LCA Methodology

Functional Unit for Systems Using Natural Raw Materials

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Abstract

The necessity of a functional unit, which considers the equality of all benefits, is underlined especially for systems using such natural raw materials as wood.

The example of identifying the ecological optimal extent of paper recycling is therefore examined by using the data of IIASA [1]. It can be shown that the calculated quantity of the ecological optima particularly depend on the selected model of the comparison. In general, a functional unit of LCA should be based on a model which considers all benefits of the compared systems. The additional benefits of forests have to be taken into account as well. Otherwise, no statement concerning the ecological optima is possible.

1 Introduction

In the beginning of a Life Cycle Assessment (LCA), the functional unit has to be defined. According to the Society of Environmental Toxicology and Chemistry (SETAC) [9], the functional unit is the measure of performance which the system delivers. This functional unit is the reference quantity for the calculation of the ecological burdens of the compared systems. A draft of the International Standard Organisation [10] provides recommendation for comparative LCA-studies to consider an equivalent function of the compared systems in the functional unit. Today, however, no clear rules are available concerning a method of formulating the functional unit.

2 Comparability

2.1 Equality of Benefits

A precondition of a comparative LCA is the equality of all benefits of the compared systems. This has to be considered by formulating the functional unit, i. e. the reference quantity of comparison.

Different systems have to be compared, for example, for identifying the ecological optimal share of secondary material in the product by LCA. These systems can principally consist of process chains producing the product A from raw materials, process chains producing the product A via secondary materials or process chains producing the product A via raw and secondary materials. This comparison concerning the ecological burdens will only be possible if the compared systems cause the same benefits (B). According to BROCKHAUS [8] benefit, is a characteristic of goods which is based on subjective assessment of value.

The problem of subjectivity is that different ecological burdens – which are caused by different systems – cannot be assessed. If system 1 causes more benefits (products A and C) and more ecological burdens, while system 2 causes fewer benefits (only product A) and fewer ecological burdens, no ecological assessment is possible. For an ecological assessment it must be decided whether the higher ecological burdens of system 1 can be compensated by the additional benefit of the product C. Because of the subjectivity of this decision, however, a solution is questionable.

Consequently, a system causing an additional benefit by an additional product could not be part of an ecological comparison [4]. Nevertheless, particular systems with different recycling/disposal path ways produce different benefits. In order to achieve comparability in spite of different benefits of the compared life cycles, the systems have to be enlarged. The extension is the life cycle of the respective lacking product [3].

This approach is presented in **Figure 1**. Aside from product A_1 system 1 generates product C_1. The comparable system 2 only generates the product A_2. Thus, these two systems are not comparable (equation 1), because only the quality and quantity of the products A_1 and A_2 – and the benefits of these products – are equal (equation 2). The comparability can be induced by extending system 2 with the so-called complementary good (C_k) [3]. If the quality and quantity of the products C_1 and C_k are equal, both systems generate equal benefits (equation 4). These comple-

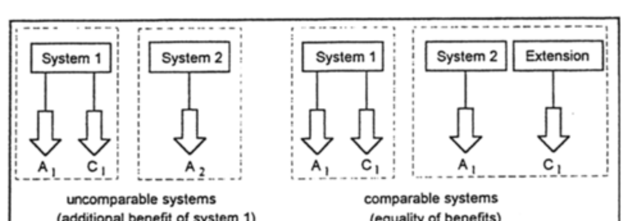

Fig. 1: Transferring uncomparable systems into comparable ones by enlarging the systems

mentary goods have to be produced from raw materials because there are no secondary materials available in the system boundaries.

$$A_1 \cup C_1 \neq A_2 \quad (1)$$
$$A_1 = A_2 \quad (2)$$
$$C_1 = C_K \quad (3)$$
$$A_1 \cup C_1 = A_2 \cup C_K \quad (4)$$

Note: A, B and C are different products. In the case of differnt quantities of one kind of product (e.g. energy) in the compared systems the maximum quantify of this kind of product is used to generate equal benefits in all systems.

The equality of benefits has to be considered in a comparative LCA. This has to occur in defining the functional unit. The German Institute for Standardisation (DIN) [2] defines the functional unit as the unit of comparison referring to the benefit and achievement (this is stressed by the German wording: "functional equivalence"). The ecological burdens of all systems compared refer to the same benefit.

Until now, the functional unit only considers primary benefits (in **Figure 1** the product A) which is in the centre of interest by performing the respective LCA. The additional benefits (the product C in **Figure 1**) are often not taken into account. However, the equality of benefits could not be fulfilled and this LCA-studies cannot be meaningful because of the considerations above.

Small differences in the quality of the compared products do not influence the comparability of products. This is not the subject of this article. These small differences are no problem as long as the compared systems generate products which fulfil the same profile of requirements for a certain use. The required characteristics can vary within certain limits. This can be important, especially for the comparison of products out of raw materials and products out of secondary resources. Occasionally, the recycling causes a degradation of characteristics which do not signify a different benefit for use, in spite of leaving the limits of the profile of requirements (e.g. recycled paper with lower brightness). Determining to which extent this degradation in the characteristics is possible without endangering the comparability will be a subject of further research.

There is the problem whether the equality of benefits is possible in all cases in principle. A special case are systems which consume more or less natural, renewable raw materials. Thus, different quantities (and perhaps qualities) of natural benefits exist (beauty of forests, humus, etc.) which cannot be substituted by technical systems. No complementary goods (C_k in **Figure 1**) for these natural benefits have thus far been produced by man as a technical, artificial substitut. Therefore a special procedure which is described in the following has been developed.

2.2 Equality of benefits in systems with natural raw materials: The example of paper production in Europe

The method for ensuring comparability between systems with different natural benefits is developed considering the example of paper production in Europe. Here even the question as to whether the reduction of wood consumption has a positive or negative benefit on forests is answered controversially . The owners of forests argue that less wood sold means less care and attention. Environmentalists criticise this kind of care for forests or argue that less recycling does not mean more consumption of "sustainable wood", but rather the consumption of cheaper "not sustainable wood".

According to this debate, the additional benefit of paper recycling concerning the protection of forests by consuming less wood is difficult to assess because of the subjectivity of this problem. The solution of this problem is the equality of benefits. This equality is a main precondition of identifying the ecological optimal recycling rate by LCA.

Following the remarks in section 2.1, not only the amount of paper produced with a defined quality has to be regarded as in the IIASA-study [1]. The system paper production generates different benefits for every recycling rate. In order to perform a clarification, these systems are presented in a simplified way in **Figure 2**. Only few inputs and outputs are shown (e.g. the solar energy has been eliminated). A system with a 100 % share of recycled paper in the paper product is impossible because of technical reasons. This system represents a borderline case. A system without any paper recycling in Europe is not possible without endangering the ecological balance of forests.

All systems will put the same quantity (and quality) of paper (P) at disposal if the quality of recycling paper is assumed to be nearly equal to virgin paper. The quantities of energy produced by waste paper incineration (E) and the forest products (undergrowth, biodiversity, beauty, humus, etc.) emerged without human influence, however, are different.

For these considerations, the same quality of recycled and virgin paper are assumed. According to the considerations of section 2.1, the brightness of paper (P) can vary within certain limits and the benefits (e.g. write, copy) can be presumed to be similar. Because energy is generated from the virgin waste paper, the quantity of energy (E) decreases with an increasing recycling rate (equation 5). This simplified statement does not refer to the energy consumption of the systems, but to their energy generation. In this simplified recycling scenario, only the paper incineration – and not the landfill – is considered. Since forest products are generated without human influence, there are some differences to abiotic resources in the earth's crust which fulfil no

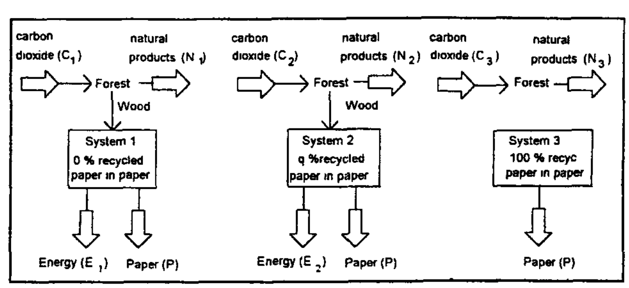

Fig. 2: Different benefits according to different recycling rates (simplified)

function or benefit and generate no products without human influence. This difference is important because a reduction in the consumption of abiotic resources has no benefit as a consequence. The preservation of abiotic resources for the future will be no benefit in itself, if benefit is defined by goods or products. The amount of forest products increases with increasing recycling rate (equation 6). As a consequence, the forest-absorption and storing (in humus, undergrowth or paper) of carbon dioxide is different in all systems (equation 7). For the global warming effect, the emission of methane by biodegradation can be important as well [1].

$$E_1 > E_2 > E_3 = 0 \quad (5)$$

$$N_1 < N_2 < N_3 \quad (6)$$

$$C_1 \neq C_2 \neq C_3 \neq C_1 \quad (7)$$

The consequences of two different functional units on the result are examined at the department of waste minimisation and recycling of the Technical University of Berlin. Only the model can be the basis for defining a functional unit which fulfils the precept of a complete equality of benefits (B), i. e. the main and the additional benefits have to be equal.

A possible functional unit [5] considers – beside the amount of paper – the additional benefit of (netto) energy generation resulting from the combustion of waste paper in the waste incineration. The comparison using this **model 1** is based on the same quantity (and quality) of paper and energy (equations 8 to 10).

System with 0 % recycled paper in product:

$$B_1 = P \cup E_1 \cup N_1 \quad (8)$$

System with q % recycled paper in product:

$$B_2 = P \cup E_1 \cup N_2 \quad (9)$$

System with 100 % recycled paper in product:

$$B_3 = P \cup E_1 \cup N_3 \quad (10)$$

Because of different quantities of forest products (equation 6), the **model 1** does not fulfil the principle of a complete equality of benefits (equation 11). Therefore, this model cannot be regarded by defining a functional unit.

$$B_1 \neq B_2; \quad B_2 \neq B_3; \quad B_3 \neq B_1 \quad (11)$$

If the functional unit would be based on this model, systems without paper recycling will transform all waste paper into energy (E_1) by incineration in a "CO_2-neutral" manner if the wood for paper came from mass-sustainable forests. Mass-sustainable forest management guarantees that the consumed wood can grow again (regard that the aim of some forest management is even to guarantee the preservation of all functions of the forests as well). The emitted CO_2 of paper incineration can be absorbed again, i. e. this energy E_1 is "CO_2-neutral". A system with high recycling rate has to level out the theoretical energetic deficit by using non-CO_2-neutral fossil energy (the quantity is $E_1 - E_3$ or $E_1 - E_2$). The energy of the European public power supply systems is not "CO_2-neutral" because the energy generation in Europe is mainly based on fossil energy sources like coal or natural gas.

While the model 1 [5] does not consider the complete equality of all benefits, the idea of the **model 2** is to equalise all identified benefits *(→ Fig. 3)*.

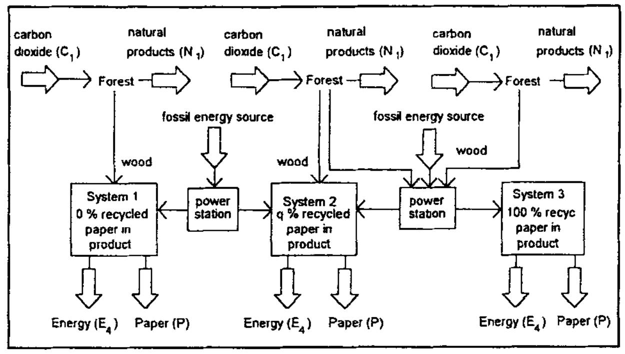

Fig. 3: Equality of benefits in spite of different recycling rates (simplified)

While it is possible to achieve an equality of energetic benefits by adding power stations in the life cycle, it is impossible to produce products of forest in another, technical manner. Today, one cannot substitute the manifold forest products with complementary goods. This is the reason why the same quantity of wood (theoretically) must be taken out of the forest. Thus, all systems generate the same natural benefit. This hypothetical consumption of the theoretical supplementary wood from systems with higher recycling rates is a necessary hypothetical conception for solving the methodical problem concerning comparability, because the manifold of benefits in the forest cannot be considered adequately. This is the result of the above mentioned dispute between forest owners and environmentalists as well. Following this approach of equality, the system with a high recycling rate can use the supplementary wood for producing energy. The energetic equality has to be guaranteed by power stations.

The quantity and quality of energy which all systems have to generate (E_4) is equal to the highest quantity and quality of energy which is (netto) generated by one of the compared systems out of the incineration of waste paper and the combustion of the supplementary wood.

In contrast to the model 1, the model 2 includes the same quantities and qualities of paper, energy and forest products. In consequence, the precondition for comparison – the complete equality of benefits – is fulfilled (equation 12) in contrast to other functional units [1], [5].

$$B_1 = B_2 = B_3 = P \cup E_4 \cup N_1 \quad (12)$$

3 Results

In order to assess the importance of considering the equality of all benefits, the effects of both described models on the result of an LCA are calculated. The inventory (cradle-to-grave), the impact assessment and the interpretation are performed for paper products in Europe using the two different functional units. The data of the study "Environmental Impacts of Waste Paper Recycling" [1] by Sten NILSON and Yrjö VIRTANEN (International Institute for Applied System Analysis, IIASA) are used. This study represents a Life Cycle Inventory for paper industries in Great

Britain, France, Italy, Netherlands, Austria, Germany, Sweden and Finland.

The models determine the quantities and qualities of paper (P), energy (E) and forest products (N), which have to be generated by each system. The applied method is described by SCHMIDT [7]. In impact assessment impact categories concerning global warming, acidification, eutrophication (terrestrical and aquatic), toxicity (terrestrical and aquatic) and abiotic resource depletion are used.

The result of an LCA primarily depends on the way the functional unit is formulated:

- An LCA using the model 1 as a basis for the functional unit identifies the system without paper recycling as the best ecological option. The model 1 leads to different benefits of the compared systems because of different quantities and qualities of forest products: Consumption of about 44.7 million tons of different paper products per year in the mentioned countries, generation of about 38 TWh electricity, 56.6 PJ steam and 418 PJ heat per year for all systems but different quantity of wood consumption i.e. different quantity of natural products;
- an LCA using the model 2 as a functional unit identifies the system without paper recycling as the worst ecological option. The model 2 has equal benefits which are generated by all systems (quantities as above but 51.6 PJ steam and the products of Eurpean forest which are possible in spite of 162.7 million tons of consumed wood).

The different results of these models are shown in **Figure 4**.

Using the model 1, the acidification potential rises with the recycling rate but falls with the recycling rate when using the model 2. A similar – opposite – dependency exists between other impact categories and the recycling rate (see the aggregated ecological burdens). The aggregation of the ecological burdens to one number is based on an interpretation which aggregates the impact categories by a verbal-argumentative interpretation concerning the aspects exceedances of the critical loads of ecosystems, the number of affected humans, the size of the affected area (global/regional/ local) and reversibility. This aggregation is only

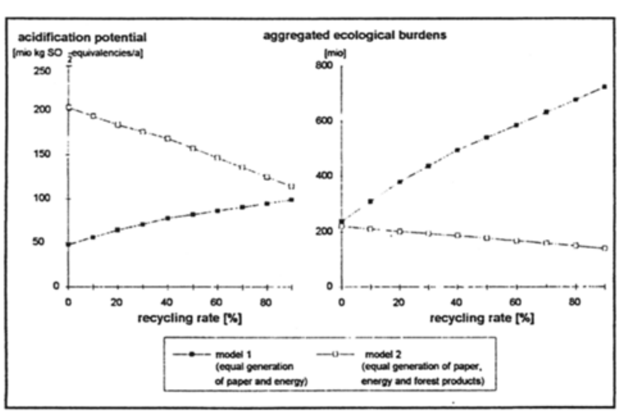

Fig. 4: Acidification potential and aggregated ecological burdens of paper consumption in 8 European countries using functional units based on different models

shown to illustrate the order of magnitude of the differences in results between the two approaches for defining the functional unit.

4 Discussion

LCA-studies with different functional units can result in opposite statements in spite of using the same data. Therefore, the standardisation of LCA will have to give clear rules for the formulation of the functional unit. The complete equality of benefits of the compared systems is the main rule for this formulation. This leads to the German wording in the DIN (German Industrial Norm) of a "funktionelle Äquivalenz" [2] (i.e. "functional equivalence") for the reference quantity.

A comparison of ecological burdens of systems causing different benefits – e.g. the energy generation and forest products beside the main benefit of "paper" (P) – is not methodically correct and is not possible (e.g. impact assessment cannot quantify nature value yet). The completely different results of LCA by using different models for defining the functional unit prove the necessity of an unambiguous standard for formulation of the functional unit: The equality of benefits. The theoretical addition of modules for energy production or the energetic utilisation of the "supplementary" wood can guarantee the comparability of systems which consume different quantities and qualities of natural, renewable materials. Thus, the model 2 is the basis for the "functional equivalence" or functional unit of an LCA for identifying the ecological recycling rate for paper production (see equation 12). Analogous functional units can be formulated for other LCA-studies which take into the regard the systems with different consumption of renewable, natural materials.

Small differences in the quality of the compared products do not influence the comparability. Otherwise, a comparison would frequently be impossible. However, this is not the subject of this article. Aside from small differences in the considered benefit (product) between the compared systems, there could be additional benefits which are principally different (e.g. paper, energy, natural benefits) and which cannot be neglected. As a rule, the number of different kinds of benefits identified is not too big, so this seems to be a practicable method.

The discussed method of equality of benefits should not be confused with the allocation problem of co-products of one process. The goal of the benefit-equality-method is to guarantee the comparability of systems with different benefits (products). The consistence of the benefit-equality method with the method of allocation for open-loop recycling [11] is verified.

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Allocation Rule for Open-Loop Recycling in Life Cycle Assessment

– A Review

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Abstract

Recycling of a product can lead to the same product or to other products. Within the Inventory Analysis of LCA, the first process is called closed-loop recycling and poses relatively small methodological problems, whereas the second, open-loop recycling, involves major allocation problems. Basically, open-loop recycling creates a new, larger system which should be treated as one system in the inventory analysis from a scientific point of view. Since this is frequently not possible, allocation rules have to be applied in order to treat one of the subsystems separately. In this review, the different allocation rules proposed are presented and discussed with respect to the criteria of mathematical neatness, feasibility and justice/incentive for both producers and users of secondary raw materials.

1 Introduction

The treatment of recycling within Life Cycle Assessment is straightforward in some cases, but difficult in others. Especially "open-loop recycling" offers unsolved problems with regard to allocation.

In the simplest case, open-loop recycling refers to a situation in which a product A, after being used, serves for the production of another product B. The product systems A and B are therefore coupled together. The same is true if low value side products are generated during the production of A which are not removed as waste, but rather reused outside the product system A. Reuse within the product system A is called "closed-loop recycling" and signifies a similar problem (which is relatively easy to solve) as the multiple use of, for instance, refillable bottles.

The problem of open-loop recycling in establishing a Life Cycle Inventory (LCI) consists of a just allocation of energy, resource depletion, emissions and wastes to the products A and B, or, in the more general case, to A, B, C etc. A scientifically unambiguous solution can only be obtained by treating the total system created by the coupling of the individual systems. This, however, is often not possible, since the products B, C, etc. are frequently not known or so numerous that the treatment of the new enlarged system would hardly be possible. In the simplest case mentioned, it would still be possible to treat the whole system if the data for both subsystems A and B is available.

There is no scientifically satisfying separation of the subsystems coupled together by open-loop recycling (SETAC 1991; BOUSTEAD 1994). A convention solving the problem by consent of the experts is also not yet in sight. Therefore, solutions have to be found which guarantee a fair distribution of the burdens and are feasible within the framework of an LCA. Different solutions have to be applied, possibly depending on the problem. The SETAC-Guidelines ("Code of Conduct", SETAC 1993) only state, "To study one of the systems in isolation, arbitrary allocation decisions have to be made"; the allocation chosen should be logical, in accordance with the aim of the study, and should be explained in the report.

2 Literature Survey on "Open-Loop Recycling"

2.1 SETAC Workshop, Vermont 1990

In the Proceedings of the 1st SETAC-LCA Workshop (SETAC 1991), "pre-consumer" und "post-consumer"

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