Eco-efficiency Analysis by BASF: The Method

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Abstract

Intention, Goal, Scope, Background. BASF has developed the tool of eco-efficiency analysis to address not only strategic issues, but also issues posed by the marketplace, politics and research. Predictable analysis times and costs are essential factors for the efficient use and efficacy of this method. It is based on assessing environmental behavior, environmental impact, possible impacts on human health and ecosystems, and on the costs of products and processes from the cradle to the grave.

The term eco-efficiency was evidently given currency by Stephan Schmidheiny and coworkers [1]. Eco-efficiency was then defined as a management philosophy by the World Business Council for Sustainable Development (WBCSD) in 1993 following the 1992 Rio summit. Business was to be encouraged to become more competitive and innovative, while at the same time exercising greater responsibility for the environment [2].

Eco-efficiency has been variously defined and analytically implemented by several workers. In most cases, eco-efficiency is taken to mean the ecological optimization of overall systems while not disregarding economic factors [3].

Eco-efficiency expresses the ratio of economic creation to ecological destruction [4]. However, the improvement of purely ecological factors, for example better utilization of resources through more efficient processes, is also frequently referred to as increased eco-efficiency [5].

This paper discusses the methodology of eco-efficiency analysis by BASF and illustrates the specific procedure using the eco-efficiency analysis of Indigo as an example [6].

1 Goal Setting

The goal of eco-efficiency analysis by BASF is to quantify the sustainability of products and processes. The choice of a pragmatic and flexible approach is intended to ensure short project times and low project costs. At the same time, there has to be a sound scientific background to ensure suitable intelligibility of the results obtained. A modular design is intended to help keep arithmetic operations transparent. As a result, ecological and economic impacts are very simple to assign to causes. This facilitates talks with customers and data suppliers to validate the overall system and improves the testing for plausibility. Finally, the results should be made available in a form where they are easily clearly communicable and provide a scope for scenario assessments and discussions.
The eco-efficiency analysis approach is now well established within BASF. Following the frequent use of this method in internal studies, there is evidence that external partners also have a need for the use of eco-efficiency analysis. In future, therefore, studies will also be communicated beyond the works fence, in BASF’s external sphere. This will add a further building block to the Responsible Care concept to which BASF is committed.

This paper is designed to improve the understanding of the eco-efficiency analysis procedure.

2 Conducting an Eco-Efficiency Analysis

Every eco-efficiency analysis passes through several stages as a matter of routine. This ensures consistent quality and the comparability of different studies. Environmental impact is determined by the method of life cycle analysis and economic data are calculated using the usual business or, in some instances, national economical models.

The basic preconditions in eco-efficiency analysis are:
• The concrete (final) customer benefit is at the heart of the analysis
• All products or processes studied have to meet the same customer benefit
• The entire life cycle is considered
• Both an ecological and an economic assessment are carried out
• Impact on health and the danger to people is assessed

Then the eco-efficiency analysis is focused on the following aspects:
• Calculation of total cost from (final) customer viewpoint
• Preparation of a specific life cycle analysis for all investigated products or processes according to the rules of ISO 14040 ff.
• Determination of impacts on the health of people
• Determination of dangers for the environment
• Determination of risk potentials
• Weighting of life cycle analysis
• Determination of relation between ecology and economy.

To this end, the impact scores developed in the life cycle analysis are aggregated by means of an overall weighting

• Analyses of weaknesses
• Assessment of scenarios
• Sensitivity analyses
• Business options
• Optionally: inclusion of social aspects (e.g. workplace conditions)

2.1 Customer benefit

The specific customer benefit always lies at the center of eco-efficiency analysis. In the majority of cases, a customer having particular needs and requirements is able to choose between a number of alternative products and processes. In the context of this choice, eco-efficiency analysis compares the economic and environmental pros and cons of each solution over the entire life cycle or within the compartments in which the systems differ in life cycle.

Eco-efficient solutions are those that provide this specific customer benefit more impactively than others from the standpoint of both financial cost and the environment. The environmental impact axis in eco-efficiency analysis encompasses, in principle, all calculated and evaluated criteria that are not allocated to the economic calculation of total costs.

The term customer benefit is identical to the functional unit of ISO 14040. Goal definition and scoping are described in eco-efficiency analysis in agreement with ISO 14040.

2.2 Life cycle

Large eco-efficiency quantum leaps for chemical products are frequently obtained in the further processing step or at the final customer. It is therefore very important to consider the entire life cycle so as not to make a decision for or against a product or process on the basis of incomplete information. Correct and complete description of a life cycle requires collaboration between customers and customers of customers, and leads to know-how bundling for the individual life cycle sections given a defined customer benefit.

Eco-efficiency assessment, as described, focuses in principle on the entire life cycle, but then concentrates specifically on specific events in a life cycle where the alternatives under consideration differ. Steps prior to or subsequent to DyStar’s [7] own production are given equal ranking with the company-internal processes in order that the environmental aspects of product systems may be systematically captured from the point of removal of the raw materials from the earth up to disposal (Fig. 1).

To be able to picture the life cycle, it is necessary to prepare environmental profiles of individual products and life cycle sections. Eco-efficiency analysis includes the cost data as well as the straight life cycle data. Fig. 2 shows that life cycle assessment is based on the environmental profile, which can be obtained for example from data provided by the plants and which includes the path from the cradle to the workgate. On extending this approach to the entire life cycle, a life cycle assessment is obtained. Adding to these additional assessment criteria again, followed by an economic assessment, then leads to an eco-efficiency analysis by BASF.

Fig. 1: Life cycle assessment
3 Procedure Illustrated with Specific Example

3.1 Definition of customer benefit, definition of alternatives

There now follows a detailed description of an eco-efficiency analysis by BASF. The example chosen is the eco-efficiency analysis of Indigo. Indigo is the dye that is used exclusively for dyeing Blue Denim. After dyeing, Blue Denim is further processed into Jeans pants. BASF was the first and, until October 2000, the largest producer of synthetic Indigo worldwide. Since October 2000, BASF Indigo is marketed by DyStar Textilfarben GmbH & Co. KG.

The first step of eco-efficiency analysis is to define not only the customer benefit (functional unit), but also the possible alternatives. As many as possible of the alternatives represented in the marketplace should be included, bearing in mind that small market shares may also be disregarded, depending on the problem posed. The customer benefit was defined as follows in the Indigo analysis: dyeing of Blue Denim for manufacturing 1000 pairs of jeans. The defined customer benefit thus also included life cycle sections that are not assigned to DyStar. Their facts and figures come from experts at DyStar [8], BASF and other companies, and also to some extent from the literature.

The alternatives considered first of all include different ways to produce Indigo. The different alternatives are shown in Fig. 3.

The use of Indigo powder requires the use of a relatively large amount of hydrosulfite to convert the water-insoluble dye into the water-soluble, dyeing leuco form. When Indigo solutions are used, the reduction to the leuco form takes place at DyStar by means of hydrogen, i.e. hydrosulfite-free.

During the process of dyeing with Indigo, some of the colorless leuco form of the Indigo is oxidized by oxygen in the air, converting it into the blue, water-insoluble form. Hydrosulfite then has to be added to complete the dyeing process even in the case of Indigo solution. In the case of the electrochemical alternative, the reduction equivalents needed are supplied by electric current and consequently the process is completely hydrosulfite-free (Fig. 3).

For completeness and to determine the most relevant subsidiary steps in the total life cycle, the eco-efficiency analysis of Indigo first considered the overall process. But as a result a multiplicity of identical modules were calculated as well. Following the eco-efficiency guidelines, the overall system can remain restricted to the truly differentiating modules, as described above. For this reason, the following figures frequently depart from the identical overall system and concentrate only on the different dye manufactures and the different dyeing steps of the various alternatives.

4 Calculation of Eco-Efficiency

4.1 Determination of environmental impacts

Environmental impacts are determined on the basis of five main aspects: the consumption of raw materials, the consumption of energy, resulting emissions, the toxicity potential, and the abuse and risk potential. Weaknesses and potentials driving environmental impacts can easily be identified and described in this way. Data acquisition and calculation is done to ISO 14040. Results are depicted in individual graphs of the respective category and initially do not contain any impact categories or weightings.

4.2 Energy consumption

Energy consumption is determined over the entire life cycle and describes the consumption of primary energy. Fossil energy media are included before production and renewable energy media before harvest or use. This captures conversion losses from electricity and steam generation. In the case of the DyStar processes, DyStar-specific data are used. In the case of non-DyStar processes, UCTE data [10] are used. But the calculation of specific scenarios for electricity and steam generation, for example in the case of site comparisons, is possible. Energy consumptions are allocated to the individual energy media. The consumption of the individual primary energy media is included accordingly for raw material consumption.

Under the category of energy consumption, no further conversion is done into specific impact categories. The calculated energy consumptions of all alternatives are normalized with respect to one another, the least favorable alternative being given the value 1 and the other alternatives lining up on an axis from 0 to 1 in relative terms to...
form a ranking. This method will also be used later to compare all other categories of the environmental impact axis with one another.

To calculate total energy requirements, the upper heating value of the primary energy equivalents is used. The energy media considered are coal, oil, gas, lignite, nuclear energy, waterpower, biomasses and others.

The following explanations and graphs demonstrate the comparison of corresponding dyeing processes. The similarly calculated, total life cycle for jeans manufacture is excluded for reasons of clarity. Fig. 4 shows the energy consumption for dyeing 1000 pairs of jeans, calculated over the life cycle. Supply energies are included. The energy needed by the dye production process is compared with the energy requirements of the dyeing process. It is found that the processes have relatively similar energy requirements, while the dyes show distinct differences in some instances. The best performers here are the Indigo solution and the electrochemical dyeing process.

4.3 Emissions

Emission values are initially calculated separately as air, water and soil emissions (waste). The calculation includes not only values, for example, from electricity and steam production and transport, but also values directly from the processes. The individual values are subsequently aggregated via a weighting scheme to form the overall value for the emissions. The weighting will be discussed in more detail in section 6.

4.3.1 Emissions to air

Table 1 lists the categories of emissions to air evaluated in the eco-efficiency analysis. After the inventories have been prepared, the impact categories are calculated. The categories of GWP, POCP, ODP and AP (see Table 1) are calculated using the factors listed in Table 2. The conversion of the emissions into their impact potentials and results of that are listed in Fig. 5.

### Table 1: Impact categories for emissions to air

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Designation in full</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>ODP</td>
<td>Ozone Depletion Potential</td>
</tr>
<tr>
<td>POCP</td>
<td>Photochemical Ozone Creation Potential</td>
</tr>
<tr>
<td>AP</td>
<td>Acidification Potential</td>
</tr>
</tbody>
</table>

### Table 2: Arithmetic values for impact potentials in the case of emissions to air

<table>
<thead>
<tr>
<th></th>
<th>GWP</th>
<th>ODP</th>
<th>POCP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO₂</td>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td></td>
<td></td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>11</td>
<td></td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>HCᵣ</td>
<td></td>
<td></td>
<td>0.416</td>
<td></td>
</tr>
<tr>
<td>Halogen HCᵣ</td>
<td>4500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₃</td>
<td></td>
<td></td>
<td>1.88</td>
<td></td>
</tr>
<tr>
<td>N₂O</td>
<td>270</td>
<td></td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>HCl</td>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>HF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
This subdivision means, for example, that an emission of 1 kg of methane is assessed at 11 kg of CO₂ units with regard to GWP. If more detailed information is available for the collective parameters for HC and halogen HC (identified by *), the detailed impact potentials of the corresponding substances are used.

4.3.2 Emissions to water
For emissions to water, there is at present no comparable standardized, scientifically documented method for calculating the impact potentials available as for the emissions to air. For the inventory of emissions to water (COD (chemical oxygen demand), BOD (biological oxygen demand), N-tot (total nitrogen), NH₄⁺ (ammonium), PO₄³⁻ (phosphate), AOX (adsorbable organic halogen), heavy metals (HMs), hydrocarbons (HCs), SO₄²⁻ (sulfate), Cl⁻ (chloride)), we therefore use the method of critical volumes or critical limits for discharges into surface waters [12]. Each pollutant emitted into water contaminates sufficient water until the statutory limit for this substance is reached (critical load). The limits used for the respective emission to water are the limits listed in the schedule of the wastewater regulations [13] (Table 3).

The greater the water hazard posed by a substance, the lower its limit. The amount of uncontaminated water needed to arithmetically dilute the respective calculated water emis-
sions to the limit is then calculated. The arithmetic values obtained are included in the total as reciprocals. This ensures that wastewaters with relatively problematical emissions receive higher critical volumes than less polluted ones (Table 3). The lower the limit for an emission, the higher the factor used to express the impact. The critical volumes can subsequently be summed to arrive at a total emission to water and normalized. This makes it possible to aggregate a multiplicity of qualitatively different emissions to water in a single value (Fig. 6).

The limits from the wastewater regulations are generally based on the relevance of the emitted substance for the environment. In some cases, technical aspects were considered as well. The use of these data has advantages because

- there is a complete database available for most emissions
- the limits are generally recognized and used
- the limits are known and up to date

### 4.3.3 Solid wastes

The results of the inventory on solid wastes are combined to form three waste categories: special wastes, wastes resembling domestic refuse and building rubble/gangue material. Absent other criteria, impact potentials for solid wastes are formed on the basis of the average costs for the disposal of the wastes (Table 4).

| Table 3: Arithmetic values for impact potentials in the case of emissions to water |
|---------------------------------|-----------------|-----------------|
| COD 75 mg/l | 0.013 | BOD 15 mg/l | 0.067 | N-tot 18 mg/l | 0.056 | NH₄⁺ 10 mg/l | 0.1 | P-tot 1 mg/l | 1 | AOX 1 mg/l | 1 | HMs 1 mg/l | 1 | HC 2 mg/l | 0.5 | SO₄²⁻ 1000 mg/l | 0.001 | Cl⁻ 1000 mg/l | 0.001 |

With the aid of these factors, the masses in the various waste categories can be weighted and aggregated (see Fig. 7).
4.4 Material consumption

Under material consumption, the mass of raw materials needed by the corresponding process is determined first. The individual materials are weighted according to their reserves according to the statistical calculations of the USGS [14] and other sources [15]. They predict for how long a particular raw material will still be producible with today’s economical methods assuming consumption stays the same (Table 5).

Evaluating the individual materials in terms of their years of reserves produces factors for weighting the individual mass streams. The consumption of 1 kg of lime is thus given a five times higher rating than, for example, the consumption of 1 kg of sand.

Renewable raw materials are valued on the basis of sustainable management of the arable land. Therefore, within the time window of 50 years under consideration, the resource removed grows back. This means infinite reserves and consequently a resource factor of 0. Of course, where renewable raw materials are not sustainably managed (e.g. rainforest logging), the appropriate resource factor is applied.

High energy consumption can be correlated with low consumption of materials when renewable raw materials, such as wood or waterpower, are used. Therefore, however, there is no putative double counting of raw material and energy consumption with these two categories.

But the use of nonrenewable raw materials in supplying renewable raw materials is included in the overall calculation. These consumptions can be allocated, for example, to fertilizer or crop protection agent production or plant processing. This also explains the relatively high value of resource consumption in the case of the alternatives that essentially utilize renewable raw materials. This applies in particular to the alternative of Indigo production from plants (Fig. 8).

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**Table 5:** Calculated reserve factors for selected raw materials

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Years of reserves (a)</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>Bauxite</td>
<td>200</td>
<td>5</td>
</tr>
<tr>
<td>Coal</td>
<td>160</td>
<td>6.3</td>
</tr>
<tr>
<td>Copper</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Dolomite</td>
<td>500</td>
<td>2</td>
</tr>
<tr>
<td>Gas</td>
<td>63</td>
<td>16</td>
</tr>
<tr>
<td>Gypsum</td>
<td>300</td>
<td>3.3</td>
</tr>
<tr>
<td>Iron</td>
<td>72</td>
<td>14</td>
</tr>
<tr>
<td>Limestone</td>
<td>500</td>
<td>2</td>
</tr>
<tr>
<td>Lignite</td>
<td>390</td>
<td>2.6</td>
</tr>
<tr>
<td>Manganese</td>
<td>92</td>
<td>11</td>
</tr>
<tr>
<td>Nickel</td>
<td>35</td>
<td>29</td>
</tr>
<tr>
<td>Oil</td>
<td>42</td>
<td>24</td>
</tr>
<tr>
<td>Phosphate</td>
<td>85</td>
<td>12</td>
</tr>
<tr>
<td>Rock salt</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>Rockstone</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>Sand</td>
<td>500</td>
<td>2</td>
</tr>
<tr>
<td>Sulfur</td>
<td>30</td>
<td>33</td>
</tr>
<tr>
<td>Zinc</td>
<td>25</td>
<td>40</td>
</tr>
</tbody>
</table>
4.5 Toxicity potential

Many life cycle analyses do not conduct an assessment of this toxicity potential. But, to arrive at a comprehensive assessment of products and processes, it is specifically this criterion which constitutes an important factor with regard to the evaluation of sustainability.

The toxicity potential is calculated using the classifications for hazardous materials under EU law. The relevant data are readily and quickly retrievable, and the classification method is recognized and widely used.

Exposure data are frequently missing, inaccurate or incomplete. For this reason, we deliberately calculate the maximum possible hazard instead of an actually existing risk. But, since all cases here are compared on the basis of potential hazards, the basis on which they are compared is again fair. An actually increased health risk is possible only after exposure, usually as a consequence of improper handling.

In the individual cases it is possible to use and compare risk assessment data and so make a bridge to risk valuation. However, care must be taken at all times to ensure that the alternatives are compared on a level playing field with regard to the basis for the calculation.

To determine toxicity potential, eco-efficiency analysis utilizes the classification and labeling guidelines of the German Chemicals Act. Our own toxicological assessments are carried out by appropriate experts (toxicologists of BASF), only when there are data, but no legal classification for the substances in question. The hazard symbols are assigned arithmetic factors based on a logarithmic scaling. The logarithmic scaling used is in line, for example, with that defined for classification-relevant values such as LD$_{50}$ values [16]. The scheme below shows the relationship between hazard symbols and the corresponding arithmetic values (Table 6).

Table 6: Assessment parameters for calculating toxicity potential

<table>
<thead>
<tr>
<th>Hazard symbol</th>
<th>Limit concentrations</th>
<th>Arithmetic value for eco-efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>T+, very toxic</td>
<td>LD$_{50}$ ≤ 25 mg/kg</td>
<td>1000</td>
</tr>
<tr>
<td>T, toxic</td>
<td>25 mg &lt; LD$_{50}$ ≤ 200 mg/kg</td>
<td>100</td>
</tr>
<tr>
<td>Xn, harmful</td>
<td>200 mg &lt; LD$_{50}$ ≤ 2000 mg/kg</td>
<td>10</td>
</tr>
<tr>
<td>C, corrosive</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Xi, irritant</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

To calculate the toxicity potential, then, similarly to the fundamental approach of eco-efficiency analysis, each product to be calculated is balanced from the cradle to the grave. All upstream products, assistants and additives are calculated similarly. An example of how such values can be calculated in principle is found in Fig. 9. It shows how upstream chains can be balanced and combined into a new module until the entire life cycle of a product has been calculated.

The process steps of production, use and disposal are captured separately and also weighted with different factors. Product steps such as application, for example, where human beings can come into direct contact with substances, are weighted more severely than process steps where human beings will come into contact with the substances only in exceptional circumstances. Following appropriate expert estimations, the particular weighting is fixed and verified in scenario analyses.

At present, we are working on a more far-reaching concept to achieve even better differentiation of the components. In future, then, the assessment base is formed directly from the R-phrases, which can then be linked to assessment numbers.

A comparable approach will then also apply to the calculation of the eco-toxicity potential.
Life Cycle Management

Eco-efficiency Analysis by BASF

Fig. 10 shows the implementation of these model calculations using the Indigo study as an example. The relatively better performance of alternatives that are produced on the basis of renewable raw materials is plain to see.

4.6 Abuse and risk potential

The abuse and risk potential reflects the dangers of accidents in the manufacture, use and recycling of the product. The approach adopted is similar to a risk assessment in the case of plant safety in that the probability of occurrence and the level of damage are estimated. The values used for the individual products are not absolute, but only comparative. The assessment quantities used are the statistical data from the employers’ accident insurance associations on workplace accidents [17], transportation accidents, abuse risks, plant safety, fire behavior, etc. Further criteria such as land use, noise, quality defects, etc. can be introduced and adapted to the particular objective.

The risk is assessed using comparative evaluations. The figures used are not absolute, but only numerical ratios which represent the relative risk of the individual alternatives in the respective risk category. Fig. 11 shows the relative risks of the respective alternatives.

5 Total Cost Calculation

The eco-efficiency analysis draws up the balance sheet for the ecological impacts all-inclusively over the entire life cycle. Similarly, total costs are likewise totaled over the life cycle. The costs in question are the real costs that occur and the

Fig. 9: Sample calculation to illustrate assessment approach for toxicity potential

Fig. 10: Assessment of toxicity potential in the Indigo study (dyeing process only) for the raw material production. (The process in itself influences the result too. This result is summarized in the ecological fingerprint)
subsequent costs, which will occur in future. Eco-efficiency analysis by BASF does not utilize the avoidance costs or other costing approaches in order that ecological and economic impacts may be separately computed and assessed. Real costs having an ecological aspect, for example water treatment plant costs, are likewise included in the overall calculation. The costs incurred are summed and combined in DM or EURO amounts without additional weighting of individual financial amounts. This helps to identify and, in certain circumstances, to optimize particularly cost-intensive areas.

The use of different costing models is likewise possible. This is particularly important, for example, when capital investments are to be protected into the future or country-specific depreciation models are to be reflected. Fig. 12 shows the costs of jeans dyeing based on the index of 100 for Indigo granule dyeing.
Table 7: Normalization using energy consumption as an example

<table>
<thead>
<tr>
<th></th>
<th>BASF Indigo granules (synthetic)</th>
<th>Indigo powder from plants</th>
<th>Biotechnologically produced Indigo</th>
<th>BASF Indigo, vat solution 40%, dyed traditionally</th>
<th>BASF Indigo, vat solution 40%, dyed electro-chemically</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption [MJ/1000 joules]</td>
<td>12219</td>
<td>18998</td>
<td>11706</td>
<td>14720</td>
<td>11639</td>
</tr>
<tr>
<td>Normalization [max=1]</td>
<td>0.64</td>
<td>1.00</td>
<td>0.62</td>
<td>0.77</td>
<td>0.61</td>
</tr>
</tbody>
</table>

6 Aggregation of Impact Categories, Representation of Result

6.1 Normalization

The representation of a multiplicity of individual results from the actual life cycle assessment is frequently opaque, difficult to interpret and thus not very meaningful. In this connection, BASF has developed a method whereby the ecological parameters are combined and ultimately plotted as a single point in a coordinate system. An absolute system of the kind employed by distance to target approaches, for example, was dispensed with. So the eco-efficiency analyses provide only comparative information and not absolute values.

The first step in compressing ecological data is normalization. The least favorable alternative is awarded a value of 1 and all other alternatives are set in relation to that (Table 7).

The next step is to combine the normalized values via a weighting scheme to form a total value for the emissions. This weighting scheme is made up of a scheme of societal weighting factors and a scheme of scientific weighting factors.

6.2 Weighting factors

6.2.1 Relevance factors (Fig. 13, Table 8, 9)

Relevance factors indicate how important the individual environmental compartment is for a particular eco-efficiency analysis. The purpose is to define the ‘scientific weighting factors’. The greater, for example, the contribution of an emission to the total emission of the field investigated, the higher the scientific weighting factor. This stops very small emissions that are immaterial to the total emission situation in Germany, for example, from being overvalued and other, larger and decisive emissions from being undervalued.

The relevance factors automatically determine the main influences during the calculation. The larger these factors, the greater the importance of this environmental compartment for the product or process under consideration. This information can also be used for critically querying the base values and models used and for determining the main influences of the system. As a result, the system will picture the circumstances in different analyses correctly in each case.

When comparing different water treatment plant designs, for example, emissions to water are given distinctly higher weighting than energy consumption. Optimization of the treatment performance is therefore to be preferred to energy optimization. If, however, different coating concepts with and without solvent are compared, for example, the POCP or the toxicity potential can be the dominant factor and have a corresponding influence on the overall result.

Relevance factors are calculated from the calculated data of the respective analysis and the published values [18] for total emissions in the balance space studied, and must therefore be considered objective factors (Eq. 1).

\[
\text{Average environmental impact of an option} = \text{Relevance}_{\text{environmental category}}
\]

\[
\text{Total environmental impact in Germany} = \text{Relevance}_{\text{environmental category}}
\]

Table 8: Calculation of the relevance factors. As an example, the energy consumptions of the alternatives are used

<table>
<thead>
<tr>
<th></th>
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<td>18998</td>
<td>11706</td>
<td>14720</td>
<td>11639</td>
</tr>
<tr>
<td>Factor for Germany [PJ]</td>
<td>14200</td>
<td>14200</td>
<td>14200</td>
<td>14200</td>
<td>14200</td>
</tr>
<tr>
<td>Relevance [%]</td>
<td>12219/14200 = 86</td>
<td>18998/14200 = 134 (Maximum)</td>
<td>11706/14200 = 82</td>
<td>14720/14200 = 104</td>
<td>11639/14200 = 82</td>
</tr>
</tbody>
</table>

Table 9: Determination of the relevance factors for each category

<table>
<thead>
<tr>
<th></th>
<th>Energy consumption</th>
<th>Emissions</th>
<th>Raw materials consumption</th>
<th>Toxicity potential</th>
<th>Risk potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Relevance factor [%]</td>
<td>134</td>
<td>178</td>
<td>147</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative relevance weighting factor [%]</td>
<td>29</td>
<td>39</td>
<td>32</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* Relevance factors are under development
6.2.2 Societal weighting factors

For these weighting factors, societal views of the individual ecological impact categories were determined jointly by management consultants Roland Berger and BASF through surveys, public opinion polling, expert interviews, etc., and recorded in a weighting scheme. This scheme is constant in the base case for all eco-efficiency analyses carried out (Fig. 14). Later, in the analysis of various scenarios, changes can be made to this scheme to observe the impact on the overall result of an eco-efficiency analysis. This sensitivity analysis can identify and evaluate critical weighting quantities and so estimate the robustness of an eco-efficiency analysis with regard to the weighting factors.

The societal weighting scheme is a BASF view based on surveys and expert opinion and is used for BASF eco-efficiency analyses. Other research groups or firms can develop their own viewpoint in departure from this BASF-specific weighting scheme, and arrive at a differentiated weighting scheme following plausibility considerations. Eco-efficiency analysis by BASF could also test these different weighting schemes in the form of sensitivity studies and subsequently deduce to what extent a changed weighting scheme has an influence on the overall result. In the case of inter-unit projects, moreover, the start of the analysis could be preceded by a consensus being arrived at with regard to which weighting scheme to use. In our experience, based on a large number of analyses, the influence of weighting factors is frequently relatively low within defined limits. If societal values are changing in the future, the scheme could be adjusted by finding a consensus in the society.

6.2.3 Overall weighting factors (Table 10, Fig. 15)

Multiplication of the calculated relevance factors of the eco-efficiency analysis of Fig. 13 and the societal weighting factors of Fig. 14 gives the total weighting factors in Fig. 15. Because the relevance factors can assume different values depending on the results of the individual analyses, the overall weighting factors will also change in accordance with a specific scheme for each analysis.

The scheme in Fig. 15 shows clearly that it is the emissions, especially the emissions to air, which receive high weighting in the Indigo study. It consequently also becomes clear that improvements in the area of these emissions will have a par-
ticularly pronounced impact of improving eco-efficiency. This statement can be endorsed and refined using dominance and scenario analyses in such a way that it is possible to precisely identify those modules which make the largest contribution to the emissions to the air category.

6.2.4 Economic weighting factors and total weighting between ecology and economics

The total costs of a system can be related to the total sales of the manufacturing industry in the field under study. This, as in the case of the calculation of relevance factors for total environmental impact, will give a relevance factor that reflects total costs, the cost relevance factor "Relevance\textsubscript{costs}". This factor reflects to what extent the alternatives studied contribute for example to the gross domestic product of a country. In absolute terms, the value is very small, but can be used for comparative purposes (Eq. 2).

\[
\text{Maximal cost of options} = \frac{\text{Sales of total manufacturing industry in Germany}}{\text{Relevance}_{\text{costs}}}
\]

On comparing the cost relevance factor with the environmental relevance factor, the dominant axis can then be quantified for the eco-efficiency portfolio (see Fig. 18) and the ratio of the two axes to each other defined in graph form. With this system, where, for example, economic factors have a higher relevance than ecological factors, analyses can take a greater account of the total costs axis. This accordingly produces a defined ratio of environment to costs, the E/C ratio (Eq. 3).

\[
\frac{\text{Relevance}_{\text{environment}}}{\text{Relevance}_{\text{costs}}} = \text{E/C ratio}
\]

7 Environmental Fingerprint by BASF

Following normalization, or normalization and weighting with regard to emissions, the corresponding arithmetic values are summarized in a special plot, the environmental fingerprint by BASF. This plot represents a graphic depiction of the relative ecological pros and cons of the alternatives under consideration. The outermost alternative, bearing a value of 1, is the least favorable alternative in the compartment in question, in that the further inward an alternative is located, the better it is.

The axes are mutually independent, so that an alternative that, for example, does well on energy consumption can do less well with regard to emissions.

The environmental fingerprint makes it possible to identify environmental impact drivers and give clues as to the areas in which improvements should be achieved in order that the overall system may be impactively optimized.

Fig. 16 is the environmental fingerprint of the Indigo study. It can be seen that the electrochemical variant is the most advantageous alternative in all categories. With the exception of risk potential, the least favorable variant on all criteria is Indigo powder from plants.
8 Calculation of Eco-Efficiency Portfolio by BASF

The calculation of total costs and the calculation of the environmental fingerprint are independent calculations of the economic and ecological aspects of a total system featuring different alternatives. On the assumption that ecology and economics have the same importance in a sustainability assessment, an economically less advantageous system can compensate for this disadvantage with a better ecological assessment, and vice versa. Alternatives having the same product of economic and ecological assessment are deemed equally eco-efficient. Alternatives with the lowest factor in the defined comparable system are the most eco-efficient ones. The BASF eco-efficiency implements the customer benefit in the calculations and compares different alternatives for this customer benefit. No absolute values are calculated. Costs are calculated against environmental positions and plotted together in a diagram.

To illustrate the concept of eco-efficiency, BASF has developed the eco-efficiency portfolio.

To calculate the input values for this portfolio, a normalizing step is initially carried out in the environmental assessment for each category. The normalized value is then multiplied by the 'overall weighting factor'. This gives the portfolio metric, which the individual criterion contributes to the overall sum total of the environmental assessment. Adding up all individual criteria gives the overall sum total of the environmental assessment of an alternative. The average of the respective ecological total impact is then entered in the portfolio (Table 11).

The total costs based on the average of all alternatives are then plotted on the other portfolio axis.

This gives a balanced overall system, based on the respective averages, in the form of a portfolio plot. As soon as the position of one ball in the portfolio changes, for example because the input data change, the positions of the balls of the other alternatives change as well.

The most favorable alternatives are located top right in the portfolio, the least favorable ones bottom left. The distance of the individual alternatives to the portfolio diagonal is a measure of the respective eco-efficiency (Fig. 17).

The information provided in the base-case portfolio is a snapshot that reflects the input data and the calculated weighting factors. By this portfolio, the observer is enabled to comprehend and interpret the result of a frequently complicated, involved calculation at a glance. The eco-efficiency portfolio for each category. The normalized value is then multiplied by the 'overall weighting factor'. This gives the portfolio metric, which the individual criterion contributes to the overall sum total of the environmental assessment. Adding up all individual criteria gives the overall sum total of the environmental assessment of an alternative. The average of the respective ecological total impact is then entered in the portfolio (Table 11).

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<table>
<thead>
<tr>
<th>Table 11: Calculation of contributions to portfolio calculation using ‘raw materials consumption’ as an example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material consumption [kg/year]</td>
</tr>
<tr>
<td>Normalization [max=1]</td>
</tr>
<tr>
<td>Total weighting factor</td>
</tr>
<tr>
<td>Portfolio metric</td>
</tr>
</tbody>
</table>
Life Cycle Management Eco-efficiency Analysis by BASF

9 Sensitivity Analysis

Apart from its description of the current state, the value of the eco-efficiency analysis tool lies in the recognition of dominant influences and in the illustration of ‘what if ...?’ scenarios.

The stability of the results is verified by means of sensitivity analyses in every project. Not only the assumptions made, but also the system boundaries and the societal weighting factors, are varied and checked within realistic ranges. And it is found in many of the analyses which have been carried out, that even substantial changes to the weighting factors have only a very small impact on the eco-efficiency conclusions. True, the positions in the portfolio change, in some instances even to the extent of the order on the ecological axis changing, but the conclusions with regard to eco-efficiency (environment and costs) change very rarely. In these rare cases, the system is termed nonstable and the products are termed similarly eco-efficient.

From experience, the largest influence on the result by far is possessed by the input data and the system boundaries. But these are in fact also the results, which such an analysis is meant to yield. Questions such as "what is the minimum yield the new process has to have in order for it to be similar in eco-efficiency to the old process?" or "which site can manufacture a product most eco-efficiently?" are typical task statements for an eco-efficiency analysis. By means of one of these factors, the positions in a portfolio are frequently very much more shiftable than is the case with a change in the weighting scheme.

An example of a scenario calculation is given in Fig. 18, where the experience in that the novel electrochemical dyeing process provides a 10% reduction in faulty batches was investigated. It is clear which eco-efficiency advantages come about as a result for this system. For clarity, the Indigo powder from alternative plants was excluded.

As a result of the midpoint centering, as explained above, the change in one ball position will lead to changes in the positions of all alternatives involved.

The following variants and sensitivities can be calculated, modified and visualized for example:

- Determination of target corridors for research
- Breakeven point calculations
- Improvement potentials
- Strengths/weaknesses analysis
- Societal factor variations
- Testing of robustness of results
- Capital expenditures, product costs, process costs
- etc.

10 Results of Eco-Efficiency Analysis to Help Decide Strategic Options for Action and System Optimizations

Eco-efficiency analysis results make it possible to identify weaknesses in products, processes and overall systems over the entire life cycle. This makes it possible to identify factors whose optimization would result in distinct improvements in the overall position of an alternative under consideration. In this connection, it is possible to:

- define research emphases and goals
- name weaknesses and strengths
- prepare and support the development of new processes
- speed up launches
- lower costs
- better envision, prepare and substantiate the short, medium and long-term withdrawal of products in certain applications from the market.

11 Options for Eco-Efficiency Analysis in Communication

Eco-efficiency analysis is able to capture, calculate, evaluate and then transparently depict even very complex matters. The possibilities of graphic representation permit intensive discussion among all the parties involved and by way of
scenario and sensitivity analyses contribute to validating the eco-efficiency analysis. In this context:

- the communication with customers and consumers is made easier
- discussions in scientific, political and social matters are fostered
- the acceptance of defined solutions to problems is increased
- the understanding for thinking in overall contexts is promoted
- the acceptance of responsibility on the part of the chemical industry under the headings of Sustainable Development and Responsible Care is illustrated

12 Possibilities of Eco-Efficiency Analysis in Marketing [19]

As well as the aspects mentioned in the context of communication, the aspects important for marketing are:

- development of marketing strategies with a joined-up focus
- identification of synergistic impacts in the overall process and possible formation of strategic alliances with customers for joined-up optimization
- integration of customers into projects to optimize the entire value chain
- compare system cost calculation with individual cost calculation, uncover hidden costs
- offer customers additional service on positioning and marketing
- communication of industry-wide problems and solutions.

13 Conclusions

The development and use of eco-efficiency analysis by BASF is intended as a quantifiable contribution to comparing the sustainability of various products and systems. The portfolio plot and scenario calculations can be used to identify the main factors influencing the overall system. Ecological impacts and total costs of product and process alternatives being compared are represented in compressed form. This enables decisions to be prepared and supported in a graphic and readily intelligible form.

Eco-efficiency analysis provides only relative comparisons in any case. Absolute values are not obtained. A product that comes out as the best alternative in one eco-efficiency analysis can be the least eco-efficient variant in another application.

Eco-efficiency analysis is not only a tool for in-house decision-makers, but also a means for placing new accents in product marketing. Previously, vague ideas about the costs and various environmental aspects are captured in the form of a fixed picture and so are more amenable to discussion.

14 Outlook

Eco-efficiency analysis can be used in a large number of applications and yields readily understandable conclusions in the case of multifactorial problems in relatively short times and at relatively low cost. Eco-efficiency analysis by BASF has already proved its worth in more than 130 studies involving not only BASF-internal, but also external project partners. In the future, eco-efficiency will become more important in the context of sustainability to show which process is more favorable than other alternatives.

References

[7] Once BASF, since October, 1st , 2000 BASF Indigo is marketed by DyStar
[8] Once BASF, since October, 1st , 2000 BASF Indigo is marketed by DyStar
[9] Once BASF, since October, 1st , 2000 BASF Indigo is marketed by DyStar
[10] Union for the Coordination of Transmission of Electricity
[12] Schriftenreihe Umwelt Nr. 132 (1991); Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern
[13] Regulation on requirements for the discharge of wastewater into surface waters (Abwasserverordnung − AbwV) of March 27 (1997)
[16] LD₅₀ = lethal dose killing 50% of experimental animals
[17] Data i.e. of BG Chemie or other BGs, VDA 2000, etc.
[18] The data may come from the statistical yearbook for Germany, for example
[19] DIN 33927 covers the use of life cycle assessments in marketing, promotion and public relations

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