpoint indicator	Endpoint indicator
Land use (m^2.yr)	Land competition (m^2.yr)	*See Ecosystem Quality*
Fossil fuels (kg)	Resource depletion (kg Sb)	Mineral resources extraction effect (MJ?)
Minerals (kg)		Fossil resources extration effect (MJ?)
Silvicultural extraction (–)	Abiotic depletion (kg Sb)	*See Ecosystem Quality*

The WIA book separates three types of resources. Biotic, a-biotic (flow, fund and stock) and land. For a-biotic (stock) resources, the book distinguishes between:

- Addition of the total mass (ores) or energy content of the resources. This approach is not recommended.
- Aggregation based on the deposit (D) and Current consumption (U), with three alternative expressions (1/D, U/D or 1/D*U/D). The main comment is that the size of the deposit is quite uncertain. From the three alternative formulas the third, proposed by [Guinée and Heijungs 1995] has most preference. This is also the approach used in the CML 2000 method. This will also be the basis for the Midpoint indicator.
- Aggregation based on environmental interventions caused by future hypothetical processes, such as the method proposed by Weidema based on the energy needed to restore resources and Müller Wenk, based on the surplus energy for future mining of low grade resources. The latter method has also been applied (with some modifications) in the Eco-indicator 99. The main comment on this type of methods is the need to assume future scenarios, which makes the characterisation factors rather uncertain.
- Exergy, as proposed to [Finveden 1997]. The main comment is that it is questionable if exergy really addresses the environmental problem, as the chemical entropy in the ores, rather then in the metal content of the ore dominates the equations. On the other hand there are some interesting aspects.

Non of the approaches is really recommended.

For A-biotic fund resources, such as water (except fossil water), and possibly sand, clay and gravel damage is not really related to the depletion, but to the ecosystem damage and local availability.

A-biotic flow resources, like solar radiation flowing freshwater and nutrient flows from weathering can not be depleted, although the use of this flows can impact Human health and Ecosystems.

2.4.2. Proposals for including resources in phase 2

Analysing the user point of view, the geologist point of view and the WIA recommendations we conclude that we should somehow include the issue of resources, in spite of the fact that it is not really clear if and when some types of resource shortages will become a real problem that damages the interest of future generations. The most important reason for this is that we do not know enough about the manageability of the problem: Can future generations always find a way to substitute a resource without too high sacrifices regarding affordability and quality?

On the other hand it is clear that some resource shortages are already causing problems for the present generations, these are especially in the area of land use and water.

Proposal for mineral stock resources
For minerals, we propose to use the marginal approach based upon the slope of the availability versus resource grade [Müller-Wenk 1999]. This indicator can be used to further model an endpoint indicator, based on the surplus energy concept (option 3 of WIA) as presently implemented in Eco-indicator 99. The following arguments can be used for this choice:

- the slope factors provide a marginal concept, which is in line with the other impact categories;
- on the midpoint level, the slope factors are relatively robust, there is no need to speculate on future energy requirements;
- the result of the surplus energy is relatively easy to explain, especially by telling a weighting panel the magnitude of the future surplus energy with present day energy consumption (which is very low).

For the endpoint, the approach of using surplus energy has been described, although refinement may be needed. For the midpoint, we propose not to use the slope itself as characterisation factor, but a "normalised" slope, that is derived when the slope is divided by the present average concentration. In both the midpoint and the endpoint approach, we disregard the substitutionability and the recycleability. If a resource is recycled this is already reflected in the inventory analysis. If not, it is highly hypothetical that the resource will ultimately be recycled, for instance from mining a landfill.

Proposal for fossil fuels
Fossil fuels can be easily substituted by each other, and it is not realistic to ignore this fact. It is true that distribution of natural gas to households is much easier than distribution of coal or oil, but it is easy to make gas from coal. Similarly cars run usually on liquid oil derived products, but gas is also used as a fuel. Conversion from coal to oil is less attractive, but liquid oil can be relatively easily made form shale. In a few decades the primary fossil fuel sources will be coal, shale and tar sands. Using present day extraction and conversion efficiencies, an increase from 0.016 MJ needed for production per MJ of energy carrier produced by liquid oil to 0.16 MJ/MJ for shale will be found; typically a tenfold increase. However, the difference between gas, liquid oil and hard coal, are not very big compared to the difference between these conventional resources and for instance shale. In Eco-indicator 99, this tenfold increase leads to relatively high characterisation factors, and it was found that characterisation factors are heavily dependent on the assumptions on the possibility of substitution. We propose to review this issue, and analyse different assumptions for substitutions.

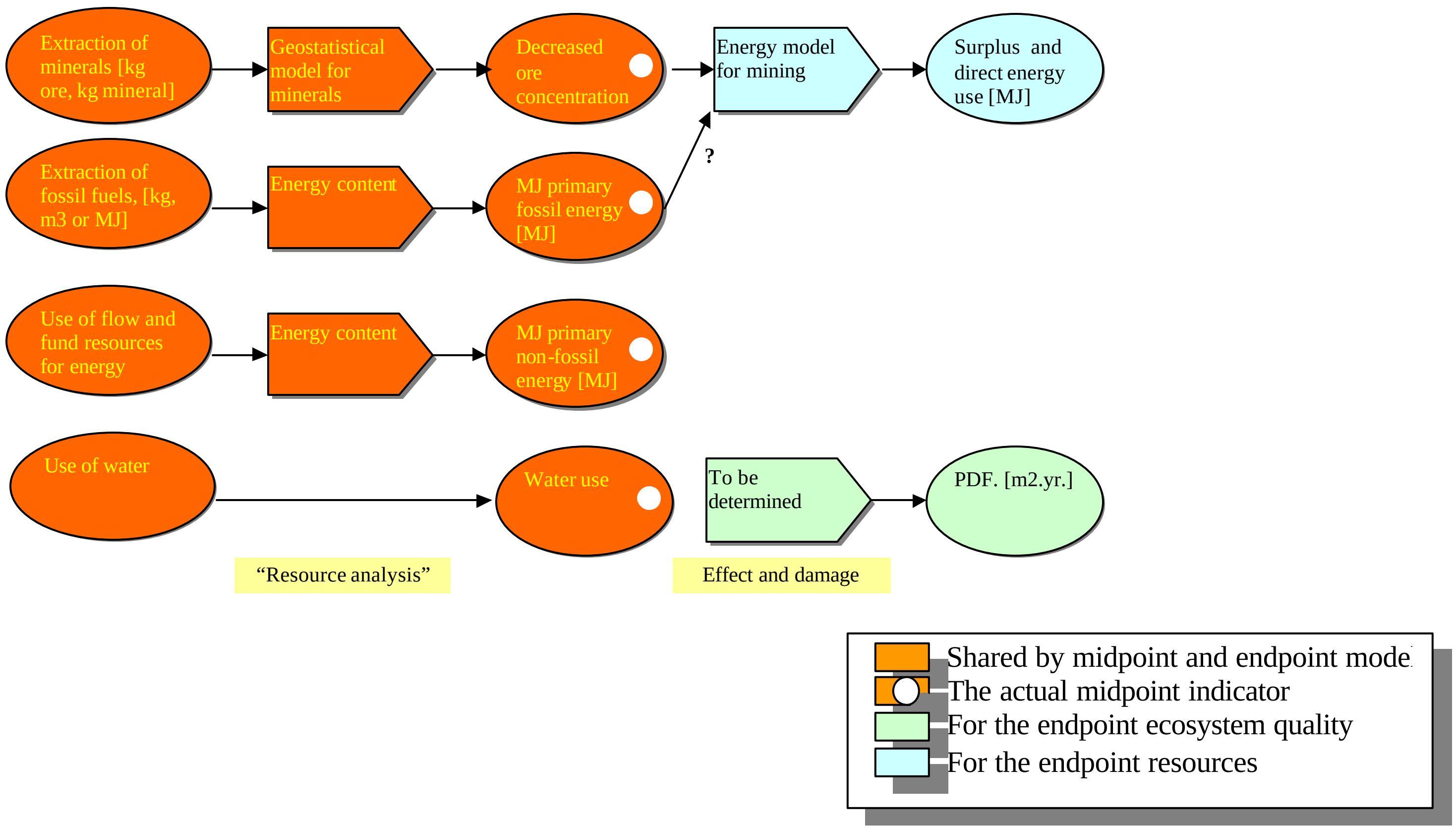
For the midpoint, the dependence on substitution assumptions is not acceptable. Therefore we propose not to integrate fossil fuels with minerals, but to make a simple robust midpoint, expressing the total fossil fuel use, in terms of energy content (MJ higher heating value).

Proposal for abiotic fund and flow resources (wind, sun, water, energy crops)
We think about proposing not to model impact categories and recommend practitioners to specify the impacts on human health and ecosystem-related categories. Especially the link to land-use can be important, but in the case of energy crops, also eutrophication and the use of pesticides can play a role.

For the same reason as mentioned above, we propose to have a midpoint indicator for non-fossil energy use, expressed in MJ primary energy, lower heating value. Most resources produce directly electric energy, which means it is not possible to express primary energy. This can cause an inconsistency within this impact category. Uranium, which is of course also a non fossil fuel can be regarded as a mineral. This means it is taken into account in the minerals impact category. This type of energy is also added to the surplus energy as explained above.

Proposal for biotic resources

Biotic resources have not yet been sufficiently researched. For the endpoint model, we would prefer to link this type of extraction to the endpoint ecosystem quality; however it is not yet clear how.


Extraction of minerals [kg ore, kg mineral]
Geostatistical model for minerals
Decreased ore concentration
Energy model for mining
Surplus and direct energy use [MJ]
Extraction of fossil fuels, [kg, m3 or MJ]
Energy content
MJ primary fossil energy [MJ]
?
Use of flow and fund resources for energy
Energy content
MJ primary non-fossil energy [MJ]
Use of water
Water use
To be determined
PDF. [m2.yr.]
"Resource analysis"
Effect and damage
Shared by midpoint and endpoint model
The actual midpoint indicator
For the endpoint ecosystem quality
For the endpoint resources

2.5. New impact categories

We are aware of the need to develop “new” impact categories in order to deal with issues that are relevant, but not yet covered. The most important once seem to be:

- the effects of noise on human health;
- erosion, salination, soil depletion, and other land-use related impact categories that may be of particular importance in tropical and sub tropical regions;
- silvicultural extraction (mainly fishing and hunting).

3. The existing methods

This chapter provides a description of the two methods for LCIA that have formed the basis of the proposed method: that of the Handbook LCA as a typical midpoint-oriented method and that of Eco-indicator 99 as a typical endpoint-oriented method.

3.1. Brief description of a midpoint-oriented approach

The baseline method for impact assessment of CML and collaborators, which is used in this document to represent all midpoint-oriented approaches, is an impact assessment method that uses mainly mid-point category indicators. It approaches impacts from the point of intervention, calculating the primary results of an intervention in a certain impact category, without applying weighting by default. Note, however, that a weighting of the indicator results into a single weighted score is well possible, provided that appropriate weighting factors are compiled. The Handbook LCA considers normalisation as a recommended step after characterisation, and provides factors to carry out this normalisation at different spatial scales. Although areas of protection are identified for each impact category, mechanisms are not followed to their endpoints, at least not in a quantitative way. The areas of protection are:

- human health;
- natural resources (biotic, abiotic);
- natural environment (ecosystem quality, biodiversity);
- man-made environment (crops, culture,…).

Fate and effect calculations are performed for most emissions, except in the category of eutrophication. The impact categories land use and resource use are assessed in terms of occupation (competitive use) and depletion, using only primary quantities (area, duration, extraction rate, ultimate reserve). Steps included are thus:

- human toxic emissions: fate, exposure, effect;
- ionizing radiation: fate, exposure, damage;
- ecotoxic emissions: fate, effect;
- eutrophying emissions: effect;
- land use: competition;
- resource extractions: depletion.

The results of the effect assessment in the categories human toxicity and ecotoxicity and acidification are expressed in number of overdoses or potential cases, based on acceptable daily intakes (ADI), predicted no-effect concentrations (PNEC), or critical loads (CL).

The Handbook LCA proposes a baseline set of impact categories with an accompanying baseline set of category indicators, characterisation models and characterisation factors. Additional impact categories and characterisation factors are available or may be developed for use in addition to or instead of the baseline categories and models.

3.2. Brief description of an endpoint-oriented method

The Eco-indicator 99, which is used in this document to represent all endpoint-oriented methods, is a method for impact assessment that uses endpoint category indicators in a "top-down" approach. This means that it has been designed with what is needed for decision-making as a starting point, whereas a "bottom-up" approach starts with what is available. The result of the method can be one single score, but it is also possible to present 11 impact category indicators, or 3 damage indicators. The impact category indicators are all defined at the level of the endpoint. The single score is found by weighting the normalised indicator results for the three damage categories (groups of endpoints). The three damage categories are:

- human health (damage in terms of DALY; see below);
- ecosystem quality (damage expressed in terms of PDF*area*time; see below);
- resources (damage in future surplus energy; see below).

An impact category causes damage in only one of the damage categories, but some interventions may be assigned to more than one impact category. Manmade environment is deliberately not included as a damage category. To calculate endpoint indicator results, several operational steps have to be implemented. For the three damage categories, these are the following :

- human health: fate, exposure, effect, damage assessment, normalisation;
- ecosystem quality for emissions: fate, effect, damage assessment, normalisation;
- ecosystem quality for land use: effect, damage assessment, normalisation;
- resources: resource analysis (regarded as inverted fate), damage assessment, normalisation.

The result of the effect assessment in the categories of human health is expressed in number of cases (e.g. number of cataract and number of skin cancer patients for ozone depletion). Impacts of land use are assessed in terms of loss of biodiversity and damage to resources in terms of increased effort for future extractions. In the calculation of the latter, ore-grade quality and fuel replacement are taken into account.

There are three actual implementations of Eco-indicator 99, hence three possible scores, as will be clarified in later sections of this document. Each is indicated by two letters, one for the characterisation perspective and one for the weighting perspective, combined as (H, A), (E, E) and (I, I).

3.3. Brief discussion of the differences in results

Due to differences in characterisation models or factors, the contributions to a certain impact category of a substance may have very different relative importance in the Handbook LCA and Eco-indicator 99, respectively. For an average western European emission profile [Oers et al.], major differences occur:

- for photo oxidation, to which CO and SO_2 do not contribute in Eco-indicator 99;
- for human toxicity, that is dominated by carcinogenic PAH in the Handbook LCA (80%) and by Cr(III) and Cr(VI) in Eco-indicator 99 (70%);
- for ecotoxicity, that is dominated by pesticides (fresh water 60%), vanadium to air (marine 80%) and aldicarb and Cr(III) (terrestrial 50%) emissions in the Handbook LCA and by zinc to soil and air and lead to air emissions in Eco-indicator 99 (80% total).

Differences in the contributions to acidification and eutrophication are probably mostly due to the very different principles employed by the two methods, as well as due to the fact that Eco-indicator 99 includes emissions to air only.

Table 6 shows the contribution that is made by a variety of interventions (emission and extractions) to the final weighted score of the emission profile of Western-Europe. Note that, although the Handbook LCA does not specify weighting factors, the weighting factors from NOGEPA have been used to aggregate the indicator results for the midpoint-oriented method.

Table 6. Selected comparison of the contribution (in %) that is made by different interventions to a weighted index for the baseline method of the Handbook LCA and the three different versions of Eco-indicator 99.

Intervention	Handbook LCA + NOGEPA	EI 99 (H, A)	EI 99 (E, E)	EI 99 (I, I)
CO_2 to air	14	6	5	8
NO_2 to air	3	9	10	3
PAH to air	10	–	–	–
Cr(III) to soil	1	10	9	4
Zn(II) to soil	0	10	14	8
CFC-11	7	7	6	9
C_2H_4	1	1	1	2
natural gas	3	2	2	–
crude oil	4	2	2	–

One can conclude that, from the point of view of substance contribution, the results differ less between the three perspectives of Eco-indicator 99 than between Eco-indicator 99 and the Handbook LCA. Note, however, that weighting is not recommended by the Handbook LCA and hence the above numbers do not result from the baseline method.

Instead of via a final weighted score, we can also compare characterisation factors of the two methods directly. The difference of the results are expressed as percentages of the value of the Handbook LCA in the following way. A positive fraction means that Eco-indicator 99 has a larger characterisation factor, of course with respect to the reference substance.[10] For global warming, differences range from –1% to +9% and for photo oxidation from –37% to +20%. For ozone depletion the differences are mostly around 0%, but a few are between +15% and +73%. For ionising radiation, the characterisation factors, when defined, are exactly the same (except for (I, I)).

3.4. Impact categories, category indicators and characterisation models

A characterisation method consists of a number of elements, among which we will discuss:

- the selection of impact categories;
- the selection of category indicators and characterisation models to address these impact categories;
- the declaration of a mathematical expression to calculate an indicator result for each impact category.

The next few sections presents these elements for the characterisation methods of Eco-indicator 99 and the Handbook LCA.

3.4.1. Selection of impact categories

Impact categories selected in the Eco-indicator 99 are listed below per damage category.

- damage to human health: carcinogenic effects, respiratory effects (organic substances), respiratory effects (inorganic substances), climate change, ionising radiation, ozone layer depletion;

[10] This limits the number of categories where we can make this comparison.

- damage to resources: minerals, fossil fuels;
- damage to ecosystem quality: ecotoxicity, acidification and eutrophication, land use (covering land occupation and land conversion and including biotic resources).

Possible additional categories are effects of noise (based on the work of Müller-Wenk and applied in car tyre study) and non-carcinogenic effects of metals (based on the work of Jolliet et al., and applied in Soldering LCA). Workplace hazards are excluded.

Some missing endpoints are:

- climate change impact on ecosystem quality (BOD, desertification, sensitive habitat destruction);
- some human health effects of climate change;
- ozone depletion and photo oxidant effect on ecosystem quality
- non-carcinogenic or respiratory damage to human health (except from the work on metals);
- eutrophying impact on human health.

Some missing impacts are:

- a land use category, that reflect disturbance (windmills, tall buildings);
- impacts of silvicultural extraction (fishing, hunting, collecting plants from nature etc.);
- eutrophication (waste heat; emissions to soil and water);
- desiccation (climate change).

The following impact categories are used as a baseline in the Handbook LCA:

- depletion of abiotic resources;
- impacts of land use (only the subcategory competition);
- climate change;
- stratospheric ozone depletion;
- human toxicity;
- ecotoxicity (with subcategories freshwater ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity);
- photo oxidant formation;
- acidification;
- eutrophication.

These categories are the recommended minimal set of ISO and WIA.

Non-baseline categories with a baseline method specification are freshwater and marine sediment ecotoxicity and effects of waste heat, odour, noise, casualties and ionising radiation. Since the latter category is part of the standard method in the endpoint-oriented method, it will be evaluated as part of the baseline method in this document to clarify the overlap between the two.

Non-baseline categories are depletion of biotic resources, land transformation (loss of biodiversity, loss of life support functions), desiccation. Workplace hazards are excluded.

A comparison of Eco-indicator 99 and Handbook LCA is obscured by the fact that the names of identical or quite similar impact categories may still differ, and that some impact categories that are treated separately in one method are taken together in the other method. A first step in clarifying the discussion that follows is therefore the harmonisation of the names of the impact categories; see Table 7 for a proposal that is used in the remainder of this document.

Table 7. Overview of the impact categories of the Handbook LCA, of Eco-indicator 99, and their common indication in this report.

Impact category	Midpoint-oriented approach			Endpoint-oriented approach	
resource depletion	depletion of abiotic resources			minerals	fossil fuels
land use impacts	land competition[11]			land use	
climate change	climate change			climate change	
ozone layer depletion	stratospheric ozone depletion			ozone layer depletion	
human toxicity	human toxicity			respiratory effects (inorganic)	carcinogenic effects
photo-oxidant formation	photo-oxidant formation			respiratory effects (organic)	
ecotoxicity	freshwater aquatic ecotoxicity	marine aquatic eco-toxicity	terrestrial ecotoxicity	ecotoxicity	
acidification	acidification			acidification	
eutrophication	eutrophication			eutrophication	
ionising radiation	impacts of ionising radiation[12]			ionising radiation	

3.4.2. Category indicators and characterisation or equivalency factors

The category indicator is a quantifiable representation of an impact category. For one specific impact category, it can be chosen at any point between the begin and the end of the environmental mechanism. The category indicators of Eco-indicator 99 are located more towards the end than those of the Handbook LCA, hence the terms midpoint-oriented method for the Handbook LCA and endpoint-oriented for Eco-indicator 99. Table 8 provides a list of category indicators for these two methods.

Table 8. Category indicators for the impact categories in the Handbook LCA and Eco-indicator 99.

Impact category	Midpoint-oriented approach	Endpoint-oriented approach	
resource depletion	ultimate reserve in relation to annual use	minerals: surplus energy	fossil fuels: surplus energy
land use impacts	land occupation	PDF	
climate change	infrared radiative forcing	DALY	
ozone layer depletion	stratospheric ozone breakdown	DALY	
human toxicity	predicted daily intake in relation to acceptable daily intake	resp: DALY	carc: DALY
photo-oxidant formation	tropospheric ozone formation	DALY	

[11] Land use impacts are divided in three subcategories: land competition (a baseline impact category), loss of biodiversity (not a baseline impact category) and loss of life support function (not a baseline impact category). Only the first of these will be maintained in the further discussion.
[12] Not a baseline impact category.

ecotoxicity	predicted environmental concentration in relation to predicted no-effect concentration	PDF
acidification	deposition in relation to acidification critical load	PDF
eutrophication	deposition in relation to N/P equivalents in biomass	PDF
ionising radiation	DALY	DALY

For most impact categories, the characterisation step itself proceeds by the use of characterisation factors, which convert an LCI result into a category indicator result. Table 9 lists these characterisation factors.

Table 9. Characterisation factors to convert LCI results into indicator results in the Handbook LCA and in Eco-indicator 99. In the latter, the characterisation factors have not received explicit names, although they are sometimes equivalent to or directly derived from POCP or other factors with a name. A "+" has therefore been inserted to indicate that characterisatiom factors are avaible to address these category indicators in Eco-indicator 99.

Impact category	Midpoint-oriented approach	Endpoint-oriented approach	
resource depletion	ADP	minerals: +	fossil fuels: +
land use impacts	1	+	
climate change	GWP	+	
ozone layer depletion	ODP	+	
human toxicity	HTP	resp: +	carc: +
photo-oxidant formation	POCP	+	
ecotoxicity	FAETP, MAETP, TETP	+	
acidification	AP	+	
eutrophication	EP	+	
ionising radiation	ionising radiation damage factor	+	

For some categories, in both types of approaches, fate and/or effect are assessed for one or a few pilot substances. For other substances, an equivalency factor is used to find a fate factor by simple multiplication; this is in Eco-indicator 99 referred to as an "umbrella approach", where it is used for climate change: the method uses three pilot substances and applies the equivalency factor for a substance to one of those three characterisation factors, according to its lifetime.

In Eco-indicator 99, characterisation factors are mostly the result of fate assessment, but sometimes this cannot be separated from effect or even damage assessment. The indicator is the quantity that is used to calculate the final numerical score for a certain impact category.

The indicator results themselves are expressed in units. In the Handbook LCA, the impacts of all interventions other than land competition are aggregated by multiplying the mass of the substance and its "potential" to cause an effect relative to a reference substance. Most of these potentials are given explicitly in the next section (equations). Since they are relative quantities, they are dimensionless and the indicator results are all in units of reference-equivalent kilograms.Table 10 gives an overview of these units.

Table 10. Units of the indicator results obtained with the characterisation models of the Handbook LCA and Eco-indicator 99.

Impact category	Midpoint-oriented approach	Endpoint-oriented approach	
resource depletion	kg Sb	minerals: MJ	fossil fuels: MJ
land use impacts	$m^2 \times yr$	$m^2 \times yr$	
climate change	kg CO2	yr (DALY)	
ozone layer depletion	kg CFC-11	yr (DALY)	
human toxicity	kg DCB	resp: yr (DALY)	carc: yr (DALY)
photo-oxidant formation	kg C_2H_4	yr (DALY)	
ecotoxicity	kg DCB	$m^2 \times yr$	
acidification	kg SO_2	$m^2 \times yr$	
eutrophication	kg PO_4	$m^2 \times yr$	
ionising radiation	yr (DALY)	yr (DALY)	

3.4.3. Equations for characterisation

Characterisation proceeds in general by multiplying a characterisation factor with the size of the intervention (emission, extraction, land use, etc.). A general formula is

$$S_j = \sum_i Q_{ji} m_i$$

where S_j is the indicator results (or "score") for impact category j, m_i is the size of the intervention of type i (for instance, the mass of a substance emitted to air), and Q_{ji} is the characterisation factor that links intervention i to impact category j. Interventions are, besides the usual kg for emissions and extractions, expressed in kBq (for ionizing radiation) or in km2*yr (land use). For each of the impact categories, we may specify the general formula in more detail, with an emphasis on the structure of the characterisation factor Q_{ji}.

Common symbols in all equations:

- index for interventions: i (subscript);
- index for endpoints (like diseases): n (superscript);
- background levels : x;
- model factors for fate : F, exposure : X, effect : E, damage : D;
- indicators results: S;
- index for emission compartment: e, final compartment: f, spatial scale: s, exposure route: r;
- index for reference substances: ref.

Impact category (j)	Midpoint-oriented approach	Endpoint-oriented approach
resource depletion	$Q_{ji} = \left(P_i / R_i^{\,2}\right) / \left(P_{ref} / R_{ref}^{\,2}\right)$	$Q_{ji} = \left(E_i^{5Q} - E_i^{1990}\right)$
land use impacts	$Q_{ji} = 1$	$Q_{ji} = 1.2 \;\; \Delta PDF_{x \to i}\, Time_i^{act}$
climate change	$Q_{ji} = GWP_i = RF_i / RF_{ref}$	$Q_{ji} = \sum_{n=1}^{6} [GWP_i^{ref}{}_i\, F_{ref_i}\, X_{(T)}\, E^n\, D \;]$
ozone layer depletion	$Q_{ji} = ODP_i = OC_i / OC_{ref}$	$Q_{ji} = \sum_{n=1}^{4} ODP_i^{ref}\; F_{ref}\; X_{(UV)}\, E^n\, D$
human toxicity	$Q_{ji} = \sum_r \left(PDI_{i,r} / ADI_{i,r}\right) / \left(PDI_{ref,r} / ADI_{ref,r}\right.$	$Q_{ji} = \left(\sum_s N_s \sum_r C_{i,e,r,s}\, E_{i,r}\right) D$
photo-oxidant formation	$Q_{ji} = POCP_i = OC_i / OC_{ref}$	$Q_{ji} = \frac{POCP_i^{C2H4}}{POCP_{NMVOC}^{C2H4}} F_{NMVOC}\, X_{(O3)}\, E^{resp}\, D$
ecotoxicity (j = fresh water; sea water; soil)	$Q_{ji} = \left(PEC_{i,j} / PNEC_{i,j}\right) / \left(PEC_{ref,j} / PNEC_{ref}\right.$	$Q_{ji} = F_{i,e,f}\, E_{i,f}\, D_f = C_{i,e,f}\, \Delta t_{i,e} \frac{1}{NOEC_{i,f}} \left.\frac{\partial PAF_f}{\partial y}\right\vert_{y=x} Area$
acidification	$Q_{ji} = HC_i / HC_{ref}$	$Q_{ji} = F_{i,e,f}\, E_{i,f}\, D_f = C_{i,e,f}\, \Delta t_{i,e} \frac{1}{NOEC_{i,f}} \left.\frac{\partial PAF_f}{\partial y}\right\vert_{y=x} Area_f$
eutrophication	$Q_{ji} = BC_i / BC_{ref}$	$Q_{ji} = F_{i,e,f}\, E_{i,f}\, D_f = C_{i,e,f}\, \Delta t_{i,e} \frac{1}{NOEC_{i,f}} \left.\frac{\partial PAF_f}{\partial y}\right\vert_{y=x} Area_f$
ionising radiation	$Q_{ji} = D\left[\sum_f F_{i,e,f}\; X_{i,f}\, E_i\right]$	$Q_{ji} = D\left[\sum_f F_{i,e,f}\; X_{i,f}\, E_i\right]$

An explanation of the symbols occurring in these characterisation formulas is given below.

Impact category	Midpoint-oriented approach	Endpoint-oriented approach
resource depletion	*P* = annual production *R* = ultimate reserve *ref* = Sb	minerals: *E* = energy needed to extract in future fossil fuels: *E* = energy needed to extract
land use impacts	–	$Time^{act}$ = time of occupation $PDF_{x \rightarrow i}$ = potential disappeared fraction of species due to change from state x to state i
climate change	*RF* = time-integrated radiative forcing *GWP* = global warming potential *ref* = CO_2	*GWP* = global warming potential *ref* = CO_2
ozone layer depletion	*OC* = change of ozone concentration *ODP* = ozone depletion potential *ref* = CFC-11	*ODP* = ozone depletion potential *ref* = CFC-11
human toxicity	*PDI* = predicted daily intake *ADI* = acceptable daily intake *ref* = DCB *r* = inhalatory, respiratory	*C* = concentration in steady state
photo-oxidant formation	*OC* = change of ozone concentration *POCP* = photo-oxidant creation potential *ref* = C_2H_4	resp. *POCP* = photo-oxidant creation potential *ref* = C_2H_4
ecotoxicity	*PEC* = predicted environmental concentration *PNEC* = predicted no-effect concentration *ref* = DCB	*C* = concentration in steady state *NOEC* = no-observed effect concentration *PAF* = potentially affected fraction of species
acidification	*HC* = number of H^+ ions that can be created *ref* = SO_2	*C* = concentration in steady state *NOEC* = no-observed effect concentration *PAF* = potentially affected fraction of species
eutrophication	*BC* = contribution to biomass *ref* = PO_4	*C* = concentration in steady state *NOEC* = no-observed effect concentration *PAF* = potentially affected fraction of species
ionising radiation	–	–

3.4.4. Characterisation models

The damage categories and areas of protection, respectively, are effectively virtually the same for Eco-indicator 99 and the Handbook LCA. In this section, they are abbreviated as HH (human health), EQ (ecosystem quality), NR (natural resources) and MME (man-made environment; only for midpoint-oriented approach).

Land use

Aspect	Midpoint-oriented approach	Endpoint-oriented approach
time	duration	duration
space	global	region
fate		
exposure		
effect	actual	actual
impact	NR, MME	EQ
indicator	competition	loss of biodiversity
principle	Measure of competition is simply (Area of land times duration of occupation) Local effect only.	PDF from ($N_{species}$=a*Area^b). Land type classification using CORINE, with characterisation factor a (richness). Final indicator value is (1.2*area*time*ΔPDF) – this combines the damage to the local area and that to the region/surroundings (1+0.2).

In the Handbook LCA, only occupation is considered, in terms of competition, impacting on NR and MME. Land transformation is considered study specific (impact on EQ). Eco-indicator 99 considers occupation as well as transformation, both in terms of loss of biodiversity (EQ). Land use includes biotic extraction (except Silvicultural extraction).

Depletion of abiotic resources

Aspect	Midpoint-oriented approach	Endpoint-oriented approach
time	(infinite)	(T 5Q)
space	global	global
fate		
exposure		
effect	actual	actual
impact	NR	NR
indicator	depletion	surplus energy
principle	current extraction rates and ultimate reserves (Guinee and Heijungs 1995).	continuous ore-grade quality degradation (lognormal), step-wise replacement of fossil fuels/extraction techniques. Reference year is 1990 (Müller-Wenk 1999)

This category differs from others as there is no environmental mechanism involved (although resource analysis can be seen as the inverse of fate modelling, and may thus be regarded as representing an environmental mechanism). A direct measure of depletion could be considered as an endpoint indicator for NR (as in the Handbook LCA), but also as a midpoint indicator for competition with MME as an area of protection. The indicator "future surplus energy demand" also seems to go beyond NR to a more economic impact.

Climate change

Aspect	Midpoint-oriented approach	Endpoint-oriented approach
time	100 yr	100 yr/200 yr
space	global	region
fate	marginal	marginal (lifetime dependent)
exposure		yes
effect		marginal
impact	all	HH
indicator	global warming	total DALY
principle	indicator result is sum of all (GWP*m), with GWP w.r.t. CO_2 (Houghton 1994, 1996 (IPCC)).	GWP (Schimel etal 1996) with reference CH_4 (lifetime<20 yr), CO_2 (20 yr<lifetime<110 yr) or N_2O (lifetime>110 yr). Marginal damage for those three from FUND (Hofstetter, Tol) using IPCC IS92a scenario. Analysis separate for nine world regions; negative damage balances positive within a region. Six endpoints/diseases taken into account.

Indirect impacts are not included in the Handbook LCA, but they are in Eco-indicator 99, for halocarbons only (negative indirect GWP). For methyl chloroform, halon 1301 and carbon tetrachloride, this results in a negative total GWP, while total direct GWP in the Handbook LCA is positive. The values of the direct GWP are the same (the literature references are actually the same source). Human displacement is in Eco-indicator 99 counted in terms of health effect only. In Eco-indicator 99, no data are available to take into account Ecosystem Quality, due to the strong positive and negative effects, that seem to balance, making the net effects very uncertain.

Ozone depletion

Aspect	Midpoint-oriented approach	Endpoint-oriented approach
time	infinite	500 yr
space	global	global
fate	marginal	marginal
exposure		yes
effect		marginal
impact	all	HH
indicator	ozone depletion	total DALY
principle	steady-state ODP with respect to CFC-11 (WMO 1999, 1995, 1992) model	time dependent ODP with respect to CFC-11. Marginal fate factor for CFC-11 from London amendment scenario. Empirical effect (cancer, cataracts) from UNEP (1998,1994), damage (Hofstetter 1998, Murray et.al. 1996)

In Eco-indicator 99, no data are available to take into account Ecosystem Quality, due to possible negative effects.

Human toxicity

In this category, it is not straightforward to compare the two methods, as Eco-indicator 99 considers carcinogenic effects and respiratory effects, while the Handbook LCA considers ozone creators and (all) other human toxic emissions. Summer smog in the Handbook LCA (photochemical ozone) is called respiratory effects (organics) in Eco-indicator 99; while winter smog in (in human toxicity) is respiratory effects (inorganics).

Human health versus Carcinogens and Respiratory (inorganics)

Aspect	Midpoint-oriented approach	Endpoint-oriented approach	
time	infinite	fate from ss conc.; damage: sedimentation	
space	global	carc: global for lifetime >1 year	resp. Europe
fate	average	carc. average EUSES	resp. average empirical
exposure		carc. EUSES, adapted for long lifetimes	resp. empirical
effect	average	carc. average	resp. marginal
impact	human health	human health	
indicator	human toxicity	total DALY	
principle	all emission (incl. winter smog (inorganics :PM10, sulfates, CO)) except pure photo oxidants. Fate assessment (Huijbregts 1999a) for three ecomp and four zones (european, arctic, temperate, tropical), with degradation, transport, exposure, intake factors : PDI. Indicator HTP = PDI/ADI*Npeople. ADI is either threshold level or the P=0.001 concentration; all ADI have equal weight.	only carcinogenic substances IARC class 1,2a,2b,3. Emissions in Europe, damage area depends on atmospheric residence time (global for >1 year). Unit Risk (worst case) per exposure path (no thresholds, no background) from several studies. Damage assessment following Murray etal 1996. Cultural perspective: include only certain classes (2.4.12). Separate fate for metals (Simplebox + empirical)	epidemiological response data for PM2.5, PM10, SO2, CO and NO2 (from primary emissions PM2.5,PM10, TSP, NOx, NH3, CO, SOx). Empirical fate data (average)

Photo oxidant formation versus respiratory effects (organics)

Aspect	Midpoint-oriented approach	Endpoint-oriented approach
time	5 days	Fate from ss conc. Damage:sedimentation
space	Europe	Europe
fate	Marginal/average [13] (hi NOx)	Europe Marginal (hi NOx)
exposure		empirical
effect		marginal
impact	All	HH
indicator	ozone creation	total DALY
principle	ozone creation only, POCP for VOC (marginal, Derwent etal 1998 , Jenkin and Hayman 1999) and for inorganic compounds (average, Derwent etal 1996). Relative to C2H4. Winter smog emissions in human toxicity (CO, NO2 and SO2 also included here, though)	method follows Hofstetter 1998 (EMEP, ExternE) Fate factors for ozone creation are marginal, for NW European conditions. Fate factors for VOC emissions calculated from that for total of non-methane VOC via POCP (Jenkin etal 1997)

Negative POCP is included in the Handbook LCA for NO (positive in inorganics in Handbook LCA) and benzaldehyde (no classification in Eco-indicator 99).

Ecotoxicity

Aspect	Midpoint-oriented approach	Endpoint-oriented approach
time	infinite	fate: from steady-state concentration
space	global	Europe
fate	average; USES LCA	average; EUSES
exposure		
effect	average	marginal
impact	EQ	EQ
indicator	Ecotoxicity	PAF×area×time
principle	emission : air, water, agricultural, industrial soil. Transport to freshwater, marine, terrestrial compartments. Degradation, no exposure. Final ETP=Sum(PEC/PNEC) for each of freshwater, marine and terrestrial separately. Huijbregts 1999a.	emission : air, water, agricultural, industrial soil. Transport to water, agricultural, industrial, natural pore water. Degradation, no exposure (no secondary poisoning). Combine via Hazard Units (conc/NOEC). Marginal combi-PAF (log logistic) with European background 24%, damage is Sum(PAF×area×time). Following Meent et al 1999 (mostly?). No acute effects. Characterization for metals different for (I,I).

Acidification

[13] The effect is marginal for VOCs and average for inorganic compounds.

Aspect	Midpoint-oriented approach	Endpoint-oriented approach
time	(Deposition)	fate: from steady-state concentration
space	Europe	Europe
fate	average	marginal; SMART
exposure		
effect		marginal; MOVE
impact	all	EQ
indicator	acidification	PDF×area×time
principle	average European characterisation factors from 40 ecosystem types (Huibregts 1999b), times deposition / critical loading. NO_2=NO_x, SO_2, NH_3	see eutrophication (simultaneous treatment)

Eutrophication

Aspect	Midpoint-oriented approach	Endpoint-oriented approach
time	N/A	fate: from steady-state concentration
space	global	Europe
fate		marginal SMART
exposure		
effect	actual	marginal MOVE
impact	EQ, AR, MME	EQ
indicator	eutrophication	PDF×area×time
principle	all emissions of nitrates and phosphates; of degradable organic compounds to water. Total effect is sum of EP (Heijungs et al 1992), based simply on total amount (?) of emitted N and P atoms and the total chemical O_2 demand of emitted organics. (P:N:O_2 = 1:1/16:1/138). No fate analysis.	only emissions to air, of inorganic substances, 100% deposited on (solid) natural area (60% for Europe) are taken into account. Fate modelling performed for Netherlands only, with the assumption that this represents Europe. For NO, NO_2 (=NO_x), SO_2, SO_3, NH_3. Damage from 900 vascular plants (target list) gives PDF. Indicator = Sum (PDF * Area * Time). No aquatic ecosystems PDF; no phosphate emissions, no COD

For European emissions, the Handbook LCA advises a non-baseline alternative (similar to acidification). The combined marginal damage in The Netherlands according to Eco-indicator 99 is found to be less than 0.001 against a background of 0.746429 p/m 0.32. SETAC advises to include waste heat in eutrophication category.

Ionising radiation

Aspect	Midpoint-oriented approach[14]	Endpoint-oriented approach
time	100,000 years	100,000 or 100 years
space	lifetime depend	lifetime depend
fate	average	average (France)

[14] Not a baseline impact category in the Handbook LCA.

exposure	yes	yes
effect	average; no age weighting preferred for DALY calculation (consistent with 100,000 year time horizon)	average
impact	HH	HH
indicator	DALY	total DALY
principle	fate and exposure models combined with epidemiological studies and the DALY-concept	see the midpoint-oriented approach

The spatial scale of the fate depends on lifetime of the radionuclide.

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Appendix: What do users of LCIA results require?

This appendix contains a Dutch summary of interviews with four Dutch users of LCA/LCIA results:

- Chris Dutilh (Unilever)
- Hans van der Wel (Philips)
- Rogier Goes (Nederlandse Bond voor Toeleveranciers Bouw)
- Niels Ruyter (Aluminiumcentrum)

The interviews were carried out by Suzanne Effting in November 2002. The texts are printed by kind permission of the interviewed persons. An English summary is given in §1.1.3.

De geïnterviewden	*Chris Dutilh, 8 november 2002* Chris Dutilh is de laatste jaren veel bezig met duurzaamheid en duurzaam ondernemen, onder andere met “Stichting Duurzaamheid in de Voedingsmiddelenketen” (DuVo). Keten-denken staat daar bij centraal. Een deel van zijn ketenkennis is gebaseerd op LCA’s uitgevoerd bij Unilever en voor Duvo. De heer Dutilh werkt voornamelijk op het niveau van management en probeert daar veranderingen teweeg te brengen. *Hans van der Wel, 12 november 2002* Hans van der Wel werkt bij Philips Environmental Services en levert vanuit de vestiging in Eindhoven ondersteuning aan Philips vestigingen wereldwijd. Eco-scan software met Eco-indicatoren is daarbij een belangrijk hulpmiddel om milieu te implementeren in ontwerpprocessen. Ook op procesniveau wordt de Eco-indicator gebruikt om milieu mee te nemen. De indicatoren worden (o.a.) door de heer van der Wel berekend en binnen Philips verspreid. LCA worden alleen intern gebruikt, en nooit extern. *Rogier Goes, 20 november 2002* Rogier Goes werkt voor de NVTB (Nederlandse Bond voor Toeleveranciers Bouw). De NVTB is de organisatie van MRPI (Milieu Relevante Product Informatie) in de bouw. Met MRPI hoopte zij de basis te leggen voor het MMG (Materiaal Gebonden Milieuprofiel), dat uiteindelijk een wettelijke status zal krijgen. MRPI maakt gebruikt van het milieuprofiel (9 gekarakteriseerde scores op basis van een CML methodiek) en milieumaten: 4 maten (energie, gevaarlijk en niet gevaarlijk afval en emissies, en hinder (laatste is niet operationeel)). Deze worden gebruikt voor externe communicatie. *Niels Ruyter, 20 november 2002* De heer Ruyter werkt bij het Aluminiumcentrum en wordt door het NVTB ingehuurd als LCA deskundige. Naast LCA voor het aluminiumcentrum, doet de heer Ruyter ook regelmatig LCA’s voor andere opdrachtgevers. Het gaat zelden om vergelijkingen, maar vooral om het vaststellen van het milieuprofiel en nagaan waar de zwaartepunten in de keten liggen zodat optimalisaties gemaakt kunnen worden. Verschillende mogelijkheden om dat te bereiken

	worden daarbij wel vergeleken. De heer Ruyter maakt voornamelijk gebruik van de CML methode.

Ervaringen met impact assessment	Met name de heer Ruyter en de heer van der Wel hebben relatief veel ervaring met impact assessment. De heer Ruyter gebruikt voornamelijk gekarakteriseerde scores van de CML methode en gaat van elke impact categorie na waar de zwaartepunten in de levenscyclus liggen. De heer van der Wel gebruikt de gewogen Eco-indicatoren. Beide vergelijken hun resultaten af en toe ook met de resultaten uit andere impact assessment methodieken om te kijken of ze allemaal dezelfde kant in wijzen. Volgens de heer Ruyter is dit niet altijd het geval. De heer Goes (her)kent impact assessment, met name het milieuprofiel dat in de bouw gebruikt wordt. Dit is een CML-achtige methode op het niveau van karakterisering. De heer Dutilh gebruikt niet of nauwelijks impact assessment. Als hij LCA toepast doet hij dat op basis van inventarisatiegegevens zoals transportkilometers en energieverbruik. Welke gegevens hij inventariseert hangt af van het onderwerp en het doel van de LCA. In het verleden heeft de heer Dutilh wel impact assessment toegepast (met name CML).

Begrijpelijkheid/ inzichtelijkheid	Zowel de heer Ruyter als de heer van der Wel zeggen inzicht te hebben in de methode die zij vaak gebruiken. De heer van der Wel kent de sterke en zwakke kanten van Eco-indicator goed. De ontwerpers die de indicatoren gebruiken kennen de achtergronden niet precies. Als er vragen komen dan informeert de heer van der Wel de gebruikers. De heer Goes geeft aan dat de meeste leden van de NVTB geen inzicht hebben in de achtergrond van het milieuprofiel of de milieumaten. Dat vinden zij ook niet belangrijk zolang er maar draagvlak is voor de methodiek is.

Interpretatie van de resultaten	Alle geïnterviewden geven aan dat het belangrijk is dat er een koppeling kan worden gelegd met de materialen en de processen die de milieubelasting veroorzaken (inventarisatie). Dat zijn immers de parameters waarop invloed uitgeoefend kan worden. Voor de heer Dutilh is de inventarisatie zo belangrijk dat hij vaak geen impact assessment nodig heeft. De variatie in de data (energieverbruik, landgebruik, massastromen etc.) is vaak al zo groot dat je die niet hoeft te vertalen naar een ingewikkelde score. Hij komt ook zelden tegen dat voor het ene alternatief de parameters gunstiger uitvallen dan voor het andere alternatief. De heer Ruyter geeft aan dat software de methodiek goed moet ondersteunen zodat het gemakkelijk is om in de levenscyclus te kijken waar de milieubelasting vandaan komt. De heer van der Wel heeft moeite met midpoints omdat de meeste producten van Philips heel veel inputs hebben en ook op veel impact categorieën scoren. Hij denkt dat dan gauw de verleiding ontstaat om

	met een weegfactor 1 toch impliciet een weging te doen en heeft liever dat er alle effecten expliciet bij elkaar genomen worden, rekening houdend met de ernst ervan. De heer Goes geeft aan dat het belangrijk is dat mensen zich wat voor kunnen stellen bij de impact categorieën. De milieumaten zijn bijvoorbeeld erg prettig omdat ze "dicht bij huis" zijn. Energie en afval, daar kan iedereen zich wel wat bij voorstellen. Voor de milieumaat emissie is dat al heel anders en de meeste leden kunnen dan ook niet zo veel met deze milieumaat. Het milieuprofiel (gekarakteriseerde scores volgens CML) is veel abstracter en daar kunnen de meeste leden dan ook niet zo veel mee. De heer Dutilh geeft aan dat het interpretatie-probleem niet bij het milieu ligt: dat is al goed gedefinieerd. Bij de milieu-afweging treden volgens de heer Dutilh geen tegenstrijdigheden meer op. Als het botst, dan botst het juist met de andere belangen zoals geld en menselijke gezondheid (bijvoorbeeld afweging verzadigde/ onverzadigde vetzuren in boter). De heer Dutilh heeft ook geen behoefte aan een parameter voor milieu die beter aansluit op de andere parameters als kosten en gezondheid, omdat hij denkt dat communicatie en beleving veel belangrijker is dan een technische oplossing (in de vorm van nieuwe milieu-indicatoren).

Communicatie naar derden	Het milieuprofiel en de milieumaten worden beide gebruikt voor communicatie naar derden. Zowel de heer Ruyter als de heer Goes geven aan dat een "standaard" erg belangrijk is. De LCA's worden door Philips niet voor communicatie naar derden gebruikt en de heer van der Wel ziet dit ook niet zitten door alle onzekerheden die ermee samenhangen. Philips gebruikt voor communicatie naar buiten 5 aandachtsgebieden (En Eco-indicator kan als 6e worden opgevat). Naar zijn idee wordt "LCA" steeds vaker door Brussel genoemd, en hij hoopt dat dit niet uit gaat draaien op een verplichting dat LCA resultaten naar buiten moeten worden gebracht op een door Brussel voorgeschreven manier. In één van de DUVO projecten zijn uitgebreide LCA's gemaakt van 5 voedingsmiddelen. Toen deze klaar waren concludeerde men dat dit niet de mannier was om management te motiveren voor duurzame ontwikkeling. De heer Dutilh gelooft niet in een technische benadering voor duurzaamheid.

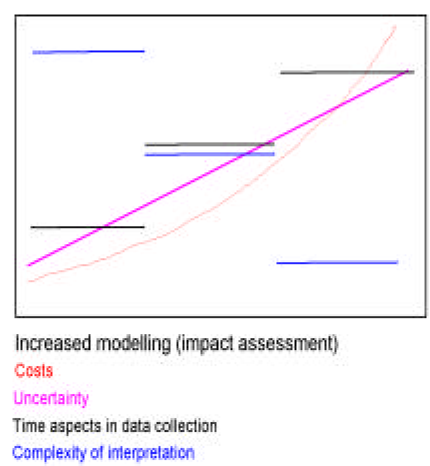
Goede methode?	De heer Goes en de heer Ruyter: • Een methode moet een goede status hebben, en door de overheid worden gesteund. • Methode moet ook op een goede mannier door software worden ondersteund. Als productvergelijking bijvoorbeeld weging niet toestaan volgens ISO, moet dit in de software ook onmogelijk zijn • De methode moet ook aansluiten bij de ontwikkelingen in Europa en op de ISO richtlijnen voor LCA. De heer van der Wel:

	• Simpel in gebruik (zodat niet alleen een milieuspecialist er mee kan werken maar ook iemand zonder milieu-achtergrond) • Een standaard die niet te vaak wisselt • Zonder hiaten (zoals nu bijvoorbeeld voor vermestende stoffen naar water)

Midpoint versus endpoint: interpretatie vs. Onzekerheden door modellengte	Voor de heer Dutilh en de heer Ruyter is met name zekerheid belangrijk. Introductie van extra onzekerheid door toegenomen modellengte is voor de heer Ruyter niet wenselijk tenzij het heel duidelijke voordelen voor interpretatie oplevert. De heer Dutilh ervaart geen interpretatieproblemen. Overigens houdt hij zich niet bezig met impact assessment en de keuze voor midpoint of endpoint is dan ook niet relevant voor de heer Dutilh. De heer Goes geeft aan dat zijn leden behoefte hebben aan iets wat gemakkelijk te interpreteren is. Extra onzekerheid is niet erg, zolang er bij de overheid draagvlak voor is. De heer van der Wel prefereert gemakkelijke interpretatie, ook al gaat dat ten koste van de zekerheid. Hoe minder categorieën met elkaar gewogen hoeven te worden hoe beter. Op het voorstel of de heer Goes en de heer Ruyter inzicht zouden willen hebben in de mate van onzekerheid van verschillende midpoints of endpoints merkte de heer Ruyter op dat hij dit minder wenselijk vindt omdat daarmee gesuggereerd wordt dat de onzekerheid zich voornamelijk in de impact assessment methode bevindt, terwijl de grootste onzekerheid waarschijnlijk in de inventarisatie zit. Door heel precies aan te geven hoe groot je I.A. onzekerheid is, onderschat je waarschijnlijk de onzekerheid in de data (inventarisatie).

Visie van de heer Ruyter op toename van model-lengte in impact assessment:

- De onzekerheid in de uitkomsten wordt groter (door de toegenomen modellengte), maar de uitkomsten zijn eenvoudiger te interpreteren.
- Door naar het endpoint toe te modelleren neemt de tijd voor dataverzameling toe (volgens de heer Ruyter zijn veel gedetailleerdere data nodig). De kosten voor een LCA stijgen daardoor exponentieel.



Wanneer midpoint en wanneer endpoint?	Alle geïnterviewden zeggen dat de keuze voor midpoint of endpoint afhangt van het doel van de LCA. Volgens de heer Ruyter bepaalt de *intended use* welk niveau van onzekerheid acceptabel is. Voor intern gebruik kunnen endpoints

	geschikt zijn, terwijl dat midpoints zullen zijn voor communicatie naar buiten. De heer van der Wel zal intern altijd voor endpoint kiezen omdat midpoint te veel verwarring oplevert. In het hypothetische geval dat er extern gecommuniceerd zou moeten worden met LCA, dan zou de heer van der Wel kiezen voor midpoint. Een combinatie van midpoint en endpoint (bijvoorbeeld om hiaten in endpoint methodiek aan te vullen met midpoint indicatoren) ziet de heer van der Wel niet zitten omdat onduidelijk blijft hoe de midpoint indicatoren mee moet wegen in de conclusie. Naar afzonderlijke midpoints kijken acht de heer van der Wel niet zo zinvol omdat hij ziet dat de wet- en regelgeving daar al op let (bijvoorbeeld toxische stoffen of vermestende stoffen naar water).

Keuzes in het model	Alle geïnterviewden geven aan dat ze de voorkeur hebben voor een standaard keuze en geen behoefte hebben om zelf te kunnen kiezen in de impact assessment methode. Belangrijk is dat het gekozene draagvlak heeft.
Keuze voor geografische schaal: regio, land, grid etc.	De heer van der Wel wil een globale methode waarbij hij geen rekening hoeft te houden met de regio (bijvoorbeeld of productie in Nederland of in China plaats vindt), omdat dit een LCA veel te complex maakt. Bij regiospecificiteit ontstaat er een nog grotere behoefte aan data. Deze gegevens zijn er niet en daarom is het niet zinvol om de impact assessment methodiek te verfijnen. Daarbij accepteert de heer van der Wel dat lokale milieueffecten zoals erosie en verdroging of geluid niet meegenomen kunnen worden. Lokale effecten hoeven geen onderdeel te zijn van de LCA omdat daar vaak wet- en regelgeving voor is. Het enige moment regiospecificiteit volgens de heer van der Wel van belang is, is bij de locatie keuze van een nieuwe fabriek. Volgens de heer van der Wel speelt milieu nu een nauwelijks een bij zulke beslissingen. Misschien dat dit in de toekomst anders wordt. Of je wereldwijd per regio of per land kiest hangt volgens de heer Ruyter af van het effect. Voor broeikaseffect is globaal bijvoorbeeld goed, voor verzuring kies je een meer locale scope. Naar mate je verder gaat met je modellering zul je volgens de heer Ruyter zo ie zo op een steeds kleinere schaal moeten gaan werken.
Keuze voor tijdsschaal	De heer Ruyter heeft de voorkeur voor een lange tijdsschaal waarbij je inzicht hebt in wanneer het effect zich (zichtbaar) voor gaat doen. Van broeikaseffect wil hij bijvoorbeeld weten hoeveel graden de aarde warmer wordt, wanneer dat is (over 2 of over 100 jaar) en hoe lang de periode is waarin de temperatuur stijgt. Dit laatste wil je weten om de ernst van het effect te kunnen interpreteren in relatie met het endpoint. Volgens de heer van der Wel mag de tijdsschaal van effecten meewegen: meer prioriteit voor effecten die op korte termijn plaats vinden dan effecten die pas over 1000 jaar merkbaar zijn.
Bewijsbaarheid van effecten	Ook hiervan willen de geïnterviewden één versie, en geen keuze. Volgens de heer Ruyter en de heer Goes moet die versie moet aansluiten bij wat wetenschappelijk/ politiek geaccepteerd is. Te

	onzekere dingen moeten niet meegenomen worden omdat je op zoek bent naar zekerheden (en die zijn er toch al weinig in LCA; in de inventarisatie zitten ook al heel veel onzekerheden). De heer van der Wel wil dat er conservatief gekozen wordt: alles meenemen tot het tegendeel bewezen is. Daarbij merkt de heer van der Wel op dat hij zich afvraagt wat LCA-technisch haalbaar is: er zijn meer dan 50.000 toxische stoffen en elke dag komen er nieuwe bij.
Positieve effecten	Dit blijkt een moeilijk onderwerp. Omdat milieu-effecten negatief zijn, zouden positieve effecten volgens de heer Ruyter niet meegenomen moeten worden. Als ze toch meegenomen worden dan mogen ze niet tegen elkaar wegvallen, maar moet expliciet gemaakt worden welk deel van de effecten positief is en welk deel negatief. De heer van der Wel pleit voor een ISO-standaard voor dit onderwerp.

Missende impact categorieën	Landgebruik is de enige categorie die de heer Ruyter en de heer Goes missen is. De heer Dutilh zegt geen impact categorieën te missen in de bestaande methodes. Ook de heer van der Wel mist niet echt categorieën, maar ziet liever dat de hiaten in bestaande categorieën worden opgelost. Lokale effecten in de methode vindt men over het algemeen niet wenselijk omdat dit de hele LCA veel complexer maakt (er moeten dan ook lokale data verzameld worden).
Derde-wereld specifieke impact categorieën: verzilting, verdroging, erosie	Hier is geen behoefte aan omdat het om lokale effecten gaat.
Man-made environment	Dit is voor de geïnterviewden geen issue en hoeft niet meegenomen te worden.
Geluid/ ongelukken	Ook aan deze categorie bestaat geen behoefte. Ongelukken bekijkt men in de arbo-sfeer en voor geluid is er wetgeving. Bovendien gaat het wederom om lokale effecten.
?	De heer van der Wel merkt op dat duurzaamheidsindicatoren, zoals armoede, een mooie aanvulling zouden vormen.

Weging	De heer Ruyter en de heer Goes vinden weging iets wat met beleidskeuzes te maken heeft. Weging is niet wetenschappelijk en de weegstap zou eigenlijk buiten het impact assessment model gehouden moeten worden. Het moet expliciet duidelijk zijn dat het om een subjectieve keuze gaat. Panel-weging en Distance-to-target lijken de voorkeur te hebben, waarbij het dan wel belangrijk is dat het panel (politiek) draagvlak heeft (in elk geval in Nederland en het liefste Europees). Het mag dus niet uitsluitend uit wetenschappers bestaan omdat dit de suggestie kan wekken dat er een wetenschappelijke grondslag is voor de weging. De heer van der Wel heeft de voorkeur voor een standaard weegset (met draagvlak). Een panel-weging is prima, waarbij een breed gekozen panel bij kan dragen aan het draagvlak. Hoe minder

	endpoints gewogen moeten worden, hoe beter.