Critical Analysis of the Mathematical Relationships and Comprehensiveness of Life Cycle Impact Assessment Approaches

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The impact assessment phase of Life Cycle Assessment (LCA) has received much criticism due to lack of consistency. While the ISO standards for LCA did make great strides in advancing the consensus in this area, ISO is not prescriptive, but has left much room for innovation and therefore inconsistency. To address this lack of consistency, there is currently an effort underway to provide a conceptual framework for Life Cycle Impact Assessment (LCIA) and a recommended practice to include a list of impact categories, category indicators, and underlying methodologies. This is an enormous undertaking, especially in light of the current fundamental lack of consensus of the basic elements to be included in a LCIA (e.g., impact categories, impacts, and areas of protection). ISO 14042 requires selection of impact categories that "reflect a comprehensive set of environmental issues" related to the system being studied, especially for "comparative assertions" that involve public marketing claims. To be comprehensive, it is necessary to have a listing of impacts that "could" be included within the LCIA before entering into discussions of impacts that "should" be included. In addition to providing a critical analysis of existing and emerging impact assessment approaches, this paper will formulate a structured representation that allows more informed selection of approaches. The definitions and relationships between midpoint, endpoint, damage, and areas of protection will be presented in greater detail, along with the equations that are common to many of the approaches. Finally, a discussion of the advantages and disadvantages of displaying results at various stages in the environmental models will be presented in great detail.

1. Introduction

Life cycle assessment (LCA) allows the assessment of inputs and outputs utilized or released during the production, transportation, use, and disposal of a product or service. (*1−3*) Several sources acknowledge that the selection of impact categories is considered dependent upon the application, goal, and scope of the study and is ultimately the responsibility of the study practitioner and commissioner. (*4−8*) While it is anticipated that the responsibility will continue to rest with the study practitioner and commissioner, it is useful to have a structure to ensure that at a minimum, a comprehensive list of impact categories has been considered prior to the selection process. (*9*) This paper will concentrate on providing a structure for better analysis of life cycle impact assessment (LCIA) approaches.

One of the common misconceptions of LCA commissioners is that there are few readily available and universally accepted "standardized methods" to conduct a LCIA. In reality, each approach is actually a collection of impact assessment methods for individual impact categories (e.g., stratospheric ozone protection, human health, etc.). In some cases these individual impact categories are selected and/or designed to provide a consistent perspective (*10*), whether that perspective represents a philosophical environmental viewpoint (e.g., Eco-indicator 99) (*11*), an industry's environmental perspective (e.g., EPS 2000) (*12*), or consistency with a nation's policies and regulations (e.g., TRACI) (*13−18*). This selection of perspective is extremely important in the design of the individual impact category methods, and can drive decisions such as whether a single score is a goal, whether midpoint, endpoint, or damage level methods (or a combination) should be used, which impact categories are included, and what underlying assumptions are most appropriate for consistency among methods.

Here, midpoints (e.g., ozone depletion potential), are defined as some point on the cause−effect chain between the inventory flows and the areas of protection while endpoints are those physical elements that society determines are worthy of protection. Usually, these endpoints are located further along the environmental mechanism chain, such as skin cancers, cataracts, malaria, plants, animals, and man-made materials. Damages are a value-based aggregation of the endpoints.

Rather than selecting an approach based solely on familiarity, popularity, or ease-of-use, it is recommended that practitioners become more familiar with the underlying drivers, choices, and assumptions within an approach in a more structured manner. Conducting this analysis can be a daunting task, but this paper includes a detailed structure for making these analyses within the Supporting Information, as well as a comprehensive table allowing a comparison of some of the most popular approaches.

The names, websites, and short descriptions of the impact assessment approaches analyzed and cataloged may be found in Table 1.1. While this list does not include the entire universe of comprehensive impact assessment approaches, the approaches were selected because they represent the broad

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TABLE 1.1 Comprehensive Impact Assessment Approaches Analyzed and Classified

approach	website	primary description
CML method	http://www.leidenuniv.nl/cml/ssp/projects/lca2/	primarily midpoint method with normalization.
eco-indicator 99	www.pre.nl/eco-indicator99	damage approach including normalization and three default weighting sets.
ecoscarcity – Swiss EcoPoints	http://www.e2mc.com/BUWAL297%20english.pdf	weighting method based on environmental policy goals to be used for midpoint categories and selected emissions/inventory flows
EDIP97	http://ipt.dtu.dk/~mic/Projects.htm#EDIP97	primarily midpoint method with normalization.
EPS 2000	http://eps.esa.chalmers.se/	category indicators at damage level + weighting as willingness to pay (WTP) to avoid damage
impact 2002+	http://www.epfl.ch/impact	primarily midpoint method + damage including normalization
LIME	http://www.jemai.or.jp/lcaforum/index.cfm	midpoint + damage + weighting. practitioner can choose the step of LCIA based on the aim of LCA.
TRACI	http://epa.gov/ORD/NRMRL/std/sab/iam_traci.htm	primarily midpoint methodologies with US normalization soon to be available.

spectrum of approaches in use today and can be found in the most widely published foundations for comprehensive impact assessment case studies. The primary descriptions in this table include the environmental mechanism chain considered (midpoint, endpoint, or damage), the availability of normalization, and the inclusion of weighting. Further details on each approach will be provided in the next section.

2. Summary of Approaches

The method used to summarize the impact assessment approaches identified by this study has been iterative. Figure 2.1 is the result of this iterative process and was formulated by first categorizing the main areas that society seeks to protect, known as the areas of protection (AoPs). AoPs, although generally accepted to contain the four areas of human health, natural environment quality, natural resources, and man-made environment, vary slightly from approach to approach. (*19*, *20*) The first area, human health, simply relates to the protection of and minimizing the potential harm to humans. The second area, natural environmental quality, is broad and all encompassing; it includes the potential impacts to ecosystems that function to support life on earth. The third area, natural resources (both abiotic and biotic), pertains to materials that are extracted, harvested, or otherwise obtained from the environment for beneficial use by humans. Natural resources are, in general, considered the "inputs" to impact assessment studies. The fourth area, the manmade environment, is the synthesized or built environment by humans, items that are produced, for example, buildings and food crops, and also the less tangible items of financial and cultural value.

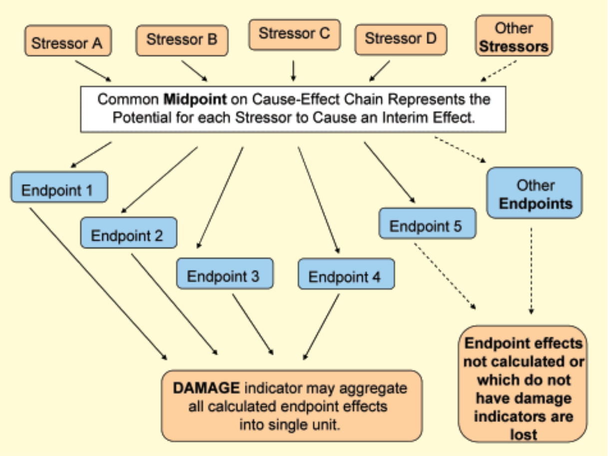

FIGURE 2.1. Progression from inventory flow to damage for classic midpoint impact categories. Note that endpoints not included in the damage indicators are lost.

From the basis of these four general areas of protection, classifications of the midpoint, endpoint, damage, and weighting factors for each area of protection are formulated. The nomenclature presented by these classifications is driven by an attempt to harmonize the unifying elements of midpoint and damage categories. Examples include the potential harm to humans by the effects of cancer, climate change, and stratospheric ozone depletion. One step further is to categorize the AoPs by the inventory flows that are associated with the classification of potential impact. Examples here include chemical releases, extraction of fossil fuels, land use, and the emission of sound.

The general practice of LCIA includes four types of factors: midpoint factors, endpoint factors, damage factors, and weighting factors. Each of these four factors represents the essential elements of the impact assessment metrics presented by the methods. While there has been some discussion about these indicators within the literature, there has not been a definitive discussion of the applicability of these indicators to the wide variety of impact categories (*21*, *22*).

Traditionally, methods have been defined by their focus on the following five impact categories: stratospheric ozone depletion, global warming, acidification, eutrophication, and smog formation; if these categories are presented and reported independently, then an approach is often labeled a midpoint approach (*21*). Similarly, if these categories are not further presented as independent results, but are further modeled to the endpoint or damage level, then these approaches are often labeled as endpoint and damage focused methods.

Here midpoints are defined as some point on the cause–effect chain between the inventory flows and the AoPs. Midpoints may include fate/exposure and potency for a specific impact category, but do not quantify the potential endpoint effects that result from the midpoint category (*21*). Those categories that conform most readily to the midpoint paradigm include stratospheric ozone protection, global climate protection, smog formation, acidification, and eutrophication. This point in the cause–effect chain is often easily identified because it can be found where all inventory flows tend to converge into a single effect, as shown by the square box in the second row from the top in Figure 2.1. It is also a point that has often been well-researched and there tends to be more consensus at this level of characterization when compared to the endpoint and damage calculations. It is important to note within Figure 2.1 where a loss in comprehensiveness occurs. When models are characterized at the midpoint level, any inventory flows not included within

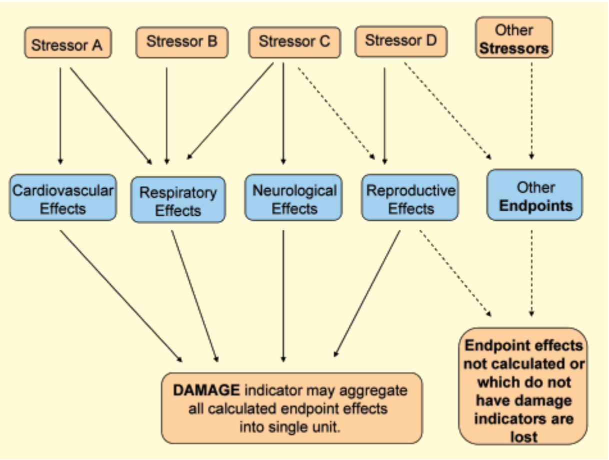

FIGURE 2.2. Progression from inventory flows to damage for human health. Note that endpoints not included in the damage indicators are lost.

the inventory or impact assessment are lost. In addition to these lost inventory flows, when calculations to the endpoint are conducted, endpoints may be lost if the models are not available to calculate these effects. Finally, at the damage level, the above-mentioned inventory flows are lost, the above-mentioned endpoints are lost, and any endpoints that do not include damage indicators will also be lost. As shown within Figure 2.1, the midpoint calculations are always as much or more inclusive and, therefore, more comprehensive than the endpoint calculations, and the damage calculations will provide the least coverage of endpoint effects.

Midpoint calculations for each impact category can be summarized as follows:

$$I_{\mathrm{i}} = \sum_{\mathrm{xmn}} F^{\mathrm{i}}_{\mathrm{xmn}} P^{\mathrm{i}}_{\mathrm{xn}} M_{\mathrm{xm}} \qquad (1)$$

where I_i is the potential impact of all chemicals (x) which have been released to all compartments or medias (m) with all modeled exposure routes (n) for a specific impact category of concern (i); $F^{\mathrm{i}}_{\mathrm{xmn}}$ is the fate and exposure pathway of chemical (x); $P^{\mathrm{i}}_{\mathrm{xn}}$ is the potency of chemical (x); M_{xm} is the mass of chemical (x).

Endpoints are those physical elements that society determines are worthy of protection. Usually, these endpoints are located further along the environmental mechanism chain, such as skin cancers, cataracts, malaria, plants, animals, and man-made materials. While damage models may have endpoint calculations underlying the damage calculations, seldom are the individual endpoints reported individually because the number of endpoints and their variety of units might be considered confusing to the decision maker.

Categories that are difficult to illustrate using the midpoint and endpoint terminology include human health and ecotoxicity. In both of these cases, the categories already exhibit an aggregation of endpoints, that is, there is no common midpoint (or common mode of action) on the cause-effect chain from inventory flow to endpoint to damages. When depicting the entire human health category (as shown in Figure 2.2), fate and transport are not the midpoints since many human toxins require different fate and transport models (e.g., VOCs, particulates, and metals). Instead, in these categories, parallel calculations may be done on each of the endpoints and then aggregated to damages (e.g., disability adjusted life years (DALYs) (*23*), or methodologies may be developed that allow the aggregation of individual endpoints within the calculation (e.g., human toxicity potentials (HTPs)). There may be advantages and disadvantages to each of these methods. While DALYs may allow additional transparency into the relative severity of impacts expected, DALYs are not available for all potential impacts, and thus some impacts will be lost in this step. Alternatively, while HTPs often utilize toxicity parameters, which enjoy a higher level of consensus (in addition to the fate and transport modeling), these toxicity parameters (e.g., reference concentrations (RfCs), reference doses (RfDs), no observable effect levels, and lowest observable effect levels) represent just one concentration and one effect. (*24*-*27*) In both cases, the models suffer from the availability of high quality toxicity, chemical, and physical property data, which ideally would assist the characterization for these categories greatly. Figure 2.2 depicts the parallel pathway of human health.

Damages are a value-weighted collection of endpoints. An example of a damage indicator would include the DALYs, or a monetary aggregation of the modeled endpoint effects. Damage indicators are most often used when a single score, or small number of scores (e.g., 3 or less) is the goal of the study. It is important to note that severity is always a value-weighted factor, and that all calculations based on damages and the smaller number of scores which result have these values incorporated.

The impact of different chemicals and media summed together for the total midpoint potential for a given category can be found by the following:

$$D_{\mathrm{c}} = \sum_{\mathrm{xmn}} F^{\mathrm{c}}_{\mathrm{xmn}} P^{\mathrm{c}}_{\mathrm{xn}} S^{\mathrm{c}}_{\mathrm{xmn}} M_{\mathrm{xm}} \qquad (2)$$

where D_{c} is the summation of the damages of all endpoints within the category, and $S^{\mathrm{c}}_{\mathrm{xmn}}$ is severity score of the endpoints.

Damages are often aggregated into a smaller number (e.g., 1-3) of environmental impact scores using normalization. Normalization is an optional step within LCIA that may be used to assist in interpreting life cycle data, and is often applied to an LCA case study prior to the weighting step. Normalization transforms the relative magnitude of results in different impact categories, and thus can significantly impact LCA-based decisions when tradeoffs exist between impact categories. The International Organization for Standardization (ISO 14042) refers to normalization as "calculating the magnitude of indicator results relative to reference information" and states "the aim of the normalization of indicator results is to better understand the relative magnitude for each indicator result of the product system under study."

Although normalization data can be gathered from various places, many of the methodologies presented are distributed with their own normalization database and they have traditionally included the annual flows of all inventory flows included in the methodology database for a specific region (often country, continent, or world). Many of the impact assessment methodologies analyzed were developed within western Europe with a western European normalization database. The availability of an accompanying normalization database may be found in Table 1.1. Over the past few years, it has become customary to conduct normalization at the national level on an annual basis, (*28*-*31*) but there is no scientific reason these spatial and temporal scales need to be chosen. Prior to aggregation, normalization is conducted, usually with specific temporal and spatial boundaries as in the following:

$$N_{\mathrm{c}} = \sum_{\mathrm{xmn}} \mathrm{F}^{\mathrm{c}}_{\mathrm{xmn}} P^{\mathrm{c}}_{\mathrm{xn}} U_{\mathrm{xm}} \qquad (3)$$

where U_{xm} is the mass released within the geographic boundaries within a specific time frame and N_c is the normalization value for the category of interest.

The valuation process is an optional step within the ISO standards whose goal is to develop value-based quantitative weighting factors to convert the many categories of potential impact—midpoint, endpoint, or damages—to a smaller set of impact categories, or in the case of some methods, to a single score. Weighting factors are formulated by nonscientific weighting schemes based on values or opinions and continues to remain one of the most contentious issues within LCA. (*31*−*36*) While panel methods seem to be one of the most common selections for determining the weighting factors that represent a group's perspective, during discussions about this topic at a workshop in 2000, none of the experts present could recommend a single example of a valuation exercise which could be used as a model for others (*21*).

When weighting is conducted with damages, these damages can be aggregated by using the following equation:

$$W = \sum_c \alpha_c D_c / N_c \tag{4}$$

where W is the weighted score for all aggregated impact categories, and α_c is the value-based weighting factor for the individual categories.

Following the weighting process, it is recommended that the aggregated score be interpreted in the full context of the study, including analysis of the data quality and the individual results within each impact category. While there continues to be concern about the presence of value-based decisions throughout LCA (*37*−*43*), within the ISO 14042 standard, weighting is strictly forbidden for comparative assertions (*44*).

2.1. CML Approach. The Dutch Guide to Life Cycle Assessment was developed by the Leiden University Institute of Environmental Sciences (CML), the Netherlands Organization for Applied Scientific Research, and the Fuels and Raw Materials Bureau, under the auspices of the National Reuse of Waste Research Program (*45*). The Dutch LCA Handbook provides comprehensive operational step-by-step guidelines for conducting an LCA study compliant with the International Organization of Standardization guidelines. The CML−LCIA method is primarily a midpoint approach covering all emission- and resource-related impacts, for which practical and acceptable characterization methods are available as determined by the authors. Best available characterization methods have been selected based on an extensive worldwide review of existing methodologies. For most impact categories, a baseline and a number of alternative characterization methods are recommended. In addition, a comprehensive list of characterization factors and normalization factors are supplied. Ecotoxicity and human toxicity are modeled adopting the multi-media USES−LCA model. The handbook provides characterization factors for more than 1500 different LCI results. Included with the methodology is a compendium of background information related to the science of LCA (*45*−*50*).

2.2. Ecoscarcity Approach (Swiss Ecopoints). The method of environmental scarcity, also know as the Swiss Ecopoints approach, is a comparative weighting and aggregation of environmental inventory flows via ecofactors. The method provides weighting factors for different emissions into air, water, and top-soil/groundwater as well as for the use of energy resources. The ecofactors are based on the annual actual flows (current flows) and on the annual flow considered as critical (critical flows) in a defined area (country or region). Estimations of current flows are taken from the newest available statistical data, while critical flows are deduced from the scientifically supported goals of the supporting country. The method has been developed top-down and is built on the assumption that a well-established environmental policy framework, including international treaties, may be used as a reference framework for the optimization and improvement of individual products and processes. The various damages to human health and ecosystem quality are considered in the target setting process of the general environmental policy; this general environmental policy in turn is then the basis for the "critical flows". An implicit weighting takes place in accepting the various goals of the environmental policy. The method has been developed with the intent of conducting environmental assessments of specific products or processes. However, it can also be used as an element of an environmental management system for companies, where the assessment of the company's environmental aspects (ISO 14001) is supported by such a weighting method. The ecoscarcity method contains common characterization/classification approaches (for climate change, ozone depletion, and acidification). Other inventory flows are assessed individually (e.g.,various heavy metals) or as a group (e.g., NM−VOC, or pesticides). Ecofactors were originally developed for the country of Switzerland in 1990. Hence their application is restricted to its national boundary. A first amendment and update was made for 1997, which is the current version. A next version, based on 2004 data, will be available in 2006. (*51*−*53*) Recently, ecofactors have been made available in Japan (*54*).

2.3. Eco-indicator 99. The Dutch Ministry of Housing, Spatial Planning and the Environment commissioned the Eco-indicator 99 project as part of their national Integrated Product Policy initiative. It was determined by the participants of this initiative that the most critical and controversial step in LCIA was the weighting of results from a comprehensive set of categories down to a chosen few, and in some instances, a single indicator. The main purpose of this initiative was to reduce the number of subjects to be weighted to the extent possible, allowing them to be more readily understood by a review panel. Weighting was simplified by reducing the methodology to three damage areas: human health, ecosystem quality, and resources, minimizing the effort among panelists to comparatively assess many issues. With this perspective, the Eco-indicator 99 methodology was developed from a top down approach, starting from agreed upon areas of protection and categorizing them to a set of three AoPs: human health, ecosystem quality, and resources. A limiting assumption is that, in principle all emission and land uses are occurring in Western Europe and that all subsequent damages occur in Western Europe, except for the damages to resources and the damages created by climate change, ozone layer depletion, air emissions of persistent carcinogenic substances, inorganic air pollutants that have long-range dispersion, and some radioactive substances. Within the Eco-indicator 99 approach, two types of uncertainties were distinguished: data uncertainties associated with technical problems of measuring and assessing factors and model uncertainties affected by whether the model is configured correctly. To address these uncertainties, the system of cultural theory was applied to separate the damage models into three personal perspective categories (*55*): **egalitarian**, long time perspective whereby a minimum of scientific proof justifies inclusion; **individualist**, short time perspective whereby only proven effects are included; **hierarchist,** balanced time perspective whereby consensus among scientists determines inclusion of effects. The hierarchist version is chosen as the default, while the other two versions are suggested as a robustness analysis. (*56*, *57*) The developers of the Eco-indicator 99 method, PRé Consultants, have initiated a joint project effort called ReCiPe with Leiden University Institute of Environmental Sciences, the developers of the Dutch CML approach. The ReCiPe project is an integrated approach that combines the midpoint approach of Dutch CML with the damage approach of Eco-indicator 99. This project is in its initial phase of development and preliminary documentation is available (*58*).

2.4. EDIP97. The Environmental Design of Industrial Products (EDIP) program is the result of collaborative efforts of five major Danish companies, two institutes of the Technical University of Denmark, and the Confederation of Danish Industries. The EDIP method has been developed for assessment of environmental impacts from products and materials and incorporation of environmental considerations in development of new products. The EDIP97 method is primarily a midpoint approach to comprehensively cover emission-related impacts, resource use issues, and working environment impacts (*59*, *60*). The EDIP method generally contains normalization based on person equivalents and weighting based on political reduction targets for environmental impacts and working environment impacts, and supply horizon for resources. Ecotoxicity and human toxicity are modeled using a simple key-property approach where the most important fate characteristics are included in a modular framework requiring relatively few substance data for calculation of characterization factors (*61*).

The EDIP97 method has been updated through EDIP2003 methodology (*62*, *63*) supporting spatially differentiated characterization modeling, encompassing a larger portion of the environmental mechanism than EDIP97, and resulting in a method closer to a pure damage-oriented approach. The EDIP2003 method covers the same impact categories with additional subcategories. The site-generic categories of aquatic eutrophication, human toxicity, and ecotoxicity of EDIP2003 are identical to the EDIP97 factors. In addition to greater spatial resolution, the EDIP2003 method incorporates characteristics further down the chain of environmental mechanisms. In the case of EDIP97, a uniform environment is assumed and is based solely on the knowledge of the emitted substance. In contrast, EDIP2003 incorporates characteristics of the receiving environment in an effort to increase the relevance of the calculated impacts.

2.5. EPS 2000. The Environmental Priority Strategies (EPS) in design method is a tool intended to augment a company's internal product development process, specifically for the purposes of supporting a choice between two product concepts. Category indicators are chosen based on their suitability for assigning values to product design choices. The development of the EPS system was initiated in 1989 with the collaborative efforts of the Volvo automotive company, the Swedish Environmental Research Institute (IVL), and the Swedish Federation of Industries. Since then it has been modified several times. The current version, EPS 2000, has been modified under the auspices of the Centre for Environmental Assessment of Products and Material Systems. In the EPS 2000 method, impact categories and category indicators are chosen to represent actual environmental impacts on five safeguard subjects: human health, ecosystem production capacity, biodiversity, abiotic resources, and recreational and cultural values. The characterization factor is the sum of a number of pathway-specific characterization factors describing the average change in category indicator units per unit of an emission (e.g., kg decrease of fish growth per kg emitted SO_2). An estimate is made of the standard deviation in the characterization factors due to real variations depending on exogenous and endogenous factors (e.g., emission location and model uncertainty). Therefore, characterization factors are available only where there are known and likely effects. Characterization factors are given for emissions defined by their location, size, and temporal occurrence. The majority of factors is for global conditions that occurred in 1990 and represents average emission rates. This means that many toxic substances, which are present mostly in trace amounts within that time frame, have a low average impact. Weighting factors for the category indicators are determined according to an individual's willingness to pay to avoid one category indicator unit of change in the AoPs (here referred to as safe guard subjects). (*64*−*66*)

2.6. IMPACT 2002+. The IMPACT 2002+ life cycle impact assessment methodology is a combined midpoint, endpoint, and damage approach, linking inventory flows to 14 midpoint categories and subsequently to four damage categories (human health, ecosystem quality, climate change, and resources). The IMPACT 2002+ method incorporates fate and effect factors to calculate human toxicity potentials and ecotoxicity potentials at the midpoint level. Both human toxicity and ecotoxicity effect factors are based on mean responses rather than on conservative assumptions consistent with risk assessment methodologies. For other categories, methods have been transferred or adapted mainly from the Eco-Indicator 99 and CML 2002 methods, from the IPCC list, the US EPA ODP list, and the EcoInvent database. For the damage portion of the method, midpoint scores are expressed in units based on a chosen reference substance and related to the four damage categories. The midpoint categories of carcinogens, noncarcinogens, respiratory inorganics, ozone layer depletion, radiation, and respiratory effects from organics are converted via damage factor in units of DALYs/kg of reference substance. The damage related to midpoint categories of aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification, terrestrial nutrification, and land occupation can be directly determined as a potentially disappeared fraction over a certain area during a given time. Damage categories related to climate change are not included in the model. Normalization can be performed either at midpoint or at damage and is done generally at the Western European level. The IMPACT 2002+ method presently provides characterization factors for approximately 1500 different LCI results (*67*−*69*)

2.7. Japanese LCIA (LIME). The Japanese method. life cycle impact assessment method based on endpoint modeling (LIME), is a portion of a national project focused on the advancement of life cycle assessment. The project aims to develop a database and LCIA methodology that facilitates the application of LCA by industry. As such, the National Institute of Advanced Industrial Science and Technology has developed a damage-oriented LCIA methodology for quantifying environmental impacts as a result of environmental loadings in Japan. The results of the project include methods of characterization, damage assessment, and weighting normalized to the Japanese domestic economy. For characterization, LIME involves eleven impact categories: global warming, ozone-layer depletion, acidification, eutrophication, photochemical oxidant creation, urban air pollution, human toxicity, eco-toxicity, land use, resource consumption, and waste. Characterization factors for local impact categories, except for global warming and ozone-layer depletion, were developed to reflect the environmental background particular to Japan. The damage assessment categories of LIME were cataloged into four areas of protection (safeguard subjects): human health, social welfare, biodiversity, and plant production. The units of DALYs), Japanese Yen (¥), expected increase in number of extinct species, and net primary production were adopted as damage indicators for human health, social welfare, biodiversity, and plant production, respectively. The LIME method includes a weighting methodology to produce a final index score (*70*). The weighting method is based on conjoint (combined) analysis to provide weighting across the four areas of protection. With conjoint analysis two types of weighting factors were collectively implemented: (1) An amount of monetary value for avoiding a unit amount of damage to a safeguard subject, and (2) a relative weighting coefficient based on an annual amount of damage to a safeguard subject.

2.8. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). TRACI is an impact assessment methodology developed by the U.S. Environmental Protection Agency that facilitates the characterization of environmental inventory flowsthat have potential effects, including ozone depletion, global warming, acidification, eutrophication, photochemical ozone (smog) formation, ecotoxicity, human health criteria-related effects, human health cancer effects, human health noncancer effects, and fossil fuel depletion. TRACI was originally designed for use within the United States with LCA, but also has wider application to pollution prevention and sustainability metrics. During the development of TRACI, impact categories were selected based on their level of commonality with the existing literature, their consistency with EPA regulations and policies, their current state of development, and their perceived societal value. Human health was subdivided into cancer, noncancer, and criteria air pollutants to better reflect the focus of EPA regulations and to allow methodology development consistent with the regulations, handbooks, databases, and guidelines (e.g., EPA Risk Assessment Guidelines, and Human Exposure Factor Handbook) (*14*−*18*). Smog formation effects were not further aggregated with other human health impacts to maintain transparency. Criteria pollutants were preserved as a separate human health impact category to allow a modeling approach that could take advantage of the extensive epidemiological data associated with the impacts of criteria pollutants. The majority of the impact categories were characterized at the midpoint level for various reasons, including a higher level of societal consensus concerning the certainties of modeling at this point in the cause−effect chain. All chemical emissions impact categories use the fate, transport, and effects modeling most appropriate to the impact category (e.g., multimedia modeling for cancer and noncancer, but NAPAP source-receptor matrices for acidification) (*71*). Because a large number of the TRI chemicals were being considered for incorporation into the methodology, human toxicity potentials were developed using standard human health metrics (e.g., RfCs and RfDs) to determine the relative potential for human health impacts (*72*−*75*). Severity of impacts methodologies (e.g., DALYs) were not used for these categories because many of the chemicals within the set have limited animal toxicity data available, and a variety of human health impacts could be caused if a full battery of animal toxicity and human epidemiological data were available representing exposure to different concentrations and different scenarios (e.g., in combination with other chemicals). Research in the impact categories of acidification, smog formation, eutrophication, human health cancer, human health noncancer, human health criteria pollutants was conducted to construct methodologies for representing potential effects in the United States. Probabilistic analyses allowed the determination of an appropriate level of sophistication and spatial resolution necessary for impact modeling for several impact categories, yet the tool was designed to accommodate current variation in practice (e.g., site-specific information is often not available). Resource depletion was recognized as being important within the realm of potential environmental effects for most studies; however, there was much less consensus on which categories should be included and how the characterization should be conducted. A normalization database consistent with TRACI's impact categories and inventory flows is under development and should be released separately, but no weighting will be recommended.

3. Analysis of Methods

3.1. Areas of Protection. Although one of the original goals of the United Nations Environment Program Life Cycle Initiative was to come to consensus on AoPs, this proved to be a much more difficult task than originally envisioned (*46*−*48*). AoPs are a grouping of the physical elements that society has determined worthy of maintaining, either at the current state, or at an ideal state. An AoP is defined as a class of endpoints and generally includes human health, natural environment, and natural resources. The AoP of manmade environment is also included. No attempt was made to further break down the natural environment AoP to sub-AoPs of natural resources, biodiversity nor to include grouping of life support functions (LSFs). What was found to be most successful to comprehensively, yet concisely categorize the several variations of AoPs was to fit all models into the four AoPs: human health, natural environment quality, natural resources, and the manmade environment.

The first AoP, human health, was classified to include those direct and indirect impacts on human health. The second area, natural environmental quality, is broad and includes the potential impacts to ecosystems. This area includes the sub-AoPs of LSFs and biodiversity, but not those areas of the environment that have commercial utility. This is reserved for the third area, natural resources both abiotic and biotic, and pertains to materials that are extracted, harvested, or otherwise obtained from the environment for the beneficial use by humans. The fourth area, the manmade environment, includes those living and nonliving items that are produced through human intervention. The "big four" AoPs capture both the intrinsic and functional values associated with assessing potential harm to human health and the environment, no distinction is made between these values as others have had elsewhere, as they would only further obfuscate the process of classification.

3.2. Midpoint, Endpoint, Damage Weighted, and Combined Methodologies. As previously discussed, although LCIA approaches are generally talked about in the aggregated sense (e.g., TRACI, Eco-indicator 99), in actuality, each of these methods is composed of a collection of impact assessment models that underlie individual impact categories. In some cases these individual impact categories are selected and/or designed to provide a consistent perspective, whether that perspective represents a philosophical viewpoint (e.g., Eco-indicator 99), an industry's environmental perspective (e.g., EPS 2000), or consistency with a nation's policies and regulations (e.g., TRACI). This selection of perspective is extremely important in the desired approach taken to assess potential impact, driving decisions such as whether midpoints, endpoints, or damage level methods (or a combination) should be used.

While completing this research, it was apparent that many of the midpoint categories were more comprehensive in coverage of potential impacts when compared to damage weighted models. This is evident when one considers a midpoint category such as stratospheric ozone protection. See Figure 3.1. A midpoint category would include the potential for impacts in every effect that may occur at an endpoint level, including skin cancer, crop impacts, impacts on plants & animals, cataracts, impacts on plastics, and any other potential endpoints. By contrast, the damage-weighted models are limited by endpoints that can be calculated. In most cases the data does not exist to support quantification of all the known pathways to an endpoint. For example, in one of the above-surveyed approaches, in the ozone depletion model shown, only potential harm to humans via skin cancers and cataracts could be calculated at the endpoint level, and thus, only skin cancer and cataracts are included within the damage level. In those cases, the "single score", which is often aggregated using a damage indicator, does not include all of the potential impacts that were available at the midpoint level, but only a small fraction of the endpoint effects.

It was also interesting to compare the number of inventory flows covered by the various methodologies. In general,

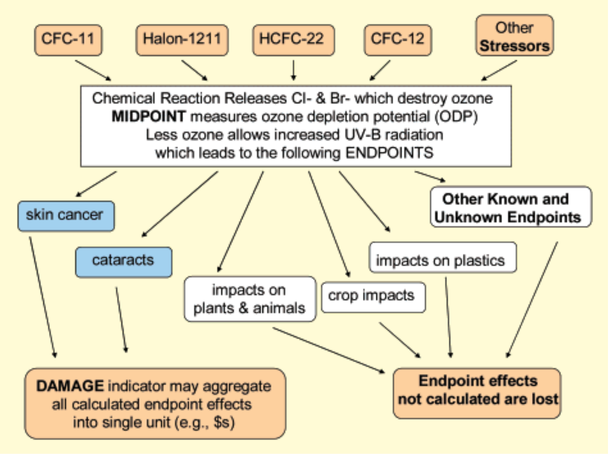

FIGURE 3.1. Progression from inventory flows to midpoints to endpoints to damage for ozone depletion potential. Note that endpoints not included in the damage indicators are lost.

midpoint methodologies tend to have more comprehensive coverage of inventory flows than damage methodologies. Because endpoint categories may require additional information to calculate the characterization factors, the number of inventory flows that contain the appropriate level of detail may be limited.

Weighting and the incorporation of values into LCIA has been a very contentious issue in ISO 14042 and the worldwide use of LCA for comparative assertions, preferable purchasing, environmental publicity claims, and international trade declarations. (*8*, *9*, *52*−*57*) It is worth noting that damage factor approaches include weighting, and hence valuation occurs.

Endpoint indicators must include more modeling assumptions (which often incorporate more value-laden perspective) than midpoint modeling. Damage indicators include these modeling assumptions and incorporate even more value choices to allow a wide variety of impacts to be aggregated to a small number (perhaps one) of environmental scores. Proponents of damage methodologies will say that it is better to make the values consistent and more transparent within the methodology than within the weighting step, but the debate continues about whose values should be used. Different values are apparent for different cultures, socioeconomic groups, and even closely related individuals. Within a country a diversity of opinions exist as exhibited by the political affiliations, environmental and human rights subgroups, and religious backgrounds of the individuals within the country. The question remains about how to most appropriately determine values of a represented group, and then whether these values should be imposed upon the group and/or others who are impacted by the decisions made by the group. The valuation process was (and is) also in need of advancement. Participants in an international workshop on midpoints versus endpoints held in Brighton, England, in May 2000 could not point out any examples of successful, unbiased panel procedures that could guide future valuation processes. (*21*) Finally, ISO 14042 tells us that it is not desirable to conduct weighting in LCAs conducted for public claims of environmental equivalence or superiority (the definition of comparative assertions) (*76*).

Discussion

This paper provides one of the most comprehensive and detailed reviews of the most popular impact assessment methodologies used in LCIA today. For the first time ever, the most commonly used methodologies are dissected in a logical way, providing midpoint, endpoint, damage, and weighting level information to practitioners who are not familiar with the underlying details, thus allowing them to compare competing methods. The format chosen for display is unique, but follows the traditional pattern of analyzing methods based on the basic Areas of Protection: human health, natural environmental quality, natural resources, and manmade environment.

To further aid in the discussions concerning the comprehensiveness and consistency within LCIA, a clear, yet novel distinction was made between midpoint, endpoint, and damage indicators. Although some of this distinction has been recognized in the published literature in the past, the advantages and disadvantages of each step are discussed in much greater detail here, with the recognition that there is increasing incorporation of value choices the closer one gets to a damage-aggregated single score. It is apparent that when LCIA model developers go beyond the midpoint level, they seldom stop at the endpoint level, since doing so would provide "too much information", that is, the number of endpoints and their variety of units would be less valuable to the decision maker than an aggregated "damage indicator" such as monetary units or DALYs. Endpoint indicators, by design, include more modeling assumptions than midpoint modeling. Damage indicators include these modeling assumptions and incorporate even more value choices to allow a wide variety of impacts to be aggregated to a small number (perhaps one) of environmental scores.

Environmental impact assessment approaches were analyzed and cataloged. During the analysis it became apparent that approaches that are mostly focused on midpoint methodologies incorporated more endpoints than the damage models. This is true because midpoint models represent an earlier point on the cause−effect chain and thus require fewer assumptions and value choices while modeling the environmental mechanisms, whereas damage models will often ignore endpoints that are not easily modeled. Five impact categories were clearly characterized as midpoint categories (i.e., ozone depletion, global climate, acidification, eutrophication, and smog formation).

When single scores are important, damage level models may inform the valuation process; however, within this paper (as within ISO 14042), it is not recommended that the decision be based entirely on damage models. If damage models are used, the user must still be very conscientious about the gaps in coverage and the additional uncertainties which are incorporated within the model, and the user should make a conscious effort to reflect those impacts which were lost and to address or explain any biases or perspectives which are reflected. Damage methodologies are limited by those endpoints that can be, and thus, are calculated. In many of the traditional midpoint categories (e.g., ozone depletion, global warming, and acidification), the data does not exist to take many of the known branches to an endpoint. For example, in the ozone depletion model shown, only the skin cancers and cataracts could be calculated at the endpoint level, and thus, only the skin cancers and cataracts are included within the damage level. Thus the following endpoints (and more) may be dropped during damage analysis of ozone depletion: human health (immune system suppression), natural environment quality (impacts on plants and animals), and man-made environment (impacts on materials such as plastics, impacts on agriculture). In those cases, the "single score", which is often aggregated using a damage indicator, does not include all of the potential impacts that were available at the midpoint level, but may include only a small fraction of the endpoint effects. ISO 14042 guidance recommends more comprehensive coverage of impacts, more scientifically based modeling, and more international consensus within the models, all of which are best addressed within midpoint models.

The categories and subcategories related to human toxicity and ecotoxicity were generally classified as damage categories, since there is no commonly accepted point earlier in the cause−effect chain, which are generally chosen to represent the midpoint. It was also noted that in all human toxicity and ecotoxicity models many different endpoints are aggregated since it is impossible to maintain the wide variety of human (and eco) endpoints and severities that comprise human (and eco) toxicity.

This paper provides the user with additional information concerning the motivation behind, and the perspective of the various impact assessment approaches that are currently available. These motivations can be based upon a number of perspectives including a country's historical and regulatory perspective (e.g., TRACI), an assumed political and societal perspective (e.g., Eco-indicators'99), or an environmental policy goal perspective (e.g., Ecoscarcity; Swiss Ecopoints). In all cases, the perspective may be well documented within the methodology documents describing the impact assessment methods, but often the true details about how this perspective influences the methodology may be difficult to understand without becoming intimately familiar with the underlying model and input parameters. The users of LCIA models are advised to become well-informed about each of the methods and their history and perspective prior to selection of any one model.

The LCA user should consider the factors discussed in this paper when determining which approach is most appropriate for their application. For further information, references are provided for each of the approaches reviewed.

Supporting Information Available

Detailed structure based on four Areas of Protection and four comprehensive tables (corresponding to each Area of Protection) allowing a comparison of eight popular impact assessment approaches. This material is available free of charge via the Internet at http://pubs.acs.org.

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A Critical Analysis of the Mathematical Relationships and Comprehensiveness of Life Cycle Impact Assessment Approaches

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ABSTRACT

The impact assessment phase of Life Cycle Assessment (LCA) has received much criticism due to lack of consistency. While the ISO standards for LCA did make great strides in advancing the consensus in this area, ISO is not prescriptive, but has left much room for innovation and therefore inconsistency. To address this lack of consistency, there is currently an effort underway to provide a conceptual framework for Life Cycle Impact Assessment (LCIA) and recommended practice to include a list of impact categories, category indicators, and underlying methodologies. This is an enormous undertaking, especially in light of the current fundamental lack of consensus of the basic elements to be included in a LCIA (e.g., impact categories, impacts, and Areas of Protection). ISO 14042 requires selection of impact categories that "reflect a comprehensive set of environmental issues" related to the system being studied, especially for "comparative assertions" that involve public marketing claims. In order to be comprehensive it is necessary to have a listing of impacts that "could" be included within the LCIA before entering into discussions of impacts that "should" be included. In addition to providing a critical review of existing and emerging impact assessment approaches, this paper will formulate a structured representation that allows more informed selection of approaches. The definitions and relationships between midpoint, endpoint, damage, and Areas of Protection will be presented in greater detail, along with the equations that are common to many of the approaches. Finally, a discussion of the advantages and disadvantages of displaying results at various stages in the environmental models will be presented in great detail.

Supporting Information

This paper includes a detailed structure based on four Areas of Protection with four comprehensive tables (corresponding to each Area of Protection) allowing a comparison of eight popular impact assessment approaches.

Human Health

Method	CML	Eco-Indicator 99	Ecoscarcity	EDIP97	EPS 2000d	Impact 2002+	LIME	TRACI
Climate Protection								
Midpoint	GWPs	Not reported separately.	GWPs	GWPs	Not reported separately.	GWP	GWPs	GWPs
Endpoint	All included. Not calculated independently.	Malaria, dengue fever, schistosomiasis, cardio & resp disease, displaced populations	All included. Not calculated independently.	All included. Not calculated independently.	Life expectancy, severe morbidity, morbidity, severe nuisance, nuisance	Mortality and morbidity of species	Thermal stress, cold stress, malaria, dengue fever, disaster, food shortage	All included. Not calculated independently.
Damage	Not calculated	DALYs	Not calculated	Not calculated	Person-years	Not calculated	DALYs	Not calculated
Weighting	Not calculated	DALYs and 3 perspectives	Critical Flows	Political Reduction of Targets.	ELU/inidcator based on WTP	Not calculated	(Yen/DALYs) or (WTP Yen * Weighting Factor)	Not calculated
Stratospheric Ozone Protection								
Midpoint	ODPs	Not reported separately.	ODPs	ODPs	Not reported separately.	ODPs	ODPs	ODPs
Endpoint	All included. Not calculated independently.	Skin cancers and cataracts.	All included. Not calculated independently.	All included. Not calculated independently.	Life expectancy	Cancer.	Unknown.	All included. Not calculated independently.
Damage	Not calculated	DALYs	Not calculated	Not calculated	Person-years	DALYs	DALYs	Not calculated
Weighting	Not calculated	DALYs and 3 perspectives	Critical Flows	Political Reduction of Targets.	ELU/inidcator based on WTP	Not calculated	(Yen/DALYs) or (WTP Yen * Weighting Factor)	Not calculated
Acidification								
Midpoint	AP s	None	AP s	AP s	Not reported separately.	None	None	AP s
Endpoint	All included. Not calculated independently.	None	All included. Not calculated independently.	All included. Not calculated independently.	Life expectancy, severe morbidity, morbidity, severe nuisance, nuisance	None	None	All included. Not calculated independently.
Damage	Not calculated	None	Not calculated	Not calculated	Person-years	None	None	Not calculated
Weighting	Not calculated	None	Critical Flows	Political Reduction of Targets.	ELU/inidcator based on WTP	None	None	Not calculated
Smog Formation								
Midpoint	PCOPs	Not reported separately.	Emissions maxima to air	PCOPs	Not reported separately.	PCOPs	PCOPs	PCOPs
Endpoint	All included. Not calculated independently.	Not reported.	Not calculated	All included. Not calculated independently.	Life expectancy, severe morbidity, morbidity, severe nuisance, nuisance	Respiratory	Acute death, respiratory disease, asthma attack	All included. Not calculated independently.
Damage	Not calculated	DALYs	Not calculated	Not calculated	Person-years	DALYs	DALYs	Not calculated
Weighting	Not calculated	DALYs & 3 perspectives	Critical Flows	Political Reduction of Targets.	ELU/inidcator based on WTP	Not calculated	(Yen/DALYs) or (WTP Yen * Weighting Factor)	Not calculated
Eutrophication								
Midpoint	Eutrophication Potentials	None	Annual emissions: P:lakes; N: saltwater basins	N&P equivalents based on Redfield factor	Not reported separately.	None	None	Eutrophication Potentials
Endpoint	All included. Not calculated independently.	None	Not calculated	All included. Not calculated independently.	morbidity, morbidity, severe nuisance, nuisance	None	None	All included. Not calculated independently.
Damage	Not calculated	None	Not calculated	Not calculated	Person-years	None	None	Not calculated
Weighting	Not calculated	None	Critical Flows	Political Reduction of Targets.	ELU/inidcator based on WTP	None	None	Not calculated
Cancer								
Midpoint	May be in other human toxicity category.	Not calculated	May be in other human toxicity category.	None	Not reported separately.	May be in other human toxicity category.	May be in other human toxicity category.	Not calculated
Endpoint	See above	Cancer	See above	None	Life expectancy, severe morbidity, morbidity, severe nuisance, nuisance	See above	See above	Cancer
Damage	See above	DALYS	See above	None	Person-years	See above	See above	HTPs
Weighting	See above	DALYs & 3 perspectives	See above	None	ELU/inidcator based on WTP	See above	See above	Not calculated
Radiation								
Midpoint	Radiation Effects	Not calculated	Not calculated	None	None	Not calculated	None	None
Endpoint	Radiation Effects	Radiation Effects	Radiation Effects	None	None	Cancer.	None	None
Damage	Yr kBq	DALYs	Volume of radioactive wastes	None	None	DALYs	None	None
Weighting	Not calculated	DALYs & 3 perspectives	Critical Flows	None	None	Not calculated	None	None
Respiratory								
Midpoint	May be in other human toxicity category.	May be found in Smog Formation category.	May be in other human toxicity category.	May be found in smog formation category.	Not reported separately.	Not calculated	Not calculated	Not calculated
Endpoint	See above	See above	See above	See above	Life expectancy, severe morbidity, morbidity, severe nuisance, nuisance	Respiratory	Respiratory disease.	Respiratory
Damage	See above	See above	See above	See above	Person-years	DALYs	DALYs	HTPs
Weighting	See above	See above	See above	See above	ELU/inidcator based on WTP	Not calculated	(Yen/DALYs) or (WTP Yen * Weighting Factor)	Not calculated
Other Human Toxicity								
Midpoint	Not calculated	None	Not calculated	Not calculated	Not reported separately.	Not calculated	Not calculated	Not calculated
Endpoint	Range of toxicity effects tested.	None	Range of toxicity effects	Range of toxicity effects	Range of toxicity effects due to metals (e.g., Hg) Life expectancy, severe morbidity, morbidity, severe nuisance	Range of toxicity effects	Respiratory disease & cancer.	Noncancerous effects
Damage	HTPs	None	Emissions maxima to air, water, and top soil	Not calculated	Person-years	DALYs	DALYs	Not calculated
Weighting	Not calculated	None	Critical Flows	Political Reduction of Targets.	Political Reducation of Targets.	Not calculated	(Yen/DALYs) or (WTP Yen * Weighting Factor)	Not calculated
Odor								
Midpoint	Not calculated	None	None	None	None	None	None	None
Endpoint	Not calculated	None	None	None	Nuisance	None	None	None
Damage	Malodorous air/water	None	None	None	Person-years	None	None	None
Weighting	Not calculated	None	None	None	ELU/inidcator based on WTP	None	None	None
Noise								
Midpoint	Unweighted aggregation of sound	None	None	None	Not reported separately.	None	None	None
Endpoint	Not calculated	None	None	None	Severe nuisance, nuisance	None	None	None
Damage	Not calculated	None	None	None	Person-years	None	None	None
Weighting	Not calculated	None	None	None	ELU/inidcator based on WTP	None	None	None
Casualties								
Midpoint	Unweighted aggregation of victims.	None	None	None	None	Not calculated	None	None
Endpoint	Casualties	None	None	None	None	Casualties	None	None
Damage	Not calculated	None	None	None	None	DALYs	None	None
Weighting	Not calculated	None	None	None	None	None	None	None

Table 1: Comparing Human Health Modeling For Eight Impact Assessment Approaches

Natural Environmental Quality								
Method	**CML**	**Eco-Indicator 99**	**Ecoscarcity**	**EDIP97**	**EPS 2000d**	**Impact 2002+**	**LIME**	**TRACI**
Climate Protection								
Midpoint	GWPs	None.	GWPs	GWPs	Not reported separately.	GWPs	GWPs	GWPs
Endpoint	All included. Not calculated independently.	None.	All included. Not calculated independently.	All included. Not calculated independently.	Ecosystem production capacity - crop, wood, fish, meat, base cation capacity of soil, water	Mortality and morbidity of species	Terrestrial plant species	All included. Not calculated independently.
Damage	Not calculated.	None.	Not calculated.	Not calculated.	kg	Not calculated.	Yen/NPP dry ton or WTP (Yen)	Not calculated.
Weighting	Not calculated.	None.	Critical Flows	Political Reduction of Targets.	ELU/indicator unit	Not calculated.	Yen/NPP dry ton or WTP (Yen)	Not calculated.
Stratospheric Ozone Protection								
Midpoint	ODPs	None.	ODPs	ODPs	Not reported separately.	None.	ODPs	ODPs
Endpoint	All included. Not calculated independently.	None.	All included. Not calculated independently.	All included. Not calculated independently.	Ecosystem production capacity - crop, wood, fish, meat, base cation capacity of soil, water	None.	Forest and phytoplankton	All included. Not calculated independently.
Damage	Not calculated.	None.	Not calculated.	Not calculated.	kg	None.	Yen/NPP dry ton or WTP (Yen)	Not calculated.
Weighting	Not calculated.	None.	Critical Flows	Political Reduction of Targets.	ELU/indicator unit	None.	Yen/NPP dry ton or WTP (Yen)	Not calculated.
Acidification								
Midpoint	Acidification Potentials	Not calculated.	Acidification Potentials	Acidification Potentials	Not reported separately.	Terrestrial and Aquatic Acidification Potentials	None.	Acidification Potentials.
Endpoint	All included. Not calculated independently.	Changed PH and Nutrient Availability	All included. Not calculated independently.	All included. Not calculated independently.	Ecosystem production capacity - crop, wood, fish, meat, base cation capacity of soil, water	All included. Not calculated independently.	None.	All included. Not calculated independently.
Damage	Not calculated.	Potentially Disappeared Fraction of Species	Not calculated.	Not calculated.	mol H+ equivalents	Not calculated.	None.	Not calculated.
Weighting	Not calculated.	PDFs & 3 Perspectives	Critical Flows	Political Reduction of Targets.	ELU/indicator unit	Not calculated.	None.	Not calculated.
Smog Formation								
Midpoint	Smog Potentials	None.	Emissions maxima to air	Smog Potentials	None.	Smog Potentials	None.	Smog Potentials
Endpoint	All included. Not calculated independently.	None.	Not calculated.	All included. Not calculated independently.	None.	All included. Not calculated independently.	None.	All included. Not calculated independently.
Damage	Not calculated.	None.	Not calculated.	Not calculated.	None.	Not calculated.	None.	Not calculated.
Weighting	Not calculated.	None.	Critical Flows	Political Reduction of Targets.	None.	Not calculated.	None.	Not calculated.
Eutrophication								
Midpoint	Eutrophication Potentials	See above.	Annual emissions: P:lakes; N: saltwater basins	N&P equivalents based on Redfield factor	Not reported separately.	Eutrophication Potentials	None.	Eutrophication Potentials
Endpoint	All included. Not calculated independently.	See above.	Not calculated.	All included. Not calculated independently.	Ecosystem production capacity - crop, wood, fish, meat, base cation capacity of soil, water	Mortality and morbidity of species	None.	All included. Not calculated independently.
Damage	Not calculated.	See above.	Not calculated.	Not calculated.	kg	Not calculated.	None.	Not calculated.
Weighting	Not calculated.	See above.	Critical Flows	Political Reduction of Targets.	ELU/indicator unit	Not calculated.	None.	Not calculated.
Radiation								
Midpoint	Radiation Effects	None.	Radiation Effects	None.	None.	None.	None.	None.
Endpoint	Radiation Effects	None.	Radiation Effects	None.	None.	None.	None.	None.
Damage	Yr kBq	None.	Volume of radioactive wastes	None.	None.	None.	None.	None.
Weighting	Not calculated.	None.	Critical Flows	None.	None.	None.	None.	None.
Noise								
Midpoint	Unweighted aggregation of sound	None.	None.	None.	None.	None.	None.	None.
Endpoint	Not calculated.	None.	None.	None.	None.	None.	None.	None.
Damage	Not calculated.	None.	None.	None.	None.	None.	None.	None.
Weighting	Not calculated.	None.	None.	None.	None.	None.	None.	None.

Table 2: Comparing Natural Environmental Quality For Eight Impact Assessment Approaches

Natural Resources								
Method	**CML**	**Eco-Indicator 99**	**Ecoscarcity**	**EDIP97**	**EPS 2000d**	**Impact 2002+**	**LIME**	**TRACI**
Fossil Fuel Depletion								
Midpoint	None.	None.	None	None	None	None	None.	None
Endpoint	Energy carriers & mineral together.	Depletion of fossil fuel stock	Fossil fuel use by energy content	None	Depletion of fossil fuel stock	Depletion of fossil fuel stock	Total energy consumption	Depletion of fossil fuel stock
Damage	ADP in kg antimony or MJ/kg based on exergy content.	MJ surplus energy	Energy Use	None	kg/kg reserves	MJ primary non-renewable energy	The socio-economic impact and impact on ecosystem	MJ surplus energy
Weighting	None.	MJ surplus energy & 3 perspectives	Critical Flows	None.	ELU/Indicator unit based on WTP	None	Yen/NPP or WTP (Yen) * Weighting Factor	None.
Mineral Use								
Midpoint	None.	Concentration of minerals	None	None	None	None	None.	None
Endpoint	None.	Depletion of mineral stock	None	None	Depletion of mineral stock	Depletion of mineral stock	Inverse of resource reserve	None
Damage	None.	MJ surplus energy	None	Weighting based on supply horizon	kg/kg reserves	MJ primary non-renewable energy	The socio-economic impact and impact on ecosystem	None
Weighting	None.	MJ surplus energy & 3 perspectives	None	Weighting based on supply horizon	ELU/Indicator unit based on WTP	None	Yen/NPP or WTP (Yen) * Weighting Factor	None
Land Use								
Midpoint	Land competition & loss of biodiversity & life support function	Change in habitat size and land use	Volume and weight of controlled waste deposition (use of scarce space)	None	Arable and forestry land	Change in habitat size and land use	Land transformation and land occupation	None
Endpoint	Acres Utilized	Mortality and morbidity of species (PDFs)	Waste deposition on land	None	Mortality and morbidity of species	Mortality and morbidity of species (PDFs)	Measure of land occupied and transformed	None
Damage	Unweighted Acres	Potentially Disappeared Fraction of species (PDFs)	Waste deposition on land	None	Normalized Extinction of Species	Potentially Disappeared Fraction of species (PDFs)	Vascular plant species	None
Weighting	Not calculated.	PDFs & 3 perspectives	Critical Flows	None	ELU/indicator unit based on WTP	None	Yen/NPP or WTP (Yen) * Weighting Factor	None
Water Use								
Midpoint	Not specified.	None.	None	None	None	None	None.	None
Endpoint	Not specified.	None.	None	None	None	None	None.	None
Damage	Not specified.	None.	None	Weighting based on supply horizon	None	None	None.	None
Weighting	Not specified.	None.	None	Weighting based on supply horizon	None	None	None.	None
Other Resource Consumption								
Midpoint	None.	None.	None	None	None	None	None.	None
Endpoint	None.	None.	None	None	None	None	Total energy consumption	None
Damage	None.	None.	None	Weighting based on supply horizon	None	None	The socio-economic impact and impact on ecosystem	None
Weighting	None.	None.	None	Weighting based on supply horizon	None	None	Yen/NPP or WTP (Yen) * Weighting Factor	None
Waste								
Midpoint	None.	None.	See land use	None	None	None	See land use	See land use
Endpoint	None.	None.	See land use	None	None	None	See land use	See land use
Damage	None.	None.	See land use	None	None	None	See land use	See land use
Weighting	None.	None.	See land use	None	None	None	See land use	See land use

Table 3: Comparing Natural Resource Modeling For Eight Impact Assessment Approaches

Manmade Environment								
Method	**CML**	**Eco-Indicator 99**	**Ecoscarcity**	**EDIP97/EDIP 2003**	**EPS 2000d**	**Impact 2002+**	**LIME**	**TRACI**
Abiotic								
Midpoint	None	None	None	None	None	None	None	None
Endpoint	None	None	None	None	Recreational and cultural values	None	None	None
Damage	None	None	None	None	None	None	None	None
Weighting	None	None	None	None	None	None	None	None
Biotic								
Midpoint	None	None	None	None	None	None	None	None
Endpoint	None	None	None	None	None	None	None	None
Damage	None	None	None	None	None	None	None	None
Weighting	None	None	None	None	None	None	None	None

Table 4: Comparing Manmade Environment Modeling For Eight Impact Assessment Approaches