MARKUS PIEPENBRINK
ANDREAS KICHERER

The vision of a sustainable development, in harmony with the future, is most certainly the major challenge of this century. It is largely accepted that economic, ecological and social objectives are factors of equal importance in this respect. A key criterion for evaluating sustainability is the so-called holistic approach, which takes into account not only the three aspects of sustainable development but also the dimension of time.

For the ecological assessment of products, the life cycle assessment (LCA) – i.e. analysing the product’s environmental impact over its entire life cycle (from cradle to grave) – has become well established. It also takes the time dimension into account. Especially in the packaging segment, discussion should not be restricted to the possibilities existing for its disposal and/or recycling, it is also important to consider the manufacture, transport and, above all, the use of the packaging.

When it comes to the economic and social impact, on the other hand, product analysis still focuses on its manufacture. Frequently discussed social problems include, for example, job creation, job security of the employees, safety at work and social standards, e.g. child labour, especially with regard to the growing importance of international division of labour (globalisation).

Eco-efficiency Analysis According to BASF

As a leading player in the chemical industry, BASF AG has dedicated itself to the guiding principle of sustainability. BASF’s values and principles state, for example, that “economic considerations do not take priority over safety and health issues and environmental protection” [1]. While setting such high targets is a necessary – but certainly not sufficient – condition for sustainable management, the decisive question is how the target and its attainment can be measured in the first place.

What products and processes are “more sustainable” than others? And how can conflicting targets be weighed against each other (e.g. lower emissions against higher energy consumption)? How much is an ecological benefit allowed to cost?

In order to find an answer to these questions and thus be able to examine and compare products and processes with regard to their sustainability, BASF developed, in the mid-nineties, an eco-efficiency analysis tool based on an idea put forward by Schaltegger and Sturm [2]. With over 220 performed analyses, it has

Making Sustainability of Plastics Measurable

Life Cycle Costing. Analysing the production process for plastics in order to assess sustainable processes and products does not go far enough. The experience gained from over 220 eco-efficiency analyses shows that not only the ecological but also the economic effects over the entire life cycle must be examined.
become a standard tool for BASF, and is now also being used by institutes and other companies.

The BASF eco-efficiency analysis, a holistic process for assessing and comparing products and processes, examines two dimensions of sustainability: ecology and economic efficiency. The third dimension – the social impact – is currently at the development stage, and will make the tool a fully-fledged instrument for evaluating sustainability. The key component of a comprehensive evaluation as offered by the eco-efficiency analysis is the definition of a specific customer benefit that is satisfied to an equal extent by all the alternatives. Fig. 1 summarises the basic procedure.

The Example of a Refrigerator: Buy a New One or Continue Using the Old One?

An interesting example of an eco-efficiency analysis for comparing different alternatives is the case of a refrigerator [3]: The customer benefit here involves providing a cooling capacity for the fridge’s contents, in this case, 143 litres. An old refrigerator with a high electricity consumption and a new model (Fig. 2) with a lower consumption are equally capable of doing this. High-grade insulating materials of plastic foam and modern power units have consistently reduced electricity consumption over recent years. Basically the question is whether it is better to continue using a ten-year old refrigerator or to buy a new one. Two new models are included in the analysis, one of energy efficiency category A and one of category B (New A, New B). For the old refrigerator, two alternatives are examined with different consumption data: 260 kWh/a (Old 1) and 330 kWh/a (Old 2).

**Ecological Assessment**

The system limits of an eco-efficiency analysis embrace the individual steps needed to satisfy the customer benefit. It is based on a modular structure. After taking into account all the stages of the life cycle, the necessary data are compiled and plotted in the form of eco-profiles (from cradle to factory gate). It covers steel, insulating materials and coolants as well as transport and disposal by recycling etc. The modular structure permits simple handling of very large data volumes and also provides the necessary transparency.

The environmental impact of the examined alternatives is divided into the six categories of energy consumption, materials consumption, emissions, toxicity potential, risk potential and land use. These main categories are further divided into subcategories. With emissions, for example, these are water emissions, solid waste, greenhouse potential, ozone depletion potential (ozone hole), photochemical ozone-creating potential (summer smog), and acidification potential.

Evaluation of the toxicity potential is based on categorising substances by means of R-phrases. For this purpose, BASF developed its own evaluation model that is able to record and assess toxicological data related to the life cycle [4]. The risk potential takes into account physical risks such as explosion hazards and transport risks, but also considers accidents at work, and can be determined on the basis of ABC analyses, expert assessments and statistics. These two categories are otherwise not usually taken into account in life cycle assessment, although they are very important indeed for a comprehensive sustainability assessment.

In the ecological fingerprint (Fig. 3), ecological advantages and disadvantages are shown in the six main categories for all the examined alternatives relative to each other. The alternative that is furthest out, value 1, is the most unfavourable alternative in the relevant category. The further in it is, the more favourable it is.

The list of the environmental impacts of the alternatives in the various categories provides a comprehensive life cycle assessment in line with ISO 14040 ff.

To combine the environmental effects, BASF has developed a fixed weighting method that works with relevance factors and social factors. With this method, the ecological dimension of sustainability is aggregated to form an environmental impact indicator [5].

**Economic Assessment**

Economic success, in other words ‘making a profit’, is frequently cited as a criterion for the sustainability of products and processes. This means that an economical process for manufacturing an insulating material would mean higher profits for the manufacturer and would thus be sustainable. From the point of view of a company, this is certainly correct, but is naturally only half the story.

The best solution economically from the point of view of the end-user is the alternative with the lowest overall costs. It is therefore immediately obvious that, for example, the profit margin for the plastic is completely unimportant for the end-user. The price paid for a product alone cannot be the decisive criterion as far as sustainability is concerned either. In fact, the follow-up costs connected with the acquisition of the product are equally important and, in individual cases, even more important than the buying price.

The economic comparison in the eco-efficiency analysis is carried as part of a life cycle study: so-called Life Cycle Costing, LCC [6]. Like the life cycle assessment, it includes in the cost calculation all the stages in the life of a product, in other words, production, use and disposal or recycling. To begin with, the economic aspects of alternative products are shown in an overall costing. Key values and cost-cutting potential can be identified in this way (Table 1).

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**Fig. 1. Holistic approach is needed: Basic procedure in the eco-efficiency analysis**

<table>
<thead>
<tr>
<th>Define customer benefit</th>
<th>Determine costs of the individual life cycle stages</th>
<th>Calculate total life cycle costs</th>
<th>Normalise costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify product/process</td>
<td>Calculate ecological inventory data of the individual life cycle stages</td>
<td>Determination of relevance and society factors to aggregate impact categories</td>
<td>Normalisation of environmental impact</td>
</tr>
<tr>
<td>Compile life cycle</td>
<td>Aggregation of ecological inventory data to form impact categories</td>
<td>Aggregation of the impact categories of each life cycle stage</td>
<td></td>
</tr>
</tbody>
</table>

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**Table 1. Cost calculation for the refrigerator example.**

<table>
<thead>
<tr>
<th>Model</th>
<th>Material and operation costs</th>
<th>CE costs</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Old 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New B</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The main cost factors in the refrigerator example are the buying price of the new refrigerator, the residual value and the electricity costs during the service life (Fig. 4). Refrigerator Old 1 with an electricity consumption of 260 kWh/a is, despite the higher electricity costs compared with the new refrigerators, the most economical variant. Refrigerator Old 2 has a considerable cost disadvantage over refrigerator Old 1 due to its much higher power consumption. Because of its high purchase price, refrigerator New A generates the highest costs. The buying price of the new refrigerator cannot compensate even the lowest electricity costs.

Unlike many other assessment procedures, the eco-efficiency analysis only looks at real costs that have to be paid by the customer or manufacturer. Although it includes costs for a company’s environmental protection measures, taxes, and/or the cost of environmentally friendly disposal, it does not include so-called environment damage avoidance costs, with which, in other processes, the (usually hypothetical) avoidance or elimination of environmental impacts is calculated. In other words, there is no internalisation of external costs. The environmental impact is mapped separately on the environmental impact axis.

The Eco-efficiency Portfolio

After the assessment of the ecological and economic effects, the two are added together and compared in a portfolio (Fig. 5). The horizontal axis of the portfolio shows the relative costs, and the vertical axis the relative environmental impact. The greater the distance from the diagonal to the right, the more ecologically efficient the products are. The portfolio shows that the new refrigerator with energy efficiency category A and the old 260 kWh refrigerator are comparably eco-efficient. In terms of eco-efficiency, it would be advisable to replace an old refrigerator having a high electricity consumption (330 kWh/year) with a new one having category A energy efficiency. The continued use of an old refrigerator with a lower energy consumption (260 kWh/year) is comparable eco-efficient. In terms of eco-efficiency, it is considered that the new refrigerator with energy efficiency category A and the old 260 kWh refrigerator are comparably eco-efficient. In terms of eco-efficiency, it would be advisable to replace an old refrigerator having a high electricity consumption (330 kWh/year) with a new one having category A energy efficiency. The continued use of an old refrigerator with a lower energy consumption (260 kWh/year) is comparable eco-efficient. In terms of eco-efficiency, it is important to take into account the taxation policy of the relevant countries, in addition to customs and trading regulations that play an important role in many investment decisions. The evaluation of the by-products that are frequently produced in the chemical industry is another challenge from the point of view of business economics. In such cases, it is important to correctly allocate the overall production costs to the various products that are produced, for example, in a reactor. Generally speaking, an allocation is made on the basis of value, in other words the production costs are allocated to the individual products in accordance with their relev-

Fig. 2. What is better, carry on using the old refrigerator or buy a new more economical one?

Fig. 3. Old vs. new: With the aid of the “fingerprint”, the ecological advantages and disadvantages of the various refrigerator alternatives can be seen

Ecological fingerprint

- Energy consumption
- Area use
- Emissions
- Risk potential
- Toxicity potential
- Raw material consumption

- Refrigerator new A
- Refrigerator new B
- Refrigerator old 1
- Refrigerator old 2

The economic assessment of a process differs fundamentally from the economic assessment of a product. Whereas, for a process comparison, a large amount of data material has to be compiled and processed to determine the raw material and operating costs and the capital costs, these production costs are already contained in the consumer prices. A precondition for comparing processes using the eco-efficiency analysis is that it should look at the manufacture of an identical product, e.g. a specific plastic, which is used in the same application, regardless of its method of manufacture. If different plastics are used or if the plastics have different applications (for example due to different polymer properties), it must be regarded as a product comparison.

Process comparisons consist of a full-cost calculation, which must be also backed by an investment calculation. In this way, it is possible to calculate write-offs, repair costs and costs for scheduled and unscheduled downtimes. For taking decisions on investments, the expected profit on the invested capital – the so-called return on investment (RoI) must be considered. Depending on the deployed capital, the expected return on the manufactured product will differ, and this can, in turn, be decisive for the economic assessment (total costs from the company’s point of view). The costing includes raw material and fuel costs, as well as costs for utilities, personnel, warehousing and inventories. It also includes the environmental protection costs for operating a wastewater treatment plant or safety measures for ensuring the safe operation of the production facilities. Especially when making a comparison between production sites, it is also important to take into account the taxation policy of the relevant countries, in addition to customs and trading regulations that play an important role in many investment decisions. The evaluation of the by-products that are frequently produced in the chemical industry is another challenge from the point of view of business economics. In such cases, it is important to correctly allocate the overall production costs to the various products that are produced, for example, in a reactor. Generally speaking, an allocation is made on the basis of value, in other words the production costs are allocated to the individual products in accordance with their relev-
on fuel consumption and thus on the overall eco-efficiency of a component. It is possible, for example, with a reduction in weight of 1 kg, to save approx. 5–10 EUR in fuel costs during the useful phase of the component.

If, on the other hand, we take non-durables, the costs for the production and disposal are the more important parameters. Eco-efficiency analyses were carried out to assess non-returnable and returnable packagings of plastic and glass. It was found that the protective effect of the packaging on the contents and the performance properties of the pack (possibility of complete emptying, break resistance, weight) are major factors in the assessment. Recycling or disposal costs that have to be borne by the consumer are either included in the price of the product (‘Duales System’) or have to be paid on the product’s disposal (e.g. municipal waste collection) [7]. To carry out an economic assessment, manufacturing prices have to be assimilated, market analyses carried out, or external statistics (trade associations, Federal Statistics Office) brought into play.

The users of the plastics or products should also be considered when carrying out an eco-efficiency analysis, especially with service-intensive products. With heat-insulating materials, for example, these would be the tradesmen who work with them and are in the best position to judge the differing amount of time needed for their installation. The services required during the actual service life of the product also need to be costed. Alongside the direct labour costs, it is also important to include any loss of production through extra maintenance work, scheduled servicing or, quite simply, extra personnel costs in production. In the case of capital goods, a detailed investment calculation is also carried out, taking into account aspects such as capital costs (methods of interest calculation), payment flows (net present value method), residual value costing (cash value method).

The choice of the target group that is most closely linked to the defined customer benefit leads to different ways of looking at the matter. For example, the eco-efficiency of biodiesel can depend on whether we see it through the eyes of the vehicle owner who fills up with fuel or whether we take the overall economic view. The tax exemption for biodiesel has a positive effect on the end-user’s fuel costs, but from the point of view of the government, it brings considerably less income.

The eco-efficiency analysis is thus suitable for all kinds of different matters concerning the evaluation of sustainability. On the other hand, it necessitates a precise appraisal and documentation of the customer benefit and the relevant frame-

### Distinction According to Product Groups

One particularly interesting aspect is the comparison of the alternatives in the useful phase and in the disposal phase. If we look at the useful phase, we can make a rough division into four different product groups: Durable consumer goods (refrigerator, flat screen), non-durable consumer goods (mineral water, yoghurt beaker, biodiesel), service-intensive products (composite heat-insulation systems, printing systems) and capital goods (heating systems). The influence of individual cost categories is very much dependent on the product group under examination: With durable consumer goods, the service life is of major importance. Thus, for example, carpets made of light-stable synthetic fibres have, through their longer useful life, advantages over carpets that have to be replaced earlier. As the above example shows, the properties in the useful phase are not only ecologically decisive, they are also an important economic criterion. Analyses from the automotive segment show that weight reductions made possible through the use of plastics have a major influence

### Table 1. Alt vs. new: Comparison of the costs for using the refrigerator alternatives for five years

<table>
<thead>
<tr>
<th>All figures in EUR</th>
<th>New refrigerator (A)</th>
<th>New refrigerator (B)</th>
<th>Further use of old refrigerator 1</th>
<th>Further use of old refrigerator 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase price</td>
<td>388</td>
<td>287</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Electricity costs/kWh</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Electricity costs/year</td>
<td>18</td>
<td>28</td>
<td>39</td>
<td>50</td>
</tr>
<tr>
<td>Electricity costs/customer benefit (five years)</td>
<td>90</td>
<td>139</td>
<td>195</td>
<td>248</td>
</tr>
<tr>
<td>Residual value of refrigerator after useful life</td>
<td>–194</td>
<td>–143</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total costs for five years of use (incl. 2% inflation and 2.5% interest)</td>
<td>296</td>
<td>294</td>
<td>205</td>
<td>260</td>
</tr>
<tr>
<td>Additional charge for recycling</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct costs for five-year use</td>
<td>300</td>
<td>298</td>
<td>205</td>
<td>260</td>
</tr>
</tbody>
</table>

**Fig. 4. Direct costs for five-year use of the various refrigerator alternatives**

work conditions. Whether buying a new machine – which of course also has to be manufactured – actually lessens the impact on the environment as a whole, or whether it is better to continue using the old machine, can be answered in the same way as how important the influence of the specific parameters (purchase price, electricity consumption) is on the economic side. Break-even point calculations can also be carried out with this method. In the described refrigerator example, the decision is dependent on the electricity consumption of the old machine: If it consumes more than 300 kW/h a year, it should be replaced.

**Conclusion and Outlook**

The BASF eco-efficiency analysis is the only one worldwide out of around 20 methods for evaluating eco-efficiency that has been certified by an independent organisation (TÜV Rheinland Berlin Brandenburg) [8]. It combines the ecological assessment of products or processes through a defined eco-balance analysis with appropriate strategies for calculating the total costs throughout the life cycle. With this tool, sustainability can be measured in two dimensions and depicted plausibly.

In the discussion about more sustainability in industry and society, the holistic approach must also be looked at in an economical respect. Gathering environment and cost-related data and findings alone will not result in a higher sustainability. Documents that are prepared for decision making should combine ecology and economy in an easy, understandable way. After all, only if we implement concrete alternatives will we be able to achieve improvements in the ecological and economic respect.

**REFERENCES**

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