Available online at www.sciencedirect.com
ScienceDirect
Journal of Cleaner Production 15 (2007) 1787–1796
Journal of Cleaner Production
www.elsevier.com/locate/jclepro

Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators

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Received 11 October 2005; accepted 17 April 2006
Available online 6 June 2006

Abstract

We present a new analytical tool, called COMPLIMENT, which can be used to provide detailed information on the overall environmental impact of a business. COMPLIMENT integrates parts of tools such as life cycle assessment, multi-criteria analysis and environmental performance indicators. It avoids disadvantages and combines complementary aspects of these three tools. The methodology is based on environmental performance indicators, expanding the scope of data collection towards a life cycle approach and including a weighting and aggregation step. A case study on the Thai pulp industry illustrates the usefulness of COMPLIMENT.

Keywords: Life cycle assessment (LCA); Analytic hierarchy process (AHP); Environmental performance; Eucalyptus; Pulp; Thailand

1. Introduction

The way to sustainable development as decided upon at the Rio conference in 1992 and restated in Johannesburg in 2002 poses a challenge for both the political and the industrial sector. Businesses are expected to invest in setting off on the path towards sustainable development. However, what that path is, is not always clear because most businesses contribute to a variety of interrelated environmental problems. Reducing emissions that contribute to one environmental problem often lead to higher emissions contributing to another environmental problem [1,2]. Therefore, tools are needed to assess the environmental aspects of a business, be it a single firm, a sector or the national or international economy. In environmental systems analysis and industrial ecology, there are widely recognised instruments collecting detailed information on environmental aspects. Powerful instruments are Life Cycle Assessment (LCA), Multi-Criteria Analysis (MCA) and Environmental Performance Indicators (EPIs).

Life cycle assessment (LCA) is considered a systematic tool evaluating the environmental impacts occurring throughout the entire life cycle of a product, process or activity [3,4]. This ‘cradle-to-grave’ approach leads to insight into the overall performance and the relative contributions of the different stages in its lifetime. One of the main strengths is the comprehensiveness of the approach and the resulting avoidance of problem shifting between impacts or areas. One of the main weaknesses of LCA is the large amount of detailed data, time and expert knowledge necessary to apply it (see Table 1).

Abbreviations: ADP, air-dried pulp; AHP, analytic hierarchy process; AP, acidification potential; EP, eutrophication potential; EPIs, environmental performance indicators; GWP, global warming potential; HTP, human toxicity potential; LCA, life cycle assessment; MCA, multi-criteria analysis; POF, photochemical oxidant formation.

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doi:10.1016/j.jclepro.2006.04.004

Table 1
Comparison of life cycle assessment (LCA), multi-criteria analysis (MCA) and environmental performance indicators (EPIs) with respect to their purpose of analysis, procedure, final outputs, strengths and weaknesses

	LCA	MCA	EPIs
Purpose of the analysis	To compile and evaluate the environmental impacts of a product over its entire life cycle.	To evaluate the overall environmental consequences of an alternative, taking into account multiple criteria and their relative weights.	To compare an organisation's past or present environmental performance to its environmental performance criteria.
Procedure	Goal and scope definition, inventory analysis, impact assessment and interpretation.	Establishing the decision context, identifying criteria, scoring, weighting deriving an overall value, examining the results and conducting a sensitivity analysis.	Data collection, establishment of a database, aggregation, standardisation or normalisation into a set of performance indicators.
Final output of the instrument	A limited set of environmental scores for a number of impact categories.	One environmental score based on an aggregation of criteria.	Environmental scores for a large number of performance indicators (consumption of raw materials etc.).
Strengths of the instrument	Avoids problem shifting to other issues or areas, comprehensiveness through 'cradle-to-grave' approach.	Possibility of weighting the criteria, use of criteria with their own dimensions, single score for overall evaluation.	Can be designed individually for each organisation, limited time and data requirements, widely used for benchmarking.
Weaknesses of the instrument	LCA is a complex process and requires considerable time and data input; dependence of normalisation on reference scenario; difficulties in interpreting the results.	MCA usually only takes a part of the production chain into account; relies on input from experts and stakeholders; weighting is subjective.	Indicators are only built for aspects on which data is readily available; large sets of indicators; lack of impact calculation (i.e. consequences of emissions); difficult to obtain the overall environmental performance.

Based on [3,8,36–38].

Multi-criteria analysis (MCA) is a decision-making tool used in environmental systems analysis to evaluate a problem by giving an order of preference for multiple alternatives on the basis of several criteria that may have different units. The purpose of an MCA is to compare and rank alternative options and to evaluate their (environmental) consequences according to the criteria established [5]. One of the greatest strengths is the possibility to use the criteria with their own dimensions. One of the greatest weaknesses of MCA is the subjectivity of the weighting step that is needed to value the different criteria. MCA differs from many other tools in including subjective elements and in resulting in a single number (see Table 1).

Environmental performance indicators (EPIs) measure the current or past environmental performance of an organisation and compare it to the targets set by the organisation's management [6]. One of the main strengths is the possible use for benchmarking within the sector [7]. One of the main weaknesses of EPIs is that they are often only collected for aspects on which data is readily available [8]. They differ from LCA in that they do not aim at comprehensiveness, but rather at the representation of key characteristics of a business (see Table 1).

Clearly, LCA, MCA and EPIs not only differ widely in their respective advantages and shortcomings, but also complement each other (see Table 1). Combining the tools, or part of the tools, may therefore be an appropriate and promising possibility. Several combinations of tools have already been carried out and published in scientific literature. For example, publications on combinations of LCA and MCA, where a part of an MCA is applied to LCA output data in order to calculate a single overall index (e.g. [9,10]). Additionally, parts of LCA and environmental management systems (EMS) have been combined [11] to carry out an environmental 'cradle-to-gate' assessment, i.e. from the production of raw materials until the product leaves the premises of a business. For analysing the environmental performance of an industrial enterprise or sector, the available tools are not entirely sufficient. In this paper, we focus on the methodology of a new approach and want to take previous combinations of two tools one step further by integrating three tools: LCA, MCA and EPIs.

The purpose of this study therefore is to develop a tool which can be applied by companies or sectors to carry out an overall environmental assessment requiring less detailed data, time and expert knowledge, but still providing a comprehensive analysis. We do this by exploring the possibilities of combining the three above-mentioned tools: life cycle assessment, environmental performance indicators and multi-criteria analysis with respect to their distinct advantages. The choice for these three tools was made based on the need for comprehensiveness regarding the environmental aspects which is delivered by the 'cradle-to-grave' approach of LCA, the need for a single indicator to facilitate decision-making leading to the inclusion of MCA as well as the need for a tool that can be based on easily available data which led to the inclusion of EPIs. The new combination of these three tools presented here is based on an evaluation and assessment of the results of a literature review and subsequently the development of a new methodology for combining the tools.

As an illustrative case study, we apply our new approach to the production of eucalyptus pulp in Thailand. This case study was chosen because the pulp industry contributes to a variety of environmental problems in Thailand and in Asia in general. Which of these environmental impacts should be tackled to most effectively reduce the overall environmental impact from this sector is yet unclear.

We refer to our new combination as COMPLIMENT, which is an acronym for COMbining environmental Performance indicators, LIfe cycle approach and Multi-criteria to assess the overall ENvironmental impacT. We will show that COMPLIMENT not only contains new elements, but also is a workable and useful tool, adding to the already existing tools and providing a powerful method that allows for a comprehensive evaluation of the overall environmental performance of a firm or sector in one single index.

2. Combining LCA, MCA and EPIs

When forming combinations of LCA, MCA and EPIs, only parts of the tools can and need to be used. This is because a new evaluation method is to be formed – carrying out the three single tools consecutively would not draw on all their complementary strengths and would be much too time-consuming to be implemented on a company level. With respect to LCA, the combinations analysed include its comprehensive (life cycle) approach consisting of taking all environmental aspects of the production chain into account. MCA as used in the combinations described in this paper consists of several different evaluation methods and is mainly used to establish the weights for the aggregation of different categories. For EPIs, the combinations analysed include the individual design for each organisation, making it possible to choose the relevant parts of the production chain. The reason for combining these tools lies in their complementary characteristics: LCA is objective, reproducible and its methodology has been standardised; MCA evaluation methods allow for taking into account subjective elements, such as the opinions of stakeholders and decision-makers, in the valuation of the different criteria; EPIs are less objective and reproducible than LCA but their design can vary from organisation to organisation, making EPIs particularly interesting for company level analyses.

The three selected tools, LCA, MCA and EPIs, can be combined in many different ways. In the following, we will briefly review and discuss combinations of two tools (double combinations) and introduce a new methodology for combining all three tools (COMPLIMENT). Combinations consisting of two of the selected tools have already proven to highlight possible synergistic effects. However, the combination consisting of all three tools has not been published in scientific literature before.

2.1. Combinations consisting of two tools

In this section, we will discuss three different types of combining two of the tools as described in the literature: (1) Combining LCA and MCA, (2) MCA and EPIs and (3) EPIs and LCA.

2.1.1. Combining life cycle assessment and multi-criteria analysis

This combination offers additional benefits compared to using either of the tools individually because the two tools to be combined here complement each other. LCA is standardised and reproducible, whereas MCA is subjective and different results may be obtained depending on the method or perspective selected. In this combination, the MCA evaluation method is generally used to weight and sum LCA results into a single index (after classification, characterisation and optionally also normalisation). This type of combination has already been researched and published, for example by Benoit and Rousseaux [10], who compare the suitability of several outranking methods for aggregating LCA impact categories and by Pineda-Henson and Culaba [12] and Pineda-Henson et al. [13], who let an expert panel assign weights to impact categories and rank improvement options for the semi-conductor industry and pulp and paper production. Despite the loss of information that occurs when aggregating data into a single index, the weighting of mid-point impact categories and the subsequent calculation of one overall, single number score is one of the general strengths of a combination of LCA and MCA evaluation methods. An example is the aggregation of normalised potential impacts for acidification, eutrophication and global warming into a single indicator expressing potential environmental impact. The other main strong point of these combinations is the comprehensiveness due to the LCA approach. However, these combinations of LCA and MCA also have weaknesses: they imply a large amount of information that needs to be collected and analysed, which is a bottleneck for many firms when considering their implementation. Including multi-criteria analysis in this combination means that value-laden choices are made, influencing the results and introducing some uncertainty through the loss of information when aggregating data.

2.1.2. Combining environmental performance indicators and multi-criteria analysis

A different type of combination, consisting of integrating parts of environmental performance indicators (EPIs) and MCA, can be beneficial because EPIs provide key information on the environmental performance of a company or sector, while MCA makes it possible to aggregate this information into a single environmental index. In literature, this combination has been applied to a far lesser extent than the combination of LCA and MCA. A procedure combining these tools generally consists of weighting and summing EPIs into a single number using an MCA evaluation method. Traditionally, the scope of EPIs is focussed on the manufacturing processes on a company's premises [14], although larger system boundaries have been suggested [15]. Although the resulting index will not evaluate the environmental impact but emissions and material consumption, there is an advantage in the calculation of a single score as well as the fact that it is still possible to design the EPIs individually for the organisation, according to its activities, goals and information needs. Including multi-criteria analysis in this combination means that value-laden choices are made, influencing the results and introducing some uncertainty through the loss of information when aggregating data.

2.1.3. Combining life cycle assessment and environmental performance indicators

Another combination of tools consists of joining LCA and EPIs and offers rewards, for example by expanding the system boundaries of the processes considered by using a company's EPIs as a starting point and then extending the scope towards LCA system boundaries so that production steps that do not take place on the premises, such as raw material production or waste management, are considered as well. In this way, a company not only gets a better overview of the total environmental impact of a product but can also gain insight into the most significant production steps. This combination has recently been applied to some extent in literature. For example, LCA inventory data can be aggregated into impact categories to be used as performance indicators from production processes [11]. Although the use of the resulting data for benchmarking becomes difficult, this type of combination can be advantageous because it standardises the procedure for data format and quality and thus increases transparency, reproducibility and credibility [11]. Another strong point of this combination is the expansion of scope from EPIs towards including a larger part of a product's life cycle such that outsourcing polluting production processes to improve a company's environmental performance (so-called problem shifting) does not result in an improved overall environmental impact.

2.2. Combinations consisting of all three tools

We considered three approaches for combining LCA, MCA, and EPIs: integrating LCA into a combination of MCA and EPIs, integrating EPIs into a combination of LCA and MCA, and integrating MCA into a combination of LCA and EPIs.

For the first approach, the advantages of LCA to be integrated, i.e. no problem shifting and comprehensive 'cradle-to-grave' approach, have to be included in the method at an early stage, because they influence the early stages of the procedure such as goal and scope definition and the data collection and analysis. It is very difficult therefore to include LCA-specific characteristics in a combination of MCA and EPIs (see Section 2.1.2) which is already finished. An earlier inclusion of LCA in the combination would mean that the resulting combination is similar or identical to the combinations described below, in which LCA and EPIs are combined first and then later MCA is used to evaluate the result.

The most straightforward way of carrying out the second approach is to express the result of the combination of LCA and MCA as EPIs. This results in EPIs that express the potential environmental impact of the product chain taken into account in relation to one of the organisation's key variables (e.g. turnover, number of employees). This approach would ensure that all relevant impacts are taken into account. However, by carrying out a combination of LCA and MCA first (see Section 2.1.1), this approach does not include the strengths of EPIs, i.e. individual design for each organisation, lower time and data requirements as well as use for benchmarking.

The third approach is based on the expansion of the scope of EPIs according to a life cycle approach (see Section 2.1.3), followed by weighting and aggregation using MCA. It is a logical procedure for integrating the three tools mentioned, because data availability at the beginning is high, the scope is then expanded according to the life cycle approach and it results in a single indicator for decision-making. It was considered the most promising and will be described in detail.

2.3. COMPLIMENT

COMPLIMENT ('COMbining environmental Performance indicators, LIfe cycle approach and Multi-criteria to assess the overall ENvironmental impacT') is a new combination of LCA, MCA and EPIs. It can be used for the overall environmental assessment of an enterprise or a sector and has to our knowledge not yet been published nor implemented by industry. COMPLIMENT integrates MCA into a combination of EPIs and LCA, thereby forming a combination of all three tools by expanding the scope of EPIs towards a life cycle approach and then integrating an MCA evaluation method. When evaluating the environmental impact of a sector, complexity and heterogeneity often make the use of full LCAs difficult [16]. By starting with a limited system boundary, COMPLIMENT may provide a solution to this problem.

2.3.1. Scope and purpose

The system boundary of COMPLIMENT in theory is cradle-to-grave. In practice, however, the system boundary is extended from a gate-to-gate analysis at the starting point (EPIs are usually built for gate-to-gate data) to a cradle-to-gate or cradle-to-grave analysis depending on the availability of such data for the company or sector and the number of products to be considered. The tool is designed for application to companies and sectors, but also can be applied to processes or products.

2.3.2. Methodology

The method starts with the selection of EPIs to be calculated while taking into account the goal and scope definition of an LCA, followed by data collection, analysis and conversion and subsequently the classification, characterisation and normalisation steps. Life cycle assessments are usually site-independent and time-independent, ignoring the spatial and temporal differences in the potential impact of human activities. This is particularly reflected by the use of generic characterisation factors such as acidification potentials or global warming potentials. The alternative would be to use site-dependent or site-specific characterisation factors (see [17–21]). For most world countries, however, consistent sets of site-dependent characterisation factors are not readily available. Carrying out classification, characterisation and normalisation result in a set of output data in the form of impact categories, such as global warming, acidification potential, eutrophication potential, ozone precursors and human health.

These results may be difficult to interpret by non-experts, e.g. stakeholders and decision-makers. In addition, there may be a wish to compare the environmental impacts of a company or sector in time series to check if improvements were achieved. These are two of the reasons for aggregating output data into an index, for which multi-criteria analysis (MCA) is a suitable tool. Fig. 1 is a graphical representation of this procedure.

In general, MCA is a tool that helps to establish weights for several criteria, without requiring that all data be converted into the same units. There are several distinct multi-criteria evaluation methods that can be used for such a weighting and aggregation step. These include panel methods as well as approaches based on marginal costs, distance-to-targets or 'no significant adverse effect levels' (NSAEL). Panel methods are well-known and commonly used evaluation methods, in which the weighting factors are derived from the views of a panel of experts. Marginal costs on the other hand provide information on the costs of emission reduction to reduce emissions by another unit, thereby providing a cost-based weighting method [22]. Weights derived from the distance-to-target method are based on the difference between actual emissions and policy targets for these emissions [23]. Finally, NSAEL results in weights that are based on the difference with emission levels that would not significantly affect the ecology in an adverse way [9]. As an alternative, the analytic hierarchy process (AHP) developed by Saaty [24] may be used as a way to value the different criteria. This method uses a series of pair-wise comparisons to determine the relative weights of the single criteria or indicators, with the total of all weights adding up to 100% [25]. With the use of these weights, the output data can be aggregated into an overall index. In this study, we use the AHP procedure, because it is easily applied to a wide range of criteria.

3. Case study on the eucalyptus-based Soda pulp industry in Thailand

The purpose of this case study is to illustrate the use of the new combination of tools for a realistic case and to analyse the results generated. The production of pulp in Thailand from eucalyptus using the Soda production process and followed by chlorine bleaching was chosen as a case study. Through emissions to air and water, the pulp industry contributes to a variety of environmental problems in Thailand. Although some key information is available on these emissions, more data are needed on the relative importance of the sector's contribution to these environmental impacts. This type of information will then allow for a more efficient reduction in the overall environmental impact of the sector.

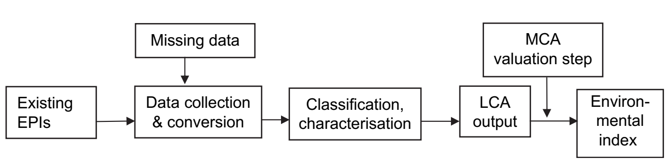

Fig. 1. Schematic overview of the steps to be carried out to implement COMPLIMENT.

Pulp production contributes to environmental impacts stemming from the emission of flue gases, high water consumption, liquid effluents and emissions of greenhouse gases from the consumption of energy [26]. This case study focuses on large-scale pulp production from eucalyptus (*E. camaldulensis*) in Thailand using the Soda production process. Eucalyptus is a fibre of growing interest, not only in Thailand but also in Asia in general. The Soda process is a pulping process characterised by the use of a sulphur-free sodium hydroxide solution, an alkaline liquor in which the eucalyptus is cooked in order to loosen the fibres. While many new pulp (and paper) plants in Thailand are equipped with Kraft processing lines, plants based on the Soda process still exist. Similar to other Asian countries [27], and despite an on-going discussion on the emissions of dioxins as by-products during pulp and paper making [28], part of the existing mills are still based on conventional bleaching lines, with a high input of chlorine, mostly in the form of elemental chlorine, hypochlorite and chlorine dioxide. In this case study, the system boundaries are set such that plantation, harvesting and transportation of eucalyptus as well as all production processes directly connected to Soda pulping of eucalyptus are considered. In addition, the following on-site processes are included: the wastewater treatment unit, the chemical recovery unit, the incinerator and the on-site electricity production. This cradle-to-gate approach is chosen because of the different products and functions that the pulp can be turned into, which in turn result in varying environmental profiles. Fig. 2 gives an overview of the production steps within the companies (gate-to-gate system) as well as the system boundaries as they are considered in COMPLIMENT (grey background).

3.1. Data collection

In this case study, the new tool, COMPLIMENT is applied for the first time. The starting point is a dataset providing performance indicators on the use of selected resources and emissions, predominantly relative to production output. The given EPIs [29] only provided data on processes taking place within the boundaries of the companies (gate-to-gate). However, for applying the new methodology the scope of the data needed to be extended towards a cradle-to-grave system boundary. To this end, more data were collected on

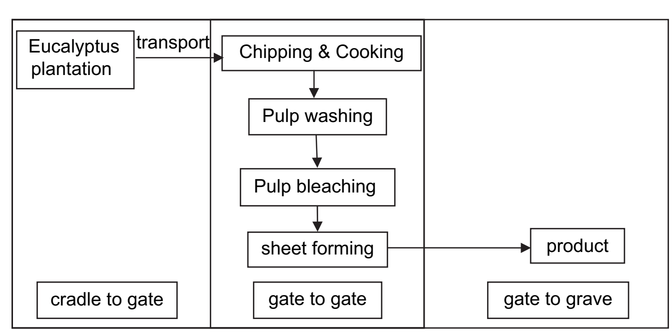

Fig. 2. System boundaries for on-site production processes (gate-to-gate) as well as for COMPLIMENT (marked in grey).

Thai eucalyptus plantations [30] as well as from literature on pulping processes such as [27,31,32] and scaled to represent the production output of the Thai pulp industry. Resource use and emissions were based on the annual production of air-dried pulp from eucalyptus using the Soda process. Aggregated emissions to air and water based on direct emissions and raw materials consumption are given in Table 2.

Table 2 assumes an annual production of 188,000 t air-dried pulp from eucalyptus and a 75% biomass-based energy supply, which is assumed to be CO_2 neutral. CO_2 emissions from biomass are therefore neglected. The system includes emissions from eucalyptus plantation as well as harvesting and transportation steps, but excludes solid waste treatment options, both for the product and solid wastes generated on-site, e.g. lime mud and ash from biomass incineration. Due to a lack of information, no data on emissions of heavy metals and only limited data on the type of chlorine compounds emitted can be included.

3.2. Calculation of potential environmental impacts

This step is taken from the LCA (impact assessment) methodology. In order to calculate the potential impact (PI), total emissions (E_x) of a substance x are multiplied by a classification factor (C_x), which is specific for each potential impact category i. These potential impacts per substance are added for each impact category i. Subsequently, the potential impacts (PI_i) are normalised by a normalisation factor (N_i) that is specific for that category and multiplied by a valuation factor ($V_{i,j}$) and summed up to result in the environmental index (I_j), where j represents different sets of valuation factors.

Table 2
Emissions (E_x) to air and water associated with the annual production of air-dried pulp from eucalyptus in Thailand

Emissions to air	ADP (kg/t)
Carbon dioxide (CO_2)	516.4
Carbon monoxide (CO)	5.9
Methane (CH_4)	1.1
Nitrous oxide (N_2O)	0.3
Sulphur dioxide (SO_2)	5.4
Nitrogen oxides (NO_x)	6.9
Non-methane volatile organic compounds (NMVOC)	1.0
Particulates (PM_{10})	1.6
Ammonia (NH_3)	<0.1
Chloroform ($CHCl_3$)	<0.1
Emissions to water	
Chemical oxygen demand (COD)	7.2
Phosphorus (P)	<0.1
Nitrogen (N)	0.1
Adsorbable organic halides (AOX)	4.7
Nitrate (NO_3^-)	2.0
Phosphate (PO_4^{3-})	1.1
Chloroform ($CHCl_3$)	0.2
Polychlorinated phenols (PCP)	<0.1

Based on [27,29,30,35].

$$\mathrm{PI}_i = \sum_{x=1}^{Y} (E_{x,i} \times C_{x,i}) \quad (1)$$

$$I_j = \sum_{i=1}^{Z} \left(\frac{\mathrm{PI}_i}{N_i} \times V_{i,j} \right) \quad (2)$$

Within the case study, these calculations are carried out for Y substances x (see Table 2 for an overview), Z impact categories i as well as for three valuation perspectives j (global, regional and local). The classification factor ($C_{x,i}$) represents the contribution to an (adverse) environmental effect relative to a standard substance. For example, the global warming potential of methane (CH_4) is 23 relative to that of carbon dioxide (CO_2) [33]. Characterisation factors (see Table 3) are not site-specific but generic and all refer to problem oriented approaches [3].

Potential environmental effects calculated include greenhouse gases contributing to global warming, acidification, eutrophication, ozone precursors and human health impacts. After aggregating the data into potential impacts per category, these potential impacts need to be related to the total potential impacts for the same category within the country, region or the world. This is done through normalisation factors. We use normalisation factors for the world for the year 1995 due to a lack of specific normalisation factors for Thailand. The data are normalised by dividing the calculated potential impact (PI_i) by the respective normalisation factor (N_i), resulting in unit-free numbers (see Table 4).

The results from these calculations show that the normalised potential impact of climate change is highest, whereas that of human health is lowest. These results give a first impression on the contribution of the Thai pulp sector towards these five environmental impacts. However, the importance of the impact categories is an aspect to be considered, especially when talking about which emissions to reduce in order to improve the state of the environment, as different emissions will need to be reduced depending on whether the global, regional or local environment should be improved.

3.3. Aggregation of impacts using a multi-criteria analysis

The analytic hierarchy process (AHP) is a multi-criteria decision-making tool that enables the user to establish weights for selected criteria by means of a series of pair-wise comparisons. To establish weights to aggregate the LCA impact categories into a single index while taking into account that environmental problems have different importance depending on the geographical scale that is looked at. We therefore develop three sets of weights based on local, regional and national perspectives, which take the geographical scale of the environmental impacts into account. This means that for example from a global perspective, greater importance is assigned to an environmental impact such as global warming, which occurs on a global scale, while local impacts such as

Table 3
Characterisation factors from [39] used for calculating potential environmental impacts

Substance unit[a]	Global warming (GWP), CO_2 eq.	Acidification (AP), SO_2 eq.	Eutrophication (EP), PO_4^{3-} eq.	Photochemical oxidant formation (POF), C_2H_4 eq.	Human toxicity (HTP), p-$C_6H_4Cl_2$ eq.
CO_2	1.00	–	–	–	–
CH_4	23.00	–	–	0.01	–
N_2O	296.00	–	–	–	–
$CHCl_3$	30.00	–	–	–	13.00
SO_2	–	1.20	–	0.05	0.10
NO_x	–	0.50	0.13	–	1.20
NH_3	–	1.60	0.35	–	0.10
H_2S	–	1.88	–	–	0.22
COD	–	–	0.02	–	–
N	–	–	0.42	–	–
P	–	–	3.06	–	–
CO	–	–	–	0.03	–
NMVOC	–	–	–	1.00	0.64
Particulate	–	–	–	–	0.82
AOX	–	–	–	–	1.00
PCP	–	–	–	–	7.20

[a] Substances not contributing to a potential environmental impact are marked "–" in the respective column.

human health and ozone precursors dominate in the local perspective.

For the global scale, the order of importance of the impact categories is:

Global Warming > Acidification > Eutrophication > Ozone Precursors > Human Health

For the regional scale the order of importance of the impact categories is:

Acidification, Eutrophication > Ozone Precursors, Human Health > Global Warming

For the local scale the order of importance of the impact categories is:

Human Health > Ozone Precursors > Eutrophication > Acidification > Global Warming

Based on these assumptions, the respective weights ($V_{i,j}$) for each of the five impact categories (PI_i) are calculated according to the AHP procedure [34]. To this end, 5×5 matrices are established with numbers between 1 and 5 expressing the degree of importance of one impact category relative to the other. According to the AHP procedure, cell values are then divided by the column totals, the resulting values summed per row and divided by the total number of impact categories i, resulting in the final weights ($V_{i,j}$) of each impact category i for each perspective j. Table 5 shows the relative degrees of importance as well as the resulting weights per impact category and perspective.

As a next step in applying COMPLIMENT, the weights per impact category ($V_{i,j}$) are multiplied by the normalised potential impacts per category (PI_i/N_i) (see Eq. 2). This is done for all three perspectives j, i.e. global, regional and local, and as a reference also for a perspective where all impacts are assumed to be of equal importance. The resulting weighted impacts per category can then be added up to form an index (I_j) of the normalised total potential environmental impact for each perspective j (see Fig. 3).

Fig. 3 shows that potential impacts on human health are insignificant in all perspectives. However, it should be noted that total emissions contributing to this impact category are underestimated due to the lack of detailed information on AOX emissions from eucalyptus pulp bleaching as well as on heavy metals emissions. Fig. 3 shows that the relative contribution of all potential impact categories except human health varies depending on the perspective. The main contributor to the overall environmental impact of the Thai pulp industry is climate change when considering a global or local perspective and acidification for the regional perspective. These differences in importance across the three perspectives have a significant effect on the preferred reduction options: while greenhouse gas emissions are important for all perspectives, pulp manufacturers in Thailand should also reduce emissions contributing to acidification and ozone precursors when considering a local perspective, from a regional perspective

Table 4
Potential impacts (PI_i), normalisation factors (N_i) [39] and resulting normalised potential impacts (PI_i/N_i) for five impact categories

Impact category[a]	Potential impact (PI_i)	Normalisation factors (N_i)	Normalised potential impact (PI_i/N_i) (no unit)
Global warming (GWP) in kt CO_2 eq.	121	4,100,000	2.95 E-05
Acidification (AP) in kt SO_2 eq.	2	320,000	5.84 E-06
Eutrophication (EP) in kt PO_4^{3-} eq.	<1	130,000	1.59 E-06
Photochemical oxidant formation (POF) in kt C_2H_4 eq.	<1	96,000	2.87 E-06
Human toxicity (HTP) in kt p-$C_6H_4Cl_2$ eq.	4	5,700,000	6.53 E-07

[a] Please refer to Table 3 for the type and number of substances taken into account for the respective impact categories.

Table 5
HP matrices containing the relative degrees of importance and resulting valuation factors ($V_{i,j}$)[a] for five impact categories (i) and three perspectives (j)

Global $j=\mathrm{G}$	GWP	AP	EP	POF	HTP	Resulting weights ($V_{i,\mathrm{G}}$)
GWP	1	2	3	4	5	0.42
AP	1/2	1	2	3	4	0.26
EP	1/3	1/2	1	2	3	0.16
POF	1/4	1/3	1/2	1	2	0.09
HTP	1/5	1/4	1/3	1/2	1	0.06
Total	2.28	4.08	6.83	10.50	15.00	
Regional $j=\mathrm{R}$	GWP	AP	EP	POF	HTP	Resulting weights ($V_{i,\mathrm{R}}$)
GWP	1	1/5	1/5	1/3	1/3	0.06
AP	5	1	1	3	3	0.34
EP	5	1	1	3	3	0.34
POF	3	1/3	1/3	1	1	0.13
HTP	3	1/3	1/3	1	1	0.13
Total	17.00	2.87	2.87	8.30	8.30	
Local $j=\mathrm{L}$	GWP	AP	EP	POF	HTP	Resulting weights ($V_{i,\mathrm{L}}$)
GWP	1	1/2	1/3	1/4	1/5	0.06
AP	2	1	1/2	1/3	1/4	0.10
EP	3	2	1	1/2	1/3	0.16
POF	4	3	2	1	1/2	0.26
HTP	5	4	3	2	1	0.42
Total	15.00	10.50	6.83	4.08	2.28	

[a] $V_{i,j} = \sum_{i=1}^{i}(\text{cell value}/(\text{column total} \times i))$.

they should reduce emissions leading to acidification and eutrophication, and from a global perspective they should only focus on reducing greenhouse gas emissions. The results are therefore considered robust, because greenhouse gas emissions should be mitigated first. Only when looking at the impacts with second-most importance do the results vary, depending on the chosen perspective.

4. Sensitivity analysis

We first calculated emissions based on 75% biomass-based energy, but a range of 50–95% was given in the original data source [35]. To investigate sensitivity to the share of biomass in the overall energy supply, additional calculations were done with 50% and 95% of the energy provided by biomass instead

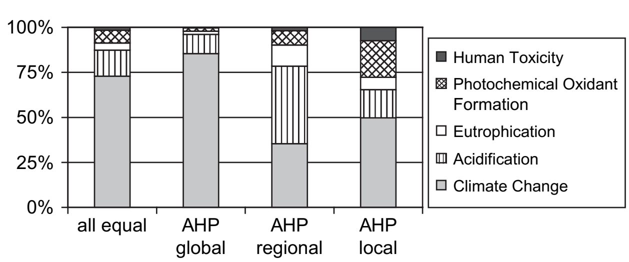

Fig. 3. Relative contribution of the impact categories to the total environmental impact, calculated for a global, regional and a local perspective as well as a reference perspective in which all impact categories are viewed as equally important.

of non-renewable energy sources. The results are given relative to the environmental index of the original data set, i.e. with a 75% biomass-based energy supply in Fig. 4.

This sensitivity analysis shows that within the same perspective, the overall environmental index decreases with increased bio-based energy supply. However, global warming remains the most important contributing factor to the overall environmental index, for 11 of the 12 indices. This means that with the exception of a 95% bio-energy supply and a local valuation perspective, global warming remains the most important factor affecting the overall environmental index, almost totally independent of the perspective and the share of bio-based energy supply. The contribution of acidification can also be seen to decrease with increasing bio-based energy supply, which is related to the sulphur content of the non-renewable energy source. Acidification also is by far the second-largest contributor to the environmental index in most perspectives. Photochemical oxidant formation becomes of significant importance in the local perspective. Eutrophication and human health do not contribute significantly to the overall environmental indices for any of the perspectives, suggesting that this is a robust result and that reductions in emissions contributing to these two impact categories will not have a considerable effect on the overall environmental impact.

One conclusion from this sensitivity analysis is that increasing the share of bio-based energy supply can reduce the overall environmental impact. Another important conclusion from this sensitivity analysis is that the overall environmental impact will vary considerably for individual companies within the Soda pulping sector, depending on their specific energy supply characteristics. With respect to the effect of the perspectives on the overall environmental index, we conclude that in this case, global warming is the most important contributor to the environmental effect of the Soda pulping sector, irrespective of the valuation perspective. However, if the goal is to reduce the environmental index further, then the next impact categories to be tackled depend on the chosen perspective. For example, from both a global and a regional perspective, acidification would be next in line, whereas from a local perspective it should be photochemical oxidant formation.

5. Discussion and conclusions

From the description of COMPLIMENT as well as from the case study on the Thai pulp industry, several strengths of the new tool become obvious. One of the main strengths is the comprehensive ‘cradle-to-gate’ approach and the prevention of problem shifting for the procedure as well as the calculation of environmental impacts are strengths stemming from the LCA approach that are upheld in COMPLIMENT. In addition to that, the step-wise data collection of the new combination, starting with data from EPIs, expanding the scope towards LCA and aggregating the output into a single index as described in this paper. This step-wise approach can be adapted to an organisation’s activities, goals and needs and the resulting index can be used as an indication of the improvement or deterioration of the organisation’s

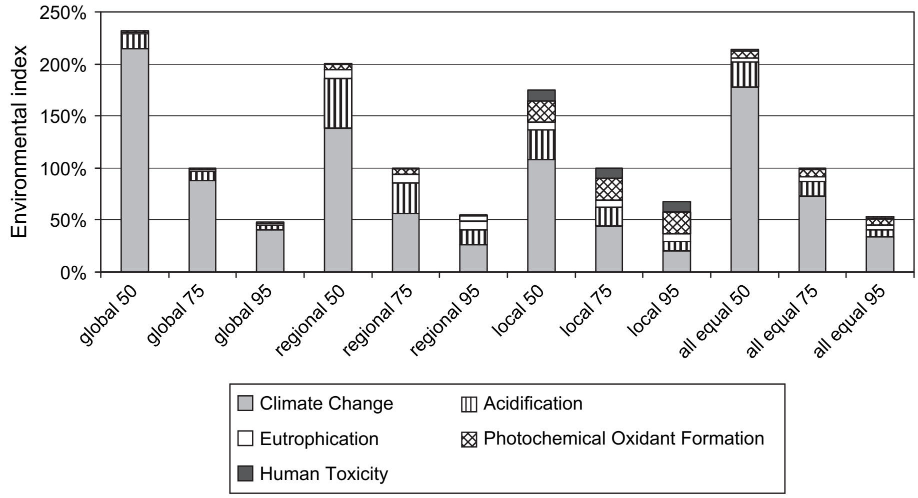

Fig. 4. Relative contribution of the impact categories to the overall environmental index I for the Thai pulp sector. Results are shown for a 50%, 75% and 95% energy supply from biomass and valuation factors based on a global (global), regional (regional) and a local (local) perspective, as well as for a reference perspective in which all impact categories are viewed as equally important (all equal).

environmental performance over time. Integrating these three tools still allows for benchmarking among firms, one of the important uses of EPIs that is upheld in COMPLIMENT, if the system boundaries are made explicit.

From a methodological point of view, a weakness of this new combination of tools may be the fact that the LCA is not carried out fully. However, a full LCA may not be needed for companies that are primarily interested in the part of the system they control, i.e. the on-site processes as well as the preceding production chain on which they have influence through their choice of suppliers. Using an MCA valuation method for weighting and aggregation (see Section 2.2) implies that value-laden choices are made, influencing the results and reducing transparency through the loss of information when aggregating data. On the other hand, the three perspectives for which environmental indices were calculated differ considerably in the values assigned to individual impact categories but results are robust with respect to the main contributor to these indices, i.e. global warming. Also, the goal was to develop a tool for use in industry, where aggregation of data will assist comparisons between current and past environmental performance and benchmarking among companies.

The results from the case study not only show that COMPLIMENT is workable, but also that it brings together strengths of the individual tools, such as the availability of established methodologies and improved data availability by starting with EPIs. In addition, the emissions inventory is more complete and comprehensive through the expansion of the scope towards a life cycle approach, and including the plantation, harvesting and transportation steps also offers an opportunity to manufacturers to improve the environment through influencing the supply chain. The analysis of the Thai pulp production shows that the influence on the final results of the perspectives used for the valuation step is significant. By making these differences explicit through elaborating three perspectives on the importance of environmental impacts, COMPLIMENT supports decision-makers and stakeholders in selecting the most important environmental impact category as well as the emitted substance in which a reduction works the most efficient for reducing the overall environmental impact of the company or sector.

The significance of this study lies in the fact that it includes the first description and application of a combination of LCA, MCA and EPIs. So far, these tools have been used in isolation. However, when assessing the environmental performance of an industrial enterprise or a sector, none of the tools alone is satisfying for reasons discussed earlier in this paper. Our analysis and case study show that combining the best parts of the three tools allows for an assessment that (1) is complete in that it includes parts of the production chain that are outside the boundaries of the industrial system itself, (2) results in one indicator, making the results easy to interpret for policy purposes, and (3) uses readily available information. This combination of characteristics makes COMPLIMENT useful and applicable for a wide range of industries.

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