LCA Methodology

The Virtual Eco-Costs '99

A Single LCA-Based Indicator for Sustainability and the Eco-Costs – Value Ratio (EVR) Model for Economic Allocation

A New LCA-Based Calculation Model to Determine the Sustainability of Products and Services

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Abstract. In literature, many models (qualitatively as well as quantitatively) can be found to cope with the problem of communicating results of LCA analyses with decision takers. In a previous article of this Journal, an LCA-based single indicator for emissions is proposed: the 'virtual pollution prevention costs '99' (Vogtländer et al. 2000a).

In this article, a single LCA-based indicator for sustainability is proposed. It builds on the virtual pollution prevention costs '99 for emissions, and adds the other two main aspects of sustainability: material depletion and energy consumption. This single indicator, the 'virtual eco-costs '99', is the sum of the marginal prevention costs of:

- Material depletion, applying 'material depletion costs', to be reduced by recycling
- Energy consumption, applying 'eco-costs of energy' being the price of renewable energy
- Toxic emissions, applying the 'virtual pollution prevention costs '99'

The calculation model includes 'direct' as well as 'indirect' environmental impacts. The main groups of 'indirect' components in the life cycle of products and services are:

- Labour (the environmental impacts of office heating, lighting, computers, commuting, etc.)
- production assets (equipment, buildings, transport vehicles, etc.)

To overcome allocation problems of the indirect components of complex product-service systems, a methodology of economic allocation has been developed, based on the so called Eco-costs/Value Ratio (EVR) model.
This EVR calculation model appears to be a practical and powerful tool to assess the sustainability of a product, a service, or a product-service combination.

Keywords: Allocation; depletion; depreciation; eco-costs; eco-efficiency; economic allocation; end of life; energy; EVR; indirect environmental impact; labour; LCA; marginal prevention costs; materials; open loop recycling; product-service systems; single indicator; sustainability; recycling; virtual pollution prevention costs

Introduction: The Philosophy Behind the Model

In March 1995, the World Council for Sustainable Development defined eco-efficiency as: 'the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity, through the life cycle, to a level at least in line with earth's carrying capacity' (WBCSD 1995).

This business oriented definition links modern management practice ('the delivery of competitively priced goods and services .... quality of life') to the need of a sustainable society ('while progressively reducing ...... to ...... earth's carrying capacity'). The first part of the sentence asks for a maximum value/costs ratio of the business chain, the second part of the sentence requires that this is achieved at a minimum level of ecological impact.

But what does this rather philosophical definition mean to business managers, designers and engineers in terms of the practical decisions they take?

There is a need to resolve simple questions like: what is the best product design in terms of ecological impact?, what is the best product portfolio in terms of sustainability?, what is the best sustainable strategy?

For that reason, the Delft University of Technology developed the eco-costs/value model as a practical tool for decision-making, based on the LCA methodology, and comprising the following features:

- One single indicator for the 3 major groups of environmental impacts (material depletion, fossil energy consumption, toxic emissions)
- a relatively simple and well defined allocation system to cope with 'service' type functions (as service systems are characterized by many 'indirect' environmental impacts, shared by many other external systems)

The basic idea of the model is to link the 'value chain' (Porter 1985) to the ecological 'product chain'. In the value chain, the added value (in terms of money) and the added costs are

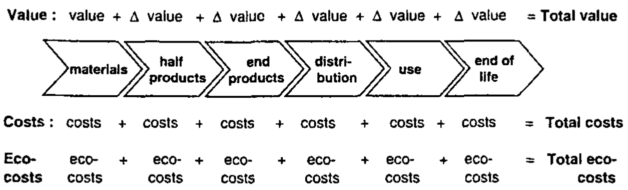

Fig. 1: The basic idea of combining the economic and ecological chain: 'the EVR chain'

determined for each step of the product 'from cradle-to-grave'. Similarly, the ecological impacts of each step in the product chain are expressed in terms of money as well as the so called eco-costs (see, **Fig. 1**).

The eco-costs are 'virtual' costs: these costs are related to measures which have to be taken to make (and recycle) a product "in line with earth's estimated carrying capacity". These eco-costs are the sum of the 'marginal prevention costs' of each 'class' (type) of pollution[1], see **Chapter 2.1**, and the costs of measures for prevention of material and energy depletion, see **Chapter 2.2** and **2.3**.

Since our society is yet far from sustainable, the eco-costs are 'virtual': they have been estimated on a 'what if' basis. The costs of the required prevention measures are not yet fully integrated in the current costs of the product chain (the current Life Cycle Costs). The discussion whether or not it should be wise to integrate the marginal prevention costs in the product costs (by means of 'eco-tax', 'tradable emission rights', or other governmental measures) is regarded as a political issue outside the EVR model: in the EVR model costs and eco-costs are treated as separate, different, entities.

1 The Value, Costs and Eco-Costs of a Product

Now we look into the production step of the business chain. The value ('fair price') of a product is determined by:

- Product quality
- service quality
- image

These 3 components of value are described in more detail by the 'eight dimensions' of Garvin (1988).

The cost-structure of a product comprises:

- The purchased materials (or components)
- the required energy
- depreciation (of equipment, buildings, etc.)
- labour

For a company in the business chain, the tax + profit equals the value minus the costs.

The direct eco-costs have been defined as follows:

- Virtual pollution prevention costs, being the costs required to reduce the emissions in the product chain ('from cradle-to-grave') to a sustainable level
- eco-costs of energy, being the price for sustainable energy sources
- material depletion costs, being (costs of 'virgin' materials) x (1-a), where a is the recycled fraction of materials to *make* a product (for details on the 'end of life' and recycling phase, see **Appendix 2**).

The indirect eco-costs are:

- Eco-costs of depreciation, being the eco-costs related to the use of equipment, buildings, etc.
- eco-costs of labour, being the eco-costs related to commuting and the use of the office (building, heating, lighting, electricity for computers, office products, etc.)

This is depicted in **Fig. 2**.

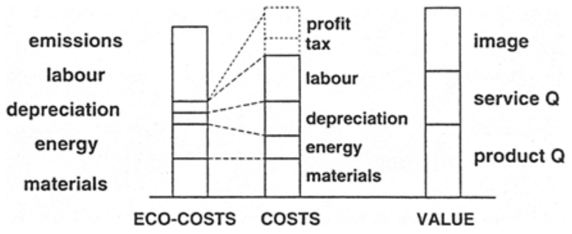

Fig. 2: The decomposition of 'virtual eco-costs', costs and value of a product

Along the business chain, the value, the costs and the eco-costs can be added up, as depicted in **Fig. 3**.

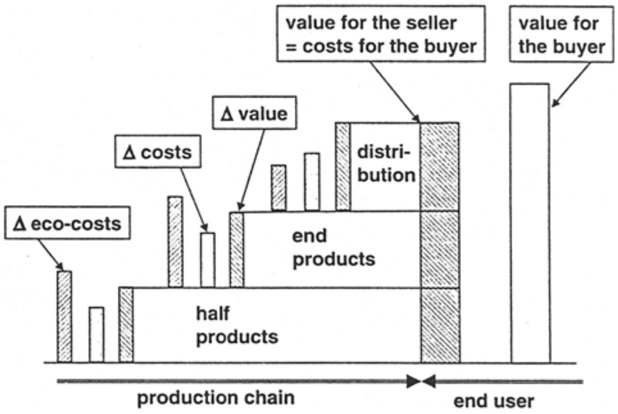

Fig. 3: The decomposition of the value in the chain

Characteristic for each process, product or service is the ratio of the value and the eco-costs.
We can define this Eco-costs/Value Ratio, EVR, at every aggregation level of the product chain (or 'product pool'):

EVR = eco-costs / value

A low EVR indicates that the product is fit for use in a future sustainable society. A high EVR indicates that the value/costs ratio of a product might become less than 1 in future (since in future, environmental regulations will become more stringent and will increase the 'internal' cost-structure), so there is no market for such a product in future.

In **Chapter 3**, we can see how we might apply the EVR for economic allocation in the LCA of complex product-service systems, but first we will define and describe the eco-costs.

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[1] Note that the marginal prevention costs have been chosen here as the norm to be able to compare different kinds ('classes') of sustainability issues. For the logic of such a choice and its implications, see Vogtländer et al. (2000a). Basically, the marginal prevention costs are the costs of the last and most expensive measures that have to be taken to bring the economy in a given region to a sustainable level. Marginal prevention costs are not equal to the so called 'external costs', since 'external costs' are related to damage and not prevention.

2 The Components of the Eco-Costs

As mentioned in Chapter 1, we define the eco-costs as the sum of 3 direct (a, b, and c) and 2 indirect (d and e) elements:

a) The virtual pollution prevention costs '99
b) the eco-costs of energy
c) the material depletion costs
d) the eco-costs of depreciation (use) of equipment, buildings, etc.
e) the eco-costs of labour

All these elements are calculated according to the LCA method, as defined in ISO 14041, as described hereafter.

2.1 The virtual pollution prevention costs '99

The virtual pollution prevention costs '99 is a single indicator for the emissions of the LCA. The model of this single indicator is described in detail in (Vogtländer et al. 2000a). These pollution prevention costs can be calculated in four steps:

1. LCA calculation according to the current standards (ISO 14041)
2. Classification of the emissions in 7 classes of pollution
3. Characterization according to characterization multipliers as used, for example, in the Eco-indicator '95, resulting in 'equivalent kilograms' per class of pollution
4. Multiplication of the data of step 3 with the 'prevention costs at the norm', being the marginal costs per kilogram of bringing back the pollution to a level 'in line with earth's carrying capacity'.

The following 'prevention costs at the norm' are proposed for The Netherlands and Europe:

- prevention of acidification: 6.40 Euros/kg (SOx equivalent)
- prevention of eutrophication: 3.05 Euros/kg (phosphate equivalent)
- prevention of heavy metals: 680 Euros/kg (calculation based on Zn)
- prevention of carciogenics: 12.30 Euros/kg (PAH equivalent)
- prevention of summer smog: 50.00 Euros/kg (calculation based on VOC equivalent)
- prevention of winter smog: 12.30 Euros/kg (calculation based on fine dust)
- prevention of global warming: 0.114 Euros/kg (CO2 equivalent)

For details on these prevention costs, see Vogtländer et al. (2000a).

Table 1 of **Appendix 1** provides a list of the virtual pollution prevention costs '99 for 33 materials. Note that the data in this Table also includes the pollution prevention costs related to the emissions of the use of energy to produce and transport these materials.

2.2 The eco-costs of energy

The calculation method to determine the eco-costs of energy is based on the assumption that fossil fuels have to be replaced by sustainable energy sources where this is feasible. The 'eco-costs of energy' is equal to the costs of the renewable energy system which has to replace the current system. The data which is used, is from the MARKAL database of ECN (ECN 1998, Gielen et al. 1998). See also the list of measures to prevent greenhouse gases (Vogtländer et al. 2000a).

The results of the calculations for 6 sources of energy are given in **Table 2** (**Appendix** 1). The technologies of MARKAL are readily available. It might be, however, that the costs of the proposed domestic sustainable energy systems become gradually lower when the techniques will be widely spread (because of the economies of scale of production costs for a big consumer market).

As an LCA provides data on both energy and its related emissions, the conversion to the related eco-costs must be done carefully, to prevent counting energy twice. Apply either the energy data and convert it to the eco-costs of energy or the emission data and convert it to pollution prevention costs.

In Chapter 5.2 it is argued that eco-costs of energy have less spread in the calculations (are more accurate) than the pollution prevention costs related to energy. Hence, eco-costs of energy must be used preferably in the conversion of LCA data to eco-costs. For the processing of materials, however, the use of fossil fuels is often highly integrated in the production process, so that the energy-related emissions must be applied instead.

2.3 The material depletion costs

With regard to the depletion of materials, the main approach in the model is:

- The eco-costs of material depletion are set equal to the market value of the 'virgin' materials when the materials are not recycled
- when a fraction α of the sourced material for the new product is recycled, a factor $(1-\alpha)$ is applied to the market value of the 'virgin' material to calculate the eco-costs of materials (for the general concept and its details, see **Appendix 2**),

therefore,

$$\text{material depletion costs} = \text{'market value of the virgin material'} \times (1-\alpha) \quad (1)$$

The underlying assumption is that the (average) market value of the virgin material for *metals* reflects the fact whether the material is scarce or hard to find and/or mine (e.g. platinum, gold, silver), or whether that will happen in the foreseeable future[2].

For plastics, however, the situation is different, because of the source of it is crude oil.

The average crude oil price was $15.50 per barrel for the period 1994-1998. This price level is also valid for much longer periods in history (for the long-term average crude oil prices, see www.wtrg.com).

However, it is more in line with the general philosophy of this model to avoid the use of fossil fuels and use ethanol based on biomass instead as a source material for plastics.

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[2] In theory, one must apply here the 'present market value' (discounted) of the 'sustainable alternative in the future' for the metal which is depleted, according to the model of Hotelling (Pearce et al., 1990). For most of the metals, however, there is no reason to believe that this 'present market value' deviates much from the current average material prices (examples: tin, copper, iron), since the functionality of these materials can be replaced by alternatives which are not more expensive for their specific functions. So the present costs have been taken in this formula.

Therefore, in the EVR model, the price of ethanol based on biomass has been chosen for the material depletion costs. This price is estimated at 0.60 Euros/kg.

The fraction α must be applied to the materials used for the new product (and not as a fraction of materials from the old product at the End of Life), after the upgrading process (if applicable). See **Fig. 5** of **Appendix 2**.

Table 3 (**Appendix 1**) provides the material depletion costs for 13 materials.

2.4 Indirect eco-cost: The eco-costs for labour

The eco-costs of labour are indirect eco-costs, since labour as such is hardly causing any environmental burden. However, there is some environmental burden related to labour, such as the environmental impacts of heating, lighting, computers, commuting, etc.

The calculations of these eco-costs are specific for the type of labour. An example is given here for work in offices.

For the category of personnel in offices, an assessment has been made for Dutch employees with average salary costs of 27,500 Euros per annum (including taxes, insurance and pension funds), having an office space of 33 m^2 (average for the banking and insurance sector):

1. Eco-costs of energy per annum per employee (for eco-costs of energy see, Table 2): – commuting by car, 20 km for 210 days per year, fuel required: 840 litres of petrol = 30 (GJ) > eco-costs = 30 (GJ) x 35.80 (Euros/GJ) = 1074 Euros – heating of the office per annum per employee, CBS data [2] for 1994 (CBS, 1996): 0.42 (GJ / m^2) x 33 (m^2) = 14 (GJ) > eco-costs = 14 (GJ) x 9.70 (Euros/GJ) = 136 Euros - electricity for the office per annum per employee, CBS data[3] for 1994 (CBS, 1996): 0.85 (GJ / m^2) x 33 (m^2) = 28 GJ > eco-costs = 28 (GJ) x 19.60 (Euros/GJ) = 549 Euros
2. eco-costs of the office building per employee per annum: – total costs related to construction, maintenance and demolition[4]: for details see Table 4 > eco-costs = 24 Euros/ m^2 x 33 (m^2) = 792 Euros
3. eco-costs of office products per employee per annum: typical, total eco-costs for office products (paper, printing ink, etc.), incl. EoL = 180 Euros

Total eco-costs labour = 2731 Euros

Since the average salary costs in this building is 27,500 Euros, the EVR ratio is here 0.10. Preliminary calculations show that the eco-costs will rise linear with the salary.
Calculations on labour inside as well as outside offices (shop floor personnel in factories, sales people, truck drivers, etc.) show that the EVR will vary in a range of 0.05-0.15 where the eco-costs of commuting and use of electricity play a rather dominant role. Therefore, it is recommended to make an LCA assessment in each typical case.

2.5 Indirect eco-costs: The eco-costs of depreciation of production facilities

The eco-costs related to the fact that fixed assets are used to make a product, are indirect eco-costs.

The calculations on the eco-costs of the use of fixed assets have the same characteristics as cost estimates for investments: for each individual situation, calculations have to be made on the applied materials and the required manpower.

The basic idea behind the 'eco-costs of depreciation' is that the eco-costs of the production facilities must be allocated to the products which are made in or with these facilities. The standard procedure is:

1. Calculate the eco-costs of the production facility.
2. Divide the eco-cost of step 1 by the life-time T (in years) of the production facility. In the EVR model, the 'economic life-time' must be applied instead of the 'technical life-time', which is 'safe side' since the economic life-time is usually shorter than the technical life-time.
3. Divide the outcome of step 2 by the number of products N which are produced per year.

In a formula:

$$\text{Eco-costs of depreciation} = (\text{eco-costs of the production facility}) / T / N \qquad (2)$$

This allocation procedure is similar to the procedure which has been used in the previous chapter for the calculation of the eco-costs of the office building per employee per annum. Note that different facilities or different subsystems of facilities might have a different life-time, T, (see, **Table 4, Appendix 1**).

Since the EVR model applies to the economic life time of the facility, formula (2) has a high similarity with the normal, linear formula for production costs related to depreciation:

$$\text{Costs of depreciation} = (\text{value of the production facility}) / T / N \qquad (3)$$

Combining formula (2) and (3):

$$\text{Eco-costs of depreciation} = (\text{costs of depreciation}) \times (\text{eco-costs / value})_{\text{production facility}} \qquad (4)$$

The meaning for formula (4) is that the eco-costs of depreciation can be derived from the normal costs of depreciation by multiplying it with the EVR of the production facility. In situations where more than one type of product is produced in a complex production system, and where a 'cost break down structure' of the product is available, formula (4) can provide an easy way out of a rather complex allocation problem.

In Chapter 3 we will show how formula (4) can be derived starting from the definition of allocation as stated in ISO 14041.

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[3] The source of the data is the Economic Statistical Institute for The Netherlands, CBS, Voorburg, The Netherlands

[4] Since the results of these kinds of calculations highly depend on the actual construction, the Delft University of Technology has started a study on the eco-costs for each typology of building construction

Calculations on production facilities show the following characteristics for the EVR:

– Complex machines	0.3
– luxurious buildings (offices)	0.3
– low cost offices	0.4
– processes in stainless steel	0.4
– refineries	0.5
– steel structures	0.6
– warehouses	0.6

In general:

- The use of steel (and other metals) is related to a high EVR (because of high pollution prevention costs, see Table 1)
- complex systems have a low EVR (because of a high labour content)

3 The EVR Model for Economic Allocation in the LCA

The reader may already have got a feel of how to apply the EVR model for economic allocation, and how to derive the 'total EVR' of a complex system from the EVRs of the system components.

In this chapter, the EVR is explained in more detail.

An important characteristic of the Eco-costs/Value Ratio of a chain is that the 'Total EVR' for a production chain is the weighted average (on value) of the EVRs of the steps in that chain. This characteristic is shown in the following formula:

$$\mathrm{EVR}_{\mathrm{Total}} = \{\Sigma \text{ eco-costs}_n \} / \text{value}_{\mathrm{Total}}$$

$$= \Sigma \{ \mathrm{EVR}_n \cdot [\Delta \text{ value}_n / \text{value}_{\mathrm{Total}}] \} \qquad (5)$$

where

$$\text{value}_{\mathrm{Total}}$$

$$= \Sigma\text{costs} + \Sigma\text{taxes} + \Sigma\text{profits} \qquad (6) \text{ (see, Fig. 1, 2 and 3)}$$

It is obvious that 'the chain' (in its one dimensional form) is a drastic simplification of 'the real world': in reality, production chains are part of production and distribution networks. Every actor in the chain is also part of other chains (they have many suppliers and many clients)[5]. In a calculation of LCAs, this causes the so called 'allocation problem': how to allocate the environmental impact of a shared use of production facilities, transport and distribution systems, etc.?

The basic methodology for allocation problems in LCAs is dealt with in ISO 14041: 'Where physical relationship cannot be established or used as the basis for allocation, the inputs should be allocated between the products and the functions in a way which reflects other relationships between them. For example, environmental input and output data might be allocated between co-products in proportion to the economic value of the products'.

This methodology can be explained by an example: the indirect environmental impact of building an airplane, allocated to a single trip[6]. The main parameters are:

- the value of a ticket for the single trip, W, of which a part of that value, X, is related to the depreciation (or leasing costs) of the plane
- the value of a plane, Y
- the eco-costs of a plane, Z (calculated from LCA data)

The question is now which part of the indirect environmental impact of building a plane, Z, has to be allocated to the trip. Applying economic allocation:

$$A = (X / Y) \times Z$$

$$= \text{'the economic proportion'} \times \text{'Environmental Impact'} \qquad (7)$$

Where A is the indirect environmental impact allocated to the ticket, which can be written as:

$$A = (Z / Y) \times X$$

$$= \mathrm{EVR} \times \text{'part of the value of the ticket related to the depreciation of the plane'} \qquad (8)$$

Formula (8) shows how the EVR model can be used for economic allocation in a complex LCA, starting with a 'cost-breakdown structure'. Especially in cases when proportions of weight are not known directly, which is often the case for services, the EVR model is a powerful tool. Note that formula (4) and formula (8) are of the same nature.

In the example, formula (8) is applied to an 'indirect' environmental impact. Formula (8) can also be applied to situations of 'direct' impact (e.g. for allocation of the fuel to one passenger). In most of the situations of 'direct' impact, however, the physical relationship is known as well, in which cases the eco-costs must be determined on that direct physical relationship and according to ISO 14041.

Although the authors of the ISO 14041 define economic allocation as a 'last option' (to be avoided, if possible), there is no need to avoid economic allocation in cases where the ratio between 'value' and 'kilograms' is fixed[7], since the ratio between eco-costs and value, the EVR, is fixed then as well.

So it is a prerequisite for EVR calculations that a specific EVR must be independent of the size (weight, volume, time, etc.) of the functional unit of the element in the LCA. Under this condition, the EVR can be used for direct impacts as well, instead of the eco-costs/weight ratio, which appears extremely practical in many cases.

The first example is on how to apply the EVR in the case of a service function (a transport chain), where economic allo-

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[5] This leads to the concept of the 'profit pool' (Gadiesh et al. 1998)

[6] There is no simple physical relationship to base the allocation on for many reasons. The major two reasons are:
- Planes transport passengers as well as freight (in the same plane on the same trip). How can one differentiate between passengers and freight? Based on volume or on weight or any combination of both?
- One plane will make many trips during its life time, all over the world. There are trips ('legs') with high occupancy rates and trips with low occupancy rates. How to cope with these differences during the life time?

[7] Under such conditions, the 'economic proportion' in formula (7) equals the 'physical proportion'.

cation can play a practical role. This example is given in Table 5 (Appendix 2).

In the example of the transport function of Table 5, only the 'one way' packaging can be directly linked to the material flow of goods. All other elements in the chain 'share' with other chains (even fuel, since the truck is normally only partly loaded by other freight on the trip back). It is feasible here to establish all 'physical relationships', although the relationships are of an extremely complex nature, so that a computer programme has been written to calculate the eco-costs. With the same program structure, costs are being calculated as well.

Analysing the output, it has been concluded that all the activities can be grouped in 'subsystems' (9 in total), since they have the same, constant, EVR (Vogtländer et al. 2000b).

Table 5 shows that the calculation of the total eco-costs for the defined function becomes extremely simple when the values (prices) for the main activities are known, by applying these EVR data. The outcome is within 3% of the outcome of the computer calculation based on the 'physical relationships'.

The second example is on how to apply the EVR model in the design stage of a product, in this case a warehouse, see Table 6 and Table 7 (Appendix 1).

In Table 6 the classical LCA is provided on the basis of materials required to build the warehouse. This methodology is suited for the situation that the detailed design of the warehouse is finalized (in The Netherlands, a powerful computer calculation model is available for such an analysis: Ecoquantum).

However, in the preliminary design stages, the exact amount of materials is not yet known. In that stage the EVR method is more applicable to analyse different alternatives for the design, see Table 7.

The design strategy to create an optimum solution is simple: fulfil the design requirements by applying elements with the lowest possible EVR values.

Table 6 and Table 7 provide an analysis on the same warehouse design. The results, however, in terms of eco-costs, are not exactly the same: the differences in both cases are caused by the use of different sources of LCA data (Note that LCA emission data can differ by a factor 2, or even more, for the same type of materials, because of differences in applied processes and/or practices !)

4 The EVR and the Virtual Eco-Costs '99 for Industrial Activities

Similar to the calculations on the pollution prevention costs of materials (Table 1), calculations have been made on these costs of industrial activities.

These calculations are based on an extensive measurement programme on the emissions of industrial sectors in The Netherlands. Furthermore, the eco-costs of energy have been calculated on the basis of the energy consumption of these industrial sectors, and the eco-costs of depreciation and labour have been estimated on financial data on these sectors. The results of the calculations are provided in Table 8 (Appendix 1).

To calculate the data of Table 8, the measured industrial pollution in 1995 (VROM 1997) has been compared with general statistic data on these industries for 1995 (CBS 1997).

Basically, the EVR data of Table 8 form the link between the LCA-based approach and the 'input-output table' based approach of macro economic environmentalists.

5 Discussion

5.1 Eco-efficiency

Since the EVR links the 'value' with the 'ecological impact', the EVR is also a parameter for the eco-efficiency as defined by the WBCSD. We propose the following formula (see, Fig. 4):

$$\text{Eco-efficiency} = b / c = (\text{ value } - \text{ eco-costs }) / (\text{ value }),$$
$$\text{or eco-efficiency} = 1 - \text{EVR} \qquad (9)$$

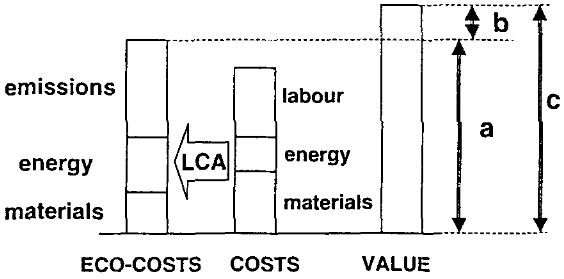

Fig. 4: The definition of eco-efficiency in the EVR model: eco-efficiency = b/c

Note that the eco-efficiency is:

- Negative when the eco-costs are higher than the value, or where EVR > 1
- 0 when the eco-costs are equal to the value, or when EVR = 1
- 1 when there are no eco-costs, or when EVR = 0

5.2 Accuracy

Rather than accuracy, practical choices on system characteristics and system boundaries are the major concern in an LCA (what is included? Which processes? Industrial averages or best practices?, etc.). Sensitivity analyses showed that these choices are dominant in the EVR calculation model (as they are in other LCA-based models applying a single indicator).

The 'value' in the equation is not as vague as many non-specialists would suspect: in the EVR model, the value is defined as the 'sales price' within the business chain and the 'fair price' in the consumer market, which are quite well determined in practice.

A way to analyse the topic of 'accuracy' is to study the variance of LCA data and sales prices within Europe. Two examples:

- For a specific design of a solid or corrugated board box, the 'best practice' versus the 'worst practice' in terms of 'clean production' differs by more than a factor of four within Europe. The value (price) in this market segment is hardly higher than the production costs. Within Europe, these production costs differ by not more than approximately 20%. Therefore, the value is quite accurate in comparison with the eco-costs.

- For electricity, the production in Holland is a factor 2 cleaner than in Portugal. In countries with hydroelectric power such as Norway, emissions are a factor 100 less than in Holland. (Rombouts et.al. 1999) Prices, however, differ not more than 30% within the EC. Again, the value is quite accurate in comparison with a single indicator for emissions.

So emissions of energy production vary enormously with the choice of type and grade of the fossil fuel. For this reason, the 'eco-costs for energy' in the EVR model are preferably based on the energy which is used, rather than its related emissions (Chapter 2.2). In the eco-costs model, energy from fossil fuels is replaced by renewable energy, rather than preventing the emissions from these fossil fuels. The accuracy of the costs estimates for renewable energy systems is estimated at 30%, which is by far better than the spread in emissions of energy from fossil fuels.

The fact that the EVR is dimensionless means that the EVR model is relatively robust with regard to exchange rate fluctuations or inflation of currencies.

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Appendix 1: Tables 1-8

Table 1: The virtual pollution prevention costs '99 of materials (Based on LCA data from (M. Goedkoop 1995) and marginal prevention costs (Vogtländer et al. 2000a))

Materials	Pollution Prevention Costs '99 (Euros/kg)
Aluminium	2.64
Secondary aluminium	0.44
Copper	3.96
Secondary copper	1.14
Stainless steel	1.15
Secondary steel	0.40
Steel, (general BUWAL data)	1.48
Steel, (Dutch manufacturing)	0.42
Steel plate	1.52
Glass	0.29
Glass wool	0.55
Ceramics	0.22
Paper board (BUWAL data)	0.36
Paper board (Dutch manufacturing)	0.09
Wood	0.12
Cellulose board	1.22
Paper	0.71
Recycled paper (BUWAL data)	0.39
Recycled paper (FEFCO data)	0.10
Concrete (reinforcing 70 kg/m2)	0.20
Acylonitril-butadiene-styrene	4.00
High density polyethylene	1.26
High impact polystyrene	2.00
Low density polyethylene	1.33
Polyamide	5.28
Polyethylene tereftalat (PET)	2.52
Polypropylene	0.92
PPE/PS	1.25
Polystyrene hard foam	5.71
PUR	1.02
PVC	1.35
Rubber (natural)	1.23
Stone wool	0.56

Table 2: The eco-costs of energy, and the corresponding EVR for energy (Costs of sustainable energy based on MARKAL data (Gielen et al. 1998, ECN 1998)

Category	**Current prices** (Euros/GJ)	**Main sustainable energy source**	**Eco-costs of energy** (Euros/GJ)	**EVR**
Industrial heat	2.80	Biomass	5.00	1.80
Diesel for trucks (in EC[1])	15.60	Ethanol from biomass	28.70	1.84
Diesel for trucks (in EC[2])	21.50	Ethanol from biomass	28.70	1,33
Electricity (industry)	12.70	Biomass +wind+hydro	19.55	1.54
Electricity (domestic)	13–26	Biomass +wind+hydro	19.60–32.80	1.5-1.25
Petrol for cars (in EC[1])	22.70	Ethanol from biomass	35.80	1.57
Petrol for cars (in EC[2])	29.20	Ethanol from biomass	35.80	1.23
Domestic heating	6.15	Suncollectors+heatpumps	9.70	1.58

[1] Approximate price for the Netherlands, Germany, France, Italy, summer 1998, excl. VAT (Brent oil $12,50 per barrel)
[2] Approximate price for the Netherlands, Germany, France, Italy, summer 2000, excl. VAT (Brent oil $32,00 per barrel)

Table 3: The material depletion costs

Materials	**Approx. Market Value of required raw material** (Euros/kg)	**Fraction aof recycled materials**	**'Materials Depletion Costs'** (Euros/kg)
Aluminium	1.40	0.0	1.40
Secondary aluminium	1.40	1.0	0.00
Copper	1.90	0.0	1.90
Secondary copper	1.90	1.0	0.00
Stainless steel	2.30	0.0	2.30
Secondary steel	0.30	1.0	0.00
Steel	0.30	0.0	0.30
Steel (Dutch manufacturing)	0.30	0.12	0.26
Paper board (from waste p.)	0.10	1.0	0.00
Wood (hardwood)	1.00	0.0	1.00
Paper (raw mat. is pulp)	0.55	0.0	0.55
Waste paper based Paper	0.10	1.0	0.00
Plastics (raw mat. is biomass)	0.60	0.0	0.60

Table 4: Summary of the eco-costs of an office building (excluding energy during the use phase !), example

Summary description of an office building (typical)	**Eco-costs** (Euros/m²)	**Life time** (years)	**Eco-costs/annum** (Euros/m²/annum)
Main materials for construction:			
– concrete, 300 kg/ m2 (eco-costs 0.20 Euros/kg, see Table 1)	60	40	1.50
– steel, 50 kg/m2 (eco-costs 1.80 Euros/kg, see Table 1 and 3)	90	40	2.25
– miscellaneous materials, 50 kg/m2 (glass, wood, PVC, etc.)	30	40	0.75
– building activity (energy, etc.)	40	40	1.00
Subtotal construction building structure	220	40	5.50
Building systems (elevators, heating, electrical, water, etc.)	60	20	3.00
Interior (painting, decorating, furniture, etc.)	120	15	8.00
Computer system (one screen per employee at 33 m2)	9	3	3.00
Maintenance of building and building systems per year	3	-	3.00
End of Life:			
Demolition + transport of materials at End of Life	20	40	0.50
Disposal of construction waste (eco-costs 0.10 Euros/kg)	40	40	1.00
Subtotal End of Life	60		1.50
Total			**24**

Table 5: An example of using the EVR model for economic allocation in a transport chain. The functional unit is defined as: 'transport of 2500 litres net volume of tomatoes from Holland to Frankfurt' (Example of volume based transport in corrugated board boxes, full truck load, truck returns empty. For a detailed analysis of this transport function (see, Vogtländer et al. 2000b))

	Chain element	**LCA subsystem**	**Value** (Euros)	**EVR '99**	**Eco-costs** (Euros)
Example of	Packaging	(one way boxes)	47	0.15	7.00
the value	Transport	Truck, fuel, road	38	0.72	27.40
structure	Storage	Building	11	0.34	3.70
of transport		Handling	2	0.33	0.70
(simplified)	End-of-life	(packaging)	2	0	0.00
Total Chain			**100**		**38.80**

Table 6: Virtual eco-costs '99 for a warehouse, 920 pallets (900 m2, 10 meters high). Calculation according to the classical approach of the LCA method, excl. Use phase and EoL phase

	greenhouse kg CO2 equ	Acidification kg SO4 equ	eutroph. kg PO4 eq	hv. metals kg Pb equ	carcin kg B(a)P eq	s. smog kg VOC eq	w.smog kg SPM eq	Eco-costs '99 (Euros)
Concrete, reinforced, 551200kg	59629	484.6	51.07	0.46	0.015	54	6490	99459
Fe360, 51000kg	58271	708.1	63.65	1.05	0.035	79	427	36592
steel sheet, 22000kg	38585	214.4	12.09	0.12	0.021	670	176	47976
PS, 40kg	164	0.2	0.04	0	0	1	0	71
PS foaming, 40kg	222	3.3	0.07	0	0.001	2	0	152
steel transforming, 22000kg	1449	9.6	0.44	0.01	0.001	1	7	367
steel transforming, 51000kg	3475	22.3	1.03	0.03	0.002	2	17	864
Eco-costs of contractors and suppliers (guestimate)								72000
Total in kg equivalent:	161798	1442.9	128.39	1.67	0.075	809	7117	
Eco-costs '99 (Euros)								257481

Table 7: Virtual eco-costs '99 for a warehouse, 920 pallets (900 m2, 10 meters high). Calculation according to a standard cost estimate system and the EVR model, excl. Use and EoL phase (The cost estimate is from the DACE database on costs (DACE is the Dutch Association of Cost Engineers). The EVR has been based on LCA data)

	Value (Euros / m^2)	EVR	Eco-costs (Euros / m^2)	Eco-costs (Euros / 900 m^2)
floor, reinforced concrete, 300 mm thick	140	0.8	112	100473
steel structure	80	0.7	56	50114
foundation of steel structure	15	0.8	12	11127
roof, steel+thermal insulation	75	0.4	30	26836
Cladding+ insulation (surface.=1.3xfloor area)	95	0.4	38	34036
Lighting, heating, sprinklers, etc.	45	0.3	14	12027
Total	**450**	**0.58**	**261**	234614

Table 8: The eco- costs of industrial activities, and the corresponding EVR (Note: the table is based on Added Value and emissions of the sector itself, excluding sourced materials)

Industry (CBI-code)		**Poll.Prev. Costs '99** (10^6 Euros)	**ECO-Costs '99** (10^6 Euros)	**Added Value** (10^6 Euros)	**EVR**
Food industry	(15,16)	1030	1430	9030	0.16
Textile- en clothing-industr.	(17,18)	95	204	838	0.24
Leather industry	(19)	26	36	81	0.44
Wood industry	(20)	109	159	415	0.38
Paper industry	(21)	498	712	1390	0.51
Printing industry	(22)	1000	1400	3400	0.41
Oil industry	(23)	2950	3220	890	3.61
Basic chemicals ind.	(2412-2414)	2950	3870	4680	0.83
Fertiliser industry	(2415)	306	incl. basic chem	incl. basic chem	incl. basic chem
Agriculture chemicals	(242)	19	25	44	0.56
Coatings- and ink-industry	(243)	47	96	420	0.23
Pharmaceutical industry	(244)	95	not available	not available	not available
Detergents industry	(245)	17	52	307	0.17
Other Chemicals	(246)	100	not available	not available	not available
Fibre industry	(247)	246	not available	not available	not available
Rubber industry	(251)	35	557	1330	0.42
Converting industry plastics	(252)	320	incl. in rubber	incl. in rubber	incl. in rubber
Building materials	(26)	711	936	1710	0.55
Basic metals industry	(27,231)	2130	2380	1840	1.29
Metal products industry	(28)	456	797	2770	0.29
Machine- en equipment ind.	(29)	106	456	3060	0.15
Electrical industry	(30-32)	429	1000	4520	0.22
Automotive industry	(34)	518	1090	1710	0.64
Shipyards	(351)	256	incl. auto ind.	incl. auto ind.	incl. auto ind.
Instrument- and optical ind.	(331)	13	50	312	0.16

Appendix 2: The End of Life stage and Recycling

The way that the EVR model deals with End of Life and Recycling is depicted in Fig. 5, and is explained hereafter.

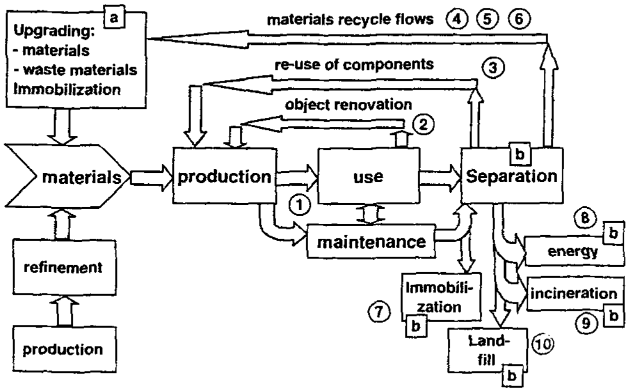

Fig. 5: The flow of materials in the life cycle

Fig. 5 depicts the major types of End of Life treatment and types of recycling. It is developed at the Delft University of Technology to describe and analyse the various kinds of complex modern life cycles of products, buildings, manufacturing plants, civil structures, etc.

The numbers in Fig. 5 relate to the 'Delft Order of Preferences', a list of the 10 major systems for End of Life used for structured and systemised analyses of (combinations of) design options:

1. Extending of the product life
2. Object renovation
3. Re-use of components
4. Re-use of materials
5. Useful application of waste materials
6. Immobilization with useful appliances
7. Immobilization without useful appliances
8. Incineration with energy recovery
9. Incineration without energy recovery
10. Landfill

It is important to realise that for big, modular objects (like buildings), there is not 'one system for End of Life' but, in reality, there is always a combination of systems. The way these complex End of Life systems can be analysed within the EVR model is beyond the scope of this publication, but two basic rules for allocation in the EVR model are:

- Costs and eco-costs of all activities marked with 'b' are allocated to the End of Life stage of a product (transportation included).
- Costs and eco-costs of all activities in the block marked with 'a' are allocated to the material use of the new product (so are allocated to the beginning of the product chain)[7].

In line with the aforementioned allocation strategy, the 'bonus' to use recycled materials is taken at the beginning of the product chain, where the new product is created. Material depletion is caused here when 'virgin' materials are applied, material depletion is suppressed when recycled materials are applied.

The eco-costs of material depletion are defined by the costs of the fraction 'virgin' materials, (1-a), which are used for the new product. In a formula:

$$\text{Eco-costs of material depletion} = (\text{costs of 'virgin' materials}) \times (1-a) \qquad (10)$$

where a is the fraction of used materials for the new product with stems from 'recycled' material (when upgrading is required, after the upgrading step).

With regard to eco-cost analyses, two final remarks have to be made within the framework of this paper:

One of the consequences of the chosen allocation system is that all the emissions and energy consumption in the LCA add to the total emissions and energy consumption, however with one exception: incineration with energy recovery (no. 8). For incineration with energy recovery, there is a surplus of energy which requires a correction in the LCA for either the eco-costs of energy or the pollution prevention costs for 'avoided emissions'. Note that there is no 'estafette effect' in this allocation system (estafette = relay race).

- For the situation in The Netherlands[8], the eco-costs of 'landfill' has to be set at 100 Euros per 1000 kg, being the costs of prevention of landfill (the main alternative systems for landfill are: making compost of bio waste, incineration of domestic waste in an environmentally acceptable way, recycling building materials).

The total concept of the 'Delft Order of Preferences' and its evaluation method via the EVR model will be published in due time.

Call for Comments

1. In the EVR model, economic allocation is applied in two cases:
   a. When subsystems are shared between many product types and the physical relationship is not determined by one parameter, like mass, volume or time. The EVR model then applies formula (7)
   b. When there is a linear relation between value and a physical parameter like mass, volume or time. In these cases, there is no difference between the 'physical proportion' and the 'economic proportion'.

   We feel that the use of economic allocation should be defined better than 'only where physical relationship cannot be established'. We suggest a list of criteria which must be fulfilled to allow economic allocation, like:
   - Relative stable prices in a transparent, free, and open market and
   - a linear relationship between value (price) and mass, volume or time

   Are there any suggestions to complete this list? Are there any comments?

2. In the EVR model, the 'bonus' of open loop recycling is allocated to the 'new product', and consequently not to the 'old product' (otherwise recycling is counted twice). Our choice was grounded on methodological aspects (avoiding endless loop systems and avoiding the methodological consequences of the build-up of materials in the cycle for products with a long life time).

   We are aware of the fact that our approach is not in line with the current practice of allocating the benefits of recycling to the 'old product'.

   Are there any comments on our choice, and/or are there any suggestions for an alternative (hybrid?) solution for allocation?

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[7] There are many reasons to allocate these activities to the new product. Three major arguments:
- The processes to use and upgrade recycled materials are often integrated with other processes to make the new product (e.g. recycled paper, recycled steel, etc.)
- Physical tracing of recycled material flows between the 'upgrading step' and the 'separation step' is not normally possible (there is generally no direct physical relation between the old product and the new product)
- For products with a long life time, other allocation systems lead to wrong conclusions (Gielen 1999)

[8] The governmental policy in The Netherlands is to avoid landfill. In 1996, 14% of the total waste flow was landfill, the target for 2010 is 4%!