RECYCLING OF METALLIC MATERIALS IN LCA: RECOMMENDATIONS

CPM-report 2001:15
Report from the CPM-project Recycling

Foreword

CPM (Centre for the environmental assessment of Products and Material systems) is a competence centre established at Chalmers University of Technology in Gothenburg, Sweden, 1996. This project report is one of two deliverables from the CPM-project Recycling; the other one is Strömberg (2000) [16]. Most of work with this project was carried out during 1999. The foreword and the summary were added in December 2001, as well as some minor editorial work with the report. No changes of the text due to development of new methods etc. during the elapsed time (1999-December 2001) have been introduced. It should however be noted that the ISO 14025standard for EPD has been accepted as a technical report (i.e. not a standard) since the report was written.

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Summary

Metallic materials can be recycled with little or no quality loss, and in many cases, recycling is economically viable today and has been so historically, too. But how should this favourable recycling be accounted for in LCA studies? At present, a number of different recommendations and allocation methods for open-loop recycling have been suggested in the literature. This CPM project was initiated because it was felt that the existing methods and guidelines were difficult to interpret and apply to recycling of metallic materials in LCA. The project has resulted in a number of recommendations on how to account for metal recycling in LCA studies, depending on the purpose of the LCA:

- If the purpose of the LCA is to identify key issues in the product life cycle, the 50/50 method or an allocation method based on relations between market prices is recommended.
- If the purpose of the LCA is to compare different disposal and recycling options, system expansion is preferred. By expanding the system boundaries in an appropriate way, the effects of different options could be explored.
- If the purpose of the LCA is marketing and benchmarking, the most important thing is that the allocation method used is accepted by all involved parties.
- If the purpose of the LCA is to be basis for an environmental product declaration, (EPD), no allocation or system expansion should be performed for open-loop recycling. Instead, inflows and outflows of recycled materials to/from the life cycle of the product should be accounted as such. The production of all raw materials used in the manufacture of the product, using either virgin raw materials or scrap, should be entirely included in the present life cycle. The waste treatment after use should also be included, but not the downstream recycling process, in which the scrap is upgraded to new raw material. However, the transport of scrap to the recycling site should be included. The procedure described is essentially the cut-off method.

Introduction

In life cycle assessment (LCA) studies of, for instance, engineering industry products, it is often found that the production of metallic materials is an important source of environmental impacts. The impacts are caused by consumption of natural resources, consumption of energy, process specific emissions to air and water, and generation of waste. However, metallic materials can be recycled with little or no quality loss, and in many cases, recycling is economically viable today and has been so historically, too. Indeed, a large fraction of the metallic scrap generated, is recycled and used as a major raw material by the smelters today. Apart from avoiding consumption of ores and other minerals, recycling saves a lot of energy in comparison to production of the virgin material. For virtually any metallic material, the energy consumed for recycling is much lower than the energy for primary production. As other environmental impacts are much lower, too, recycling of metallic materials is highly beneficial from an environmental point of view.

But how should this favourable recycling be accounted for in LCA studies? At present, a number of different recommendations and allocation methods for open-loop recycling have been suggested in the literature. This CPM project was initiated because it was felt that the existing methods and guidelines were difficult to interpret and apply to recycling of metallic materials in LCA. Metallic materials, i.e., metals and alloys are, potentially, very long-lived and highly recyclable. Some of the existing methods and guidelines, on the other hand, are clearly designed for modelling of recycling of short-lived materials that are degraded on recycling. The long life of many metal products is a complicating factor in LCA, as there is no time axis in LCA, and as the consumption rate of many metallic materials is increasing (growing markets). In addition, the processes predicted to be used for recycling, secondary production and waste treatment in some remote future must necessarily be roughly extrapolated from the processes used today.

The main objective of this CPM project is to prepare guidelines for how to model recycling of metallic materials in LCA. In these guidelines, information is given regarding which allocation methods are best suited for different types of LCAs. One major issue is whether the goal of the LCA is to describe the situation today accurately, or to investigate the environmental effects of a decision or a change. There are also recommendations on how the methods should be applied. Some of the methods have been tested in LCA calculations, using LCI (life cycle inventory) data for production and recycling of metallic materials. The results of these test calculations are evaluated in this report.

Definition of terms

First, the meaning of a number of terms must be explained:

Allocation: "Partitioning the input or output flows of a unit process to the product system under study." [1] Two cases where allocation may be needed are usually distinguished in LCA: co-product allocation and open-loop recycling.

Cascade recycling: Cascade recycling means that a material in a product, after having fulfilled one function, is recycled into another function, in another product. Then, after having fulfilled the second function, the material may be recycled into a third function, and so on. In cascade recycling, it is implied that the quality of the material is reduced on recycling. Finally, the quality of the material will be so low that only waste disposal is feasible. The term cascade recycling occurs frequently in the literature but it is less suitable for metallic materials. The term open-loop recycling is favoured in this report.

Closed-loop recycling: Return of material to its original application, usually after refining. It is implied that the quality of the recycled material must be similar to that of the new material, i.e., the material is recycled without changes to its inherent properties. [3]

Co-product allocation: Partitioning the environmental impacts caused by a joint production of two or more co-products, to these co-products.

Degradation, down-cycling: The loss of quality in a material that may, or may not, occur when the material is recycled. One example of degradation is the shortening of cellulose fibres on recycling of paper products. The contamination of a metallic material by mixing of alloys and impurities on recycling can be regarded as degradation of the material. [3]

Dismantlability: The feasibility of a product to be dismantled in order to facilitate the recovery of valuable scrap materials.

Dissipation, dissipative use: The ultimate loss of a material from the technosphere back to the geosphere or biosphere, for instance, by corrosion. A typical example is the sacrificial dissipative use of zinc coatings on steel for corrosion protection. [3]

Home scrap, revert scrap: Metallic scrap generated in the plants of the material producers. Home scrap is almost always recycled internally by the smelters and it is usually not included in scrap statistics. [3]

Life cycle: "Consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal." [1]

Life cycle assessment, LCA: "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." [1]

Life cycle inventory analysis, LCI: "Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle". [1]

Multi-function process: A process that fulfils more than one function. The process may, e.g., yield two or more valuable co-products. [2]

New scrap, process scrap, prompt industrial scrap, pre-consumer scrap: Metallic scrap generated in various manufacturing operations in the industry. This type of scrap is usually sorted according to the alloy type and may be returned to the original producer, or sold to a scrap dealer. [3]

Old scrap, used scrap, obsolete scrap, post-consumer scrap: Scrap obtained from discarded, used, worn-out or obsolete products. Old scrap is usually returned to the smelters via scrap dealers and may be contaminated with unwanted elements. [3]

Open-loop recycling: Recycling of material (or energy) from the life cycle of one product into the life cycle of another. Reprocessing of scrap material to a new application. The material may, or may not, be degraded (down-cycled) on recycling. [2,3]

Primary material, virgin material: New material not used before. [3]

Primary production, virgin production, ore-based production: Production of a material from mainly virgin (primary) raw materials, e.g., production of aluminium from bauxite ore. [3]

Product system: "Collection of materially and energetically connected unit processes which performs one or more defined functions." [1]

Raw material: "Primary or secondary material that is used to produce a product." [1]

Recyclability: The feasibility of a material used in a product to be recycled when the product is disposed of. Note that recyclability for a metallic material is mainly determined by the application, i.e. the design of the product, as metallic materials are inherently recyclable. The reasons why not all metallic scrap available is recycled are technical and economic considerations. These considerations are included in the term "recyclability". [3]

Recycling: Reprocessing or upgrading of scrap to a quality that can be used in secondary production of new material. Sometimes, the term recycling is used in a more general meaning, including also secondary production. In this report, however, the following operations are included in the term recycling: collection, sorting, fragmentation, separation and transport of the scrap material to secondary producers. See also "secondary production". [3]

Recycling rate: The recycling rate for a material can be defined as the overall percentage that is recycled, out of the total quantities of the scrap material that are theoretically available in a specified geographical area or in some other specified system during a certain time. [3] Obviously, it is impossible to calculate the theoretically available quantities of scrap material accurately. Instead, alternative definitions of "recycling rate" are also used: The percentage of recycled material that is used in the production of new material, or the percentage of secondary material that is consumed, for instance, in a specific country during one year. Export and import of materials make the statistical data more complicated to comprehend. In some statistical publications, the amounts of new and old scrap are presented separately, but not in other publications. The recycling rate for old scrap is a function of the mix and lifetime of the products in which the material is used. For a material with a high consumption growth rate and a relatively long average lifetime, the recycling rate according to the latter definitions may be low even if almost 100% of the theoretically available quantity of scrap is recycled. For specific product systems, still another definition of recycling rate may be used: If the average number N of subsequent uses of a material in a specific application, e.g. a cellulose fibre in paper, is known, then the recycling rate R can be calculated as $R=(N-1)/N$. Nevertheless, the first definition is used throughout this report, i.e. the percentage of the material that has been used in products included in the system under study, and is recycled.

Scrap: Recovered material, either previously used in products that have been disposed of (old scrap), or residual material from manufacturing processes (new scrap and home scrap). The raw material into a secondary (scrap-based) production.

Secondary material: Material that has been used before, in another application, but which has then gone through recycling and secondary production. Note that the term "secondary" denotes origin, not quality. The quality may sometimes be equal to that of virgin material. [3]

Secondary production, scrap-based production: Production of a new useful material from scrap materials. In this report, collection, sorting, fragmentation, separation and transport of the scrap material to secondary producers are not included into secondary production. See also "recycling". [3]

System boundary: "Interface between a product system and the environment or other product systems." [1]

System expansion: Expansion of the system boundaries in order to include one or several other processes into the product system.

Unit process: "Smallest portion of a product system for which data are collected when performing a life cycle assessment." [1]

Virgin material: See "primary material". [3]

Characteristics of metallic materials

There are some characteristic features of metallic materials with respect to recycling, features that should be considered in the modelling of recycling in LCA:

- All metallic materials are inherently recyclable, but whether the material used in a specific application actually will be recycled, depends on technical, economic and political factors. For this reason, the recycling rate of used aluminium beverage cans is fairly high in many countries, while the recycling rate of aluminium packaging foil is low.
- Alloys of fairly similar composition could be used in very different applications having vastly different operation lifetimes. Depending on the application, the economic values of the resulting scrap materials could be very different. In some cases, contamination of the material with, for instance, soldering or brazing alloys could lower the scrap value. In other cases, it may be difficult or costly to dismantle the product, e.g., an old building or a shipwreck.
- There are many different scrap classes for each metal. Metal scrap is sorted according to alloy type, purity, size and homogeneity of the scrap. Scrap prices for different classes may differ quite a lot and fluctuate over time. The relations between prices for different classes and the corresponding new material may also vary over time.
- The economic value of many metals and alloys is large also as scrap, which renders recycling rather profitable. Stainless steel alloys, nickel alloys, copper alloys and noble metals belong to this group.
- Also metals with high economic values could be lost during operation, or due to low collection rates of scrapped products or inefficient recovery rates in the recycling processes. A thin gold or silver layer on contacts is one such example.
- There are applications in which metals are supposed to be dissipated during use. The typical example is the use of zinc coatings on steel for corrosion protection. The zinc metal is partially lost during the use phase of the product, and the residual zinc in the coating is oxidised to zinc oxide and collected as dust when the steel is remelted. Although this re-

sidual zinc can be recovered from the dust, much of the benefit of recycling is lost, as the metal is oxidized and mixed with other elements.

- There is a large potential for saving energy and, thus, avoiding emissions, by recycling metallic materials. The reason for this is the relatively large energies required for mining and refining of metals.
- For some metallic materials, e.g. aluminium, there are production plants that use 100% primary (virgin) raw materials, although some producers add a portion of scrap to the virgin raw materials in the process. For copper, steel and many other metals, a proportion of scrap is typically mixed with virgin material at some stage of the primary production process. In addition, there are secondary (scrap-based) smelters that only use scrap raw materials (plus small amounts of alloying elements). For stainless steel and brass alloys, primary production is rare. Instead, the new materials are mainly produced from scrap (including low alloy steel scrap and copper scrap, respectively) plus relatively small amounts of virgin alloying elements. In conclusion, only for a few of the main metallic materials, LCI (life cycle inventory) data for both a 100% primary production process and a 100% secondary production process could be obtained directly. This means that, if such hypothetical LCI data are needed for a certain allocation method in LCA, they have to be constructed by some allocation procedure for most metallic materials.

An illustrative example of the life cycle for a metallic material

In Figure 1, an attempt has been made to describe the complete life cycle of a material, in this case: zinc coated (galvanised) steel. Although the flowchart may look complicated, a number of flows of raw materials, energy carriers, by-products and wastes have been left out. Most importantly, it is assumed that the product is composed of only one material, zinc-coated steel, while real products normally contain several materials. Figure 1 illustrates a number of characteristic features of metallic materials, with respect to recycling:

- The use phase of the product may last for many years. Therefore, the processes used in the manufacture phase may have become obsolete at the time of scrapping and recycling. In addition, the market prices for scrap and new materials will change during this time in a way that is impossible to predict. As the market price reflects the demand for the scrap, the future unknown prices will determine whether the material will be recycled at all, or not.
- The life cycles of several metals may be entangled, by alloying, coating or joining. In this case, the steel sheet is coated with a zinc layer for corrosion protection. Part of the zinc is lost to the environment during the use phase of the product, while the residual zinc is oxidised to zinc oxide in the EAF (electric arc furnace) steelworks. The zinc oxide is usually recycled to the zinc smelters.
- A distinction is made between 1) home scrap and new scrap that is returned to the steelworks, in which the metal was produced, and 2) new scrap and old scrap that is sold to the recycling industry ("the market"). The latter scrap may be used as a raw material by secondary (scrap-based) steelworks, but it may also be used by other primary (ore-based) steelworks. In the first case, it is indicated in Figure 1 how recycling could be modelled in an LCA, as the scrap steel is brought back to the steelworks, by the arrows, in closed loops. In genuine "closed-loop recycling", it is implied that the scrap material is returned to the original producer within a relatively short time, and that the properties of the material after processing will equal the properties of the new material produced by the plant.

In LCA calculations, closed-loop recycling is fairly simple: The amount of material actually used in the product accounts for the environmental load due to the cradle to gate production of that amount of material. The same applies to any amount of material lost to the environment or treated as waste. On the other hand, the amount of material removed by cutting, drilling or other manufacturing operations, collected and promptly returned to the producer, only accounts for the environmental impacts (energy consumption, emissions etc) caused by the collection, transport and reprocessing (i.e. remelting, refining, rolling etc) operations. Hence, it will always be favourable, also in an LCA, to produce as little waste material as possible. It should be noted that closed-loop recycling does not cover scrap sold to the open market (open-loop recycling).

New and old scrap sold to the recycling industry, upgraded and then further sold to other smelters, producing other semi-products, at a later time, is the case referred to as "open-loop recycling". The rest of this report will mainly deal with open-loop recycling.

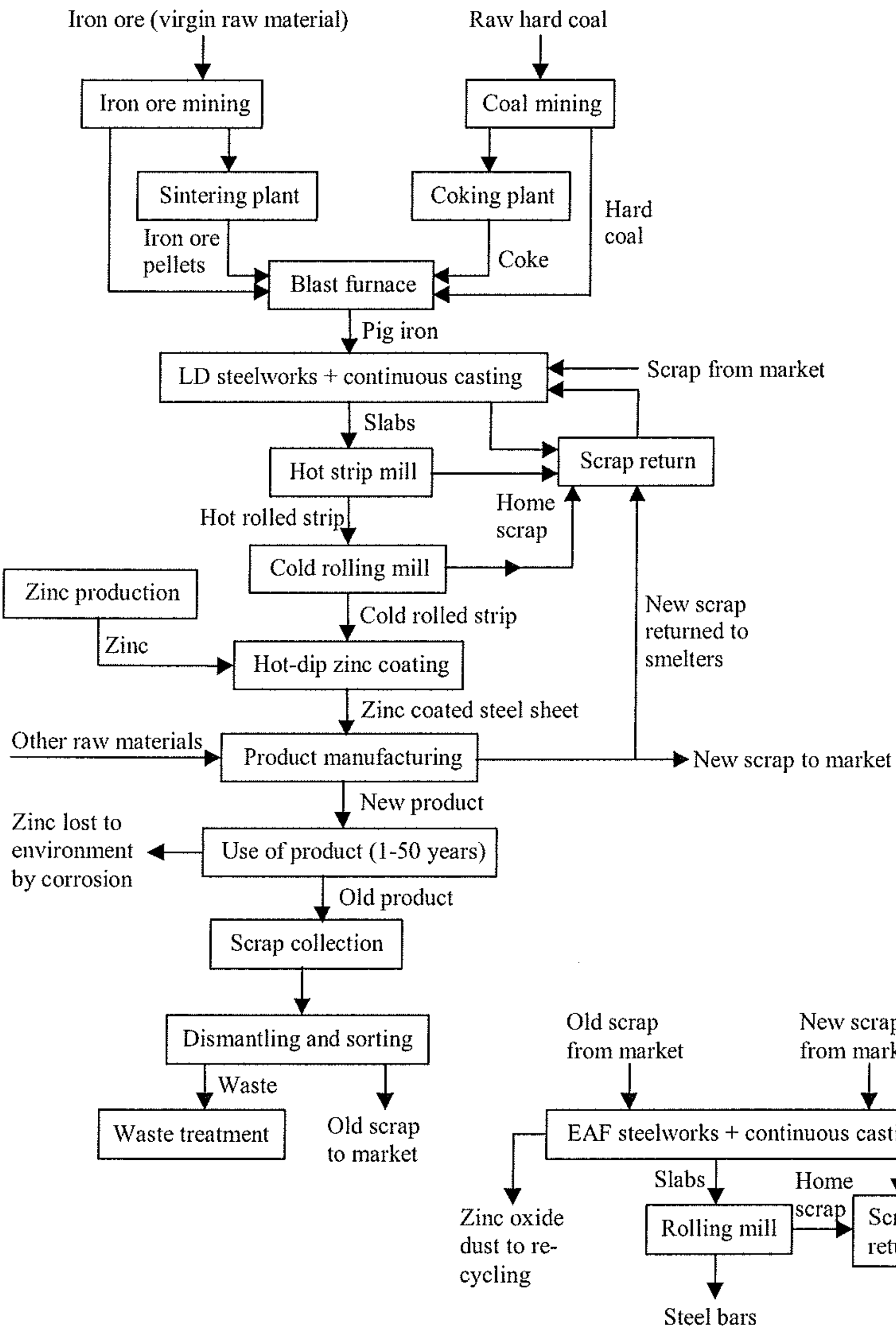

Figure 1. Production, use and recycling of steel, a simplified flowchart.

Treating the open-loop recycling allocation problem in LCA

In Figure 1, there is a presentation of open-loop recycling. The reason why an allocation problem due to open-loop recycling sometimes arises in LCA, is that we want to allocate the environmental impacts for a larger system to a specific product. In this case, open-loop recycling makes the boundaries between two (or more) product life cycles ambiguous. Should the recycling processes belong to the upstream or the downstream life cycle? Should some credit be given to a product that is designed to give a high recyclability after use? Or should rather a product containing a large proportion of recycled material be given a credit? In LCA, open-loop recycling can be treated in different ways, reflecting different aspects of the problem. Note that there will not always be an open-loop recycling problem. As illustrated in Figure 1, recycling of home scrap and new scrap can sometimes be regarded as real closed-loops. In addition, there are LCAs for which the goal is such that there need not be a system boundary in connection with recycling.

Still, in cases where there is an open-loop recycling ambiguity, it is common to make a distinction between approaches to avoid allocation, and allocation methods.

In the schematic figures shown in the following sections, it is assumed that the product contains only one material and that this material can be produced either from virgin raw material or from scrap. After use, the scrap material may be recycled or treated as waste.

Approaches to avoid allocation

There are two methods or approaches to avoid allocation that have been employed frequently in LCAs: the closed-loop recycling approximation and system expansion. However, it may be argued that, by choosing and applying one of these methods, a kind of allocation is still performed.

Closed-loop recycling approximation

In a narrow definition, closed-loop recycling applies to materials that are recycled in the same product system, i.e., in the same application. [4] Home scrap produced in smelters or semifabricating plants and reprocessed back to new material in-house is a typical closed-loop recycling case (see Figure 1).

In a wider definition, open loop recycling of all materials that are recycled with insignificant loss of relevant properties (quality) could be approximated with a hypothetical closed-loop system. [4,11] Such a system is shown in Figure 2. In this system, the amount of recyclable scrap generated by dismantling of the product, is assumed to be equal to the amount of scrap entering the Material production process. If this is not the case, there will still be an allocation problem. The recycling rate of the closed-loop can then be defined either by the rate by which the material is recycled after use, or by the share of recycled material in the product. [7] It has been suggested that the alternative that gives the highest recycling rate should be used. [7]

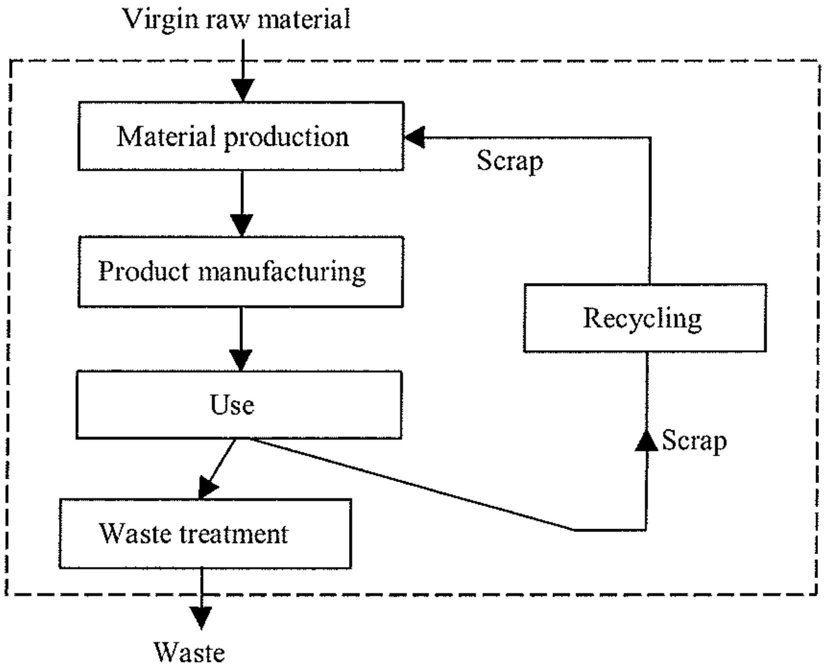

Figure 2. The closed-loop approximation. It is assumed that the amount of recyclable scrap generated by dismantling of the product, is equal to the amount of scrap entering the Material production process. Thus, only the amount of material converted to Waste has to be replaced with Virgin raw material.

System expansion

In the system expansion method, the product system boundaries are expanded to include an alternative production of the material. [7,14] In Figure 3, the downstream Recycling and Secondary production processes have been included in System 1. The product of the Secondary production process, New material, is considered to be a valuable by-product of System 1. An alternative way to produce New material is by the primary production route in System 2. The environmental impacts of System 2, corresponding to the same amount of New material as in System 1, are then subtracted from the environmental impacts of System 1.

If, in an alternative case, a proportion of scrap material is used as a raw material in the Material production process, the system may instead be expanded to include the production of this scrap material, by a hypothetical primary production route.

A crucial question in the system expansion approach is, if it should be assumed that the recycled material replaces material of the same kind produced from virgin raw material, or material produced from a market-based mix of virgin and scrap materials.

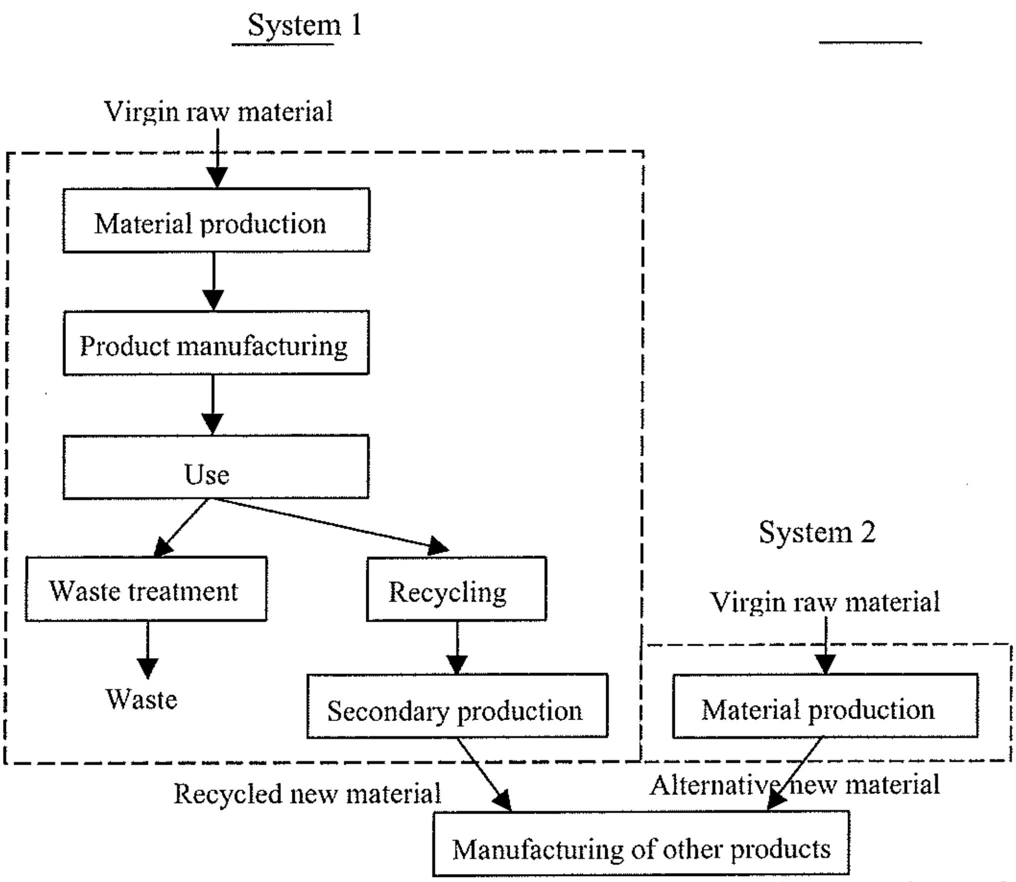

Figure 3. The system expansion approach. The environmental impacts for production of New material in System 2 are subtracted from the impacts of System 1.

Rules based on market considerations have been proposed for how system expansion should be performed in open-loop recycling and other cases. [14] It is stated that the key issue is what determines the scrap collection rate and, consequently, the degree to which the scrap will be utilised in a subsequent life cycle. Two cases are distinguished: In an expanding market for the material, which is the case for most metals, it is predicted that all collected scrap will be used for production of new material. The collection rate will be controlled by the marginal cost for collection relative to the marginal cost for primary production, according to ref. [14]. In a shrinking market, on the other hand, some of the available material will be deposited due to insufficient demand. This is the case for cadmium today, and perhaps for some other heavy metals as well.

For expanding markets (case 1), it is recommended that the upstream life cycle supplying the scrap should be given credit for the primary production displaced on the market by the new material produced from the scrap, as in Figure 3. The recycling and secondary production should be fully attributed to the upstream life cycle. The downstream life cycle receiving the scrap should be ascribed the displaced primary production, instead of the actual scrap-based production. [14]

For shrinking markets (case 2), it is recommended that the upstream (supplying) life cycle should account for the avoided waste treatment of the scrap being recycled, but should not be given any credit for displaced virgin production. [14] The downstream (receiving) life cycle should be attributed the recycling and secondary production, but no primary production. In addition, the downstream life cycle should be given credit for the avoided waste treatment of the scrap.

For a cascade recycling case, where the total environmental impacts for all life cycles in the cascade are known, the sum of the impacts for the separate product life cycles, each calculated by a system expansion approach, normally does not equal the total. This may be regarded as a problem in some situations.

Presentation models useful in the discussion of allocation methods

The closed-loop recycling model

See Figure 2 above.

The cascade model

In the cascade model, the material is assumed to be used in several consecutive product life cycles, see Figure 4. In each life cycle, a degradation or down-cycling of the material by the Use and Recycling of the material may or may not be implied. This model is frequently used when open-loop recycling in LCA is discussed. [5] Note that the average number of consecutive life cycles, N, is related to the assumed recycling rate, R, in a closed-loop recycling model, as $R=(N-1)/N$.

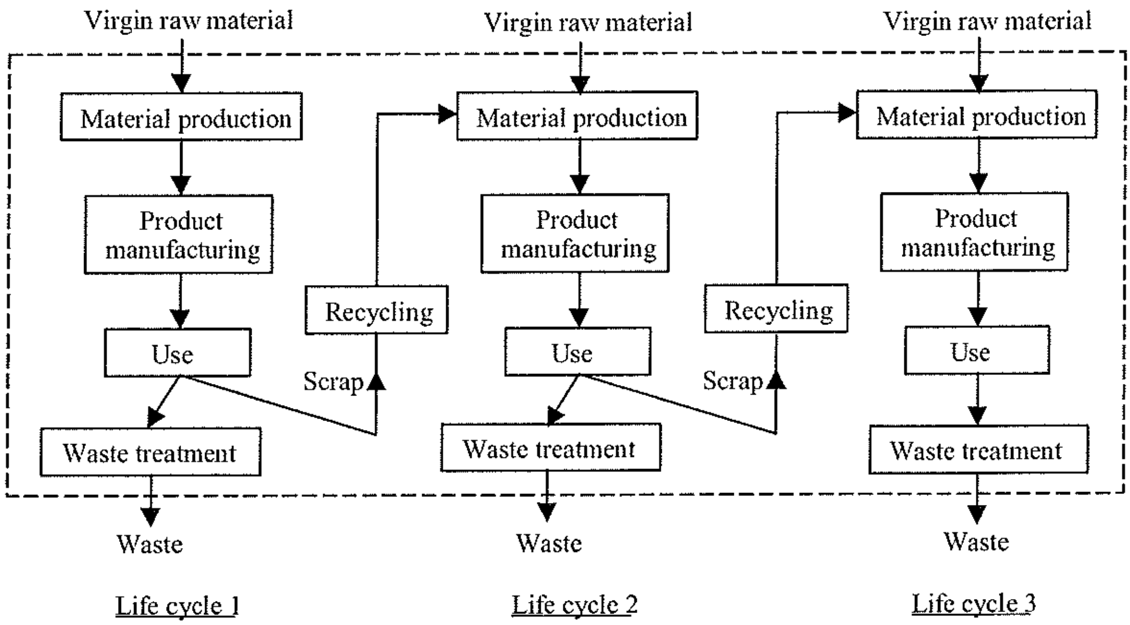

Figure 4. The cascade model. In this case, only three life cycles are included. For simplicity, the inflows of Virgin raw material into Life cycles 2 and 3, and the outflows of Waste from Life cycles 1 and 2, are sometimes omitted.

The material pool concept

In the material pool concept, material pools situated outside the product system are introduced, as illustrated in Figure 5. [6] Either the upstream or the downstream Recycling process is included in the system. An "environmental value" is attributed to the material in the pool. Different methods have been suggested for deciding the "environmental value" of a material. One option could be to use the difference between the environmental impacts for virgin material production and recycling, respectively. If the quality of the material is different in different pools, the "environmental value" must be different, too. A fee must be paid if material is taken from a material pool, while delivering material to a pool results in a credit.

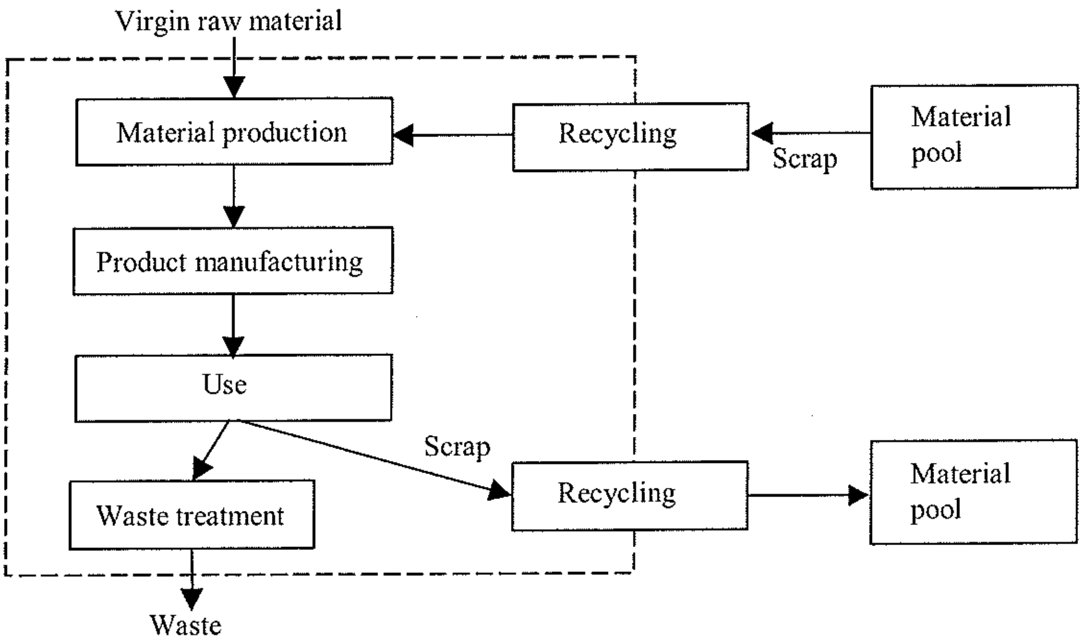

Figure 5. The material pool concept. Either the upstream or the downstream Recycling process is included in the product system.

Allocation methods suggested in the literature

In the literature, a number of methods or philosophical principles have been suggested for allocation of open-loop recycling in LCA. [5,7,8] Most of these methods are based on different ideas about what a "fair and intuitively reasonable" allocation procedure is. The main concepts are reviewed below:

The cut-off method

This is probably the easiest method to apply. The underlying idea is that the studied product should only be assigned those environmental impacts that are directly caused by the product. [5] Usually, the impacts of recycling processes are allocated downstream but, in some cases, part of the recycling processes (e.g., collection and transport of scrap) may be allocated upstream. Impacts for production of raw materials used in the manufacture of the product are entirely allocated to the product, regardless if the materials are produced from virgin raw materials or scrap. Impacts due to waste treatment other than recycling are allocated to the product. See Figure 6.

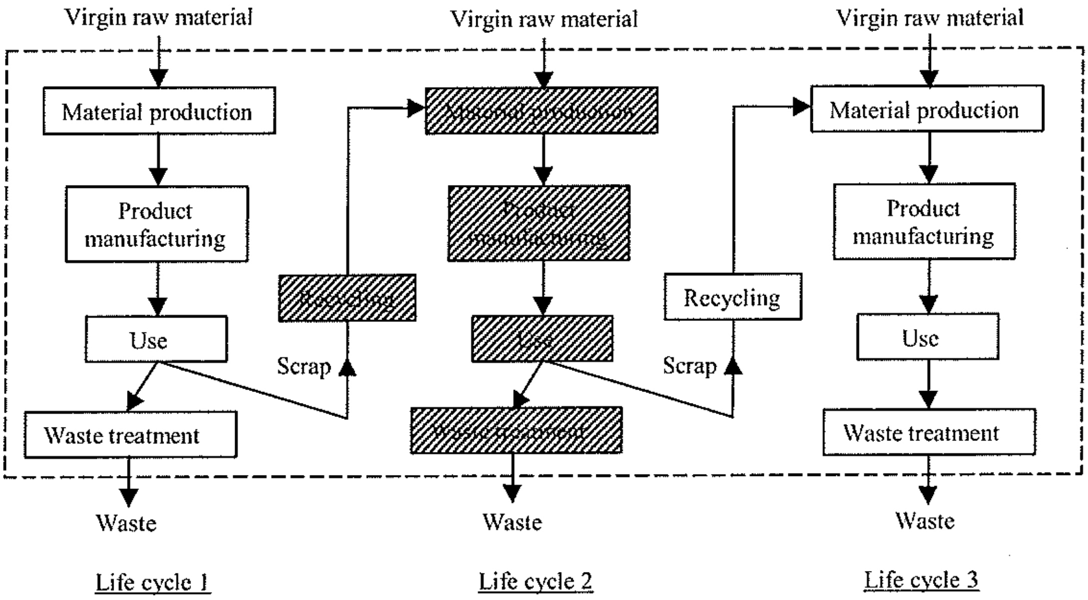

Figure 6. Processes wholly (dark shaded boxes) allocated to Life cycle 2 in the cascade model, according to the cut-off method.

Advantages: Easy to apply. No data from outside the life cycle of the present product are required. Arbitrary allocation is avoided. Data for separate virgin production and recycling processes are not required, thus, real data for production of most metallic materials can be used without manipulation of data.

Disadvantages: No real allocation is made. No benefits from recycling of the materials in the product after use are accounted for. However, benefits from using recycled materials instead of virgin materials are included.

The extraction-load method

The extraction-load allocation is based on the idea that all raw materials that are extracted from the geosphere or biosphere will end up as waste finally. [5] Therefore, it may seem fair that final waste management should be allocated to the product that uses virgin materials. No benefits from recycling of the materials after use of the products are given.

Advantages: The method promotes the use of recycled materials, providing that the impacts of recycling are less than the impacts caused by virgin production and final waste management together. This is generally the case for metallic materials.

Disadvantages: The method does not encourage production of recyclable products. Knowledge about the impacts for final waste treatment is required. It is not a widely accepted method.

The disposal-load method

The disposal-load allocation is based on the idea that all materials lost from the technosphere must be replaced through virgin material production, otherwise the amount of material available in the technosphere would be reduced. [5] Hence, virgin material production should be allocated to the product life cycle, in which the material is lost from the technosphere as waste.

Advantages: The method encourages production of recyclable products, providing that the impacts of recycling are less than the impacts caused by virgin production and final waste management together. This is generally the case for metallic materials.

Disadvantages: The method does not give any credit for using recycled materials. Knowledge about the impacts for original virgin material production is required. It is not a widely accepted method.

The 50/50 method

The 50/50 method is based on the idea that both supply and demand for recycled material are needed to enable recycling. [5,11] The environmental impacts for the following processes in a cascade of several life cycles should be allocated: 1) virgin production of material that is used in more than one product life cycle; 2) waste management of material that has been used in more than one life cycle; 3) recycling processes shared by an upstream and a downstream life cycle. The 50/50 method allocates each of these impacts equally between the life cycles involved. Impacts caused by materials not shared by several life cycles are not allocated. See Figure 7.

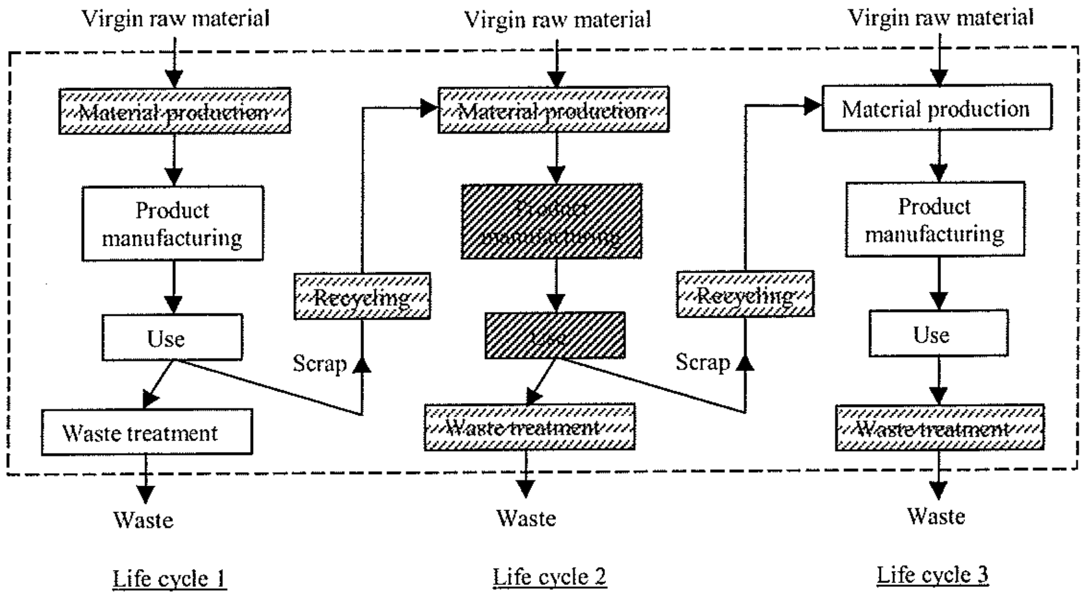

Figure 7. Processes wholly (dark shaded boxes) or partially (partly shaded boxes) allocated to Life cycle 2 in the cascade model, according to the 50/50 method.

Advantages: The method encourages both the use of recycled material and the production of recyclable products. Since all processes that, by some means, contribute to the environmental impacts related to the material are included, the 50/50 method may be useful in the identification of key issues in LCAs. Double counting is avoided.

Disadvantages: The method is based on an arbitrary number (50%). Knowledge about the impacts for both original virgin material production and final waste treatment is required. Therefore, the method might be difficult to apply. It is not a world-wide accepted method.

Allocation based on quality reduction

At least two fairly similar methods have been proposed that are based on quality reduction. [5] The method recommended by the Swedish Product Ecology Project and used in the EPS (Environmental Priority Strategies in Product Design) system recognises that man-made materials are valuable resources, that virgin material production is required to obtain this resource, and that a recycling process is needed to upgrade the quality of the material after use. In practice, this means that original virgin production of the material is allocated to the different product life cycles according to the reduction in quality of the material in each life cycle. The recycling process is wholly allocated to the upstream life cycle. The final waste management is allocated to the life cycle where it occurs.

In the method used and recommended by the Danish EDIP (Environmental Development of Industrial Products) project, also final waste management is allocated to the different product life cycles according to the loss of quality.

Advantages: The methods could, in principle, be applied both to materials that undergo substantial quality reduction on recycling, and materials that do not. In the case of a metal that is recycled back to its original quality (i.e., no quality loss), both the methods are reduced to the disposal-load method presented above.

Disadvantages: There is no general and commonly accepted definition of "quality". In reality, the economic value (i.e., the market price) is, probably, the only parameter that could be used as a quality indicator. These methods have not reached any world-wide acceptance.

Allocation based on relations between market prices

Instead of quality, economic value could be the basis for an allocation method. [13,18] The economic value of a material is normally represented by the market price at a selected time. If the market price of a scrap material is close to zero, or even negative, it is likely that the recycling of the material is rather a kind of waste treatment. In this case, the environmental impacts from the original virgin material production and the upstream recycling process, respectively, should not be allocated to the user of recycled waste material.

It has been suggested that the environmental impacts for virgin material production in a previous life cycle and upstream recycling, respectively, should be allocated to the present product life cycle in proportion to S1/M1, where S1 is the upstream value of the scrap material and M1 is the value of the original new material. [13] The impacts for virgin material production in the present life cycle and downstream recycling, respectively, should be allocated to the present life cycle in proportion to (1−S2/M2), where S2 is the downstream value of the scrap material and M2 is the value of the new material in the present life cycle. In addition, the environmental impacts should be corrected for the recyclability of the material in each of its applications, i.e., the fraction of the material that is estimated to be recycled after use. This should apply to other allocation methods as well.

Advantages: As allocation based on economic value is mentioned as one option in the ISO 14041 standard, this method and other methods based on economic value may gain acceptance.

Disadvantages: Market prices vary vigorously over time. It may be a time-consuming task to find accurate prices for both new material and different scrap categories.

Recommendations in the ISO 14041 standard

In the ISO 14041 international standard, section 6.5.4 is about "Allocation procedures for reuse and recycling". [4] First, it is said that the general allocation principles and procedures in sections 6.5.2 and 6.5.3 also apply to reuse and recycling. The principles in section 6.5.2 are:

- "the study shall identify the processes shared with other product systems and deal with them according to the procedure presented below;"
- "the sum of the allocated inputs and outputs of a unit process shall equal the unallocated inputs and outputs of the unit process;"
- "whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach."

It is also stated that the allocation procedure used "shall be documented and justified".

The stepwise procedures presented in section 6.5.3 are:

1. "Wherever possible, allocation should be avoided by: 1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes; 2) expanding the product system to include the additional functions related to the co-products..."
2. "Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them; i.e. they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system..."
3. "Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way which reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products."

Comments: These procedures have been criticized because division into sub-processes (procedure 1:1) does not reduce the allocation problem, and allocation based on physical causality (procedure 2) is not applicable to open-loop recycling. [2] Thus, only system expansion (procedure 1:2), or allocation in proportion to the economic value or some other property (procedure 3), could be applied to open-loop recycling in LCA. Furthermore, the paragraph "the sum of the allocated inputs and outputs of a unit process shall equal the unallocated inputs and outputs of the unit process" may disagree with the recommendation of system expansion.

In section 6.5.4, it is stated that "changes in the inherent properties of materials shall be taken into account" in the case of reuse and recycling. The closed-loop allocation procedure is explained:

- "a closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems, where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials. However, the first use of virgin materials in applicable open-loop product systems may follow an open-loop allocation procedure outlined below;"
- "an open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties. The allocation procedures for the shared unit processes mentioned in 6.5.3 should use, as the basis for allocation: – physical properties; – economic value (e.g. scrap value in relation to primary value); or – the number of subsequent uses of the recycled material".

Comments: According to the ISO standard, the closed-loop approximation could be applied in most open-loop recycling situations where metallic materials can be recycled without significant loss of quality. Note the three suggested bases for allocation of shared processes, i.e. physical properties, economic value (e.g. scrap value in relation to primary value) or the number of subsequent uses of the recycled material (what is meant by this?).

A principal objection to the ISO 14041 recommendations for open-loop recycling is that the same ranking order of allocation procedures is recommended for all LCA applications, regardless of the goal of the LCA study. [5]

Recommendations in Nordic Guidelines

In "Nordic Guidelines on Life-Cycle Assessment" from 1995, there are some general recommendations for how to treat the open-loop recycling problem in LCA: [11]

A. "The relative importance of every single allocation "case" is evaluated by allocating 100 percent (which is the maximum burden) to the product under study."
B. "If this does not affect the results (qualified judgement, or based on an initial calculation), a conservative approach keeping 100% of the burden, should be applied."
C. "If the allocation is found likely to affect the results, then evaluate the possibility of expanding the system boundaries. This should include the life cycles of all the open-loop flows to and from the life cycle under study. Alternatively, if appropriate, carry out the calculation as if the recovered material is used /in the place of/ (substituted for) primary materials in the life cycle under study, i.e. as if closed-loop recycling was taking place. If that is not possible, then use the allocation procedure detailed below."

Then, an allocation procedure is suggested:

1. "Allocate based on qualitative natural causality models, if not possible,"
2. "Allocate using the 50/50 method ... in "key issue identification" LCAs, if other approaches are not dictated by the goal and purpose of the study..."

About the 50/50 method, it is said that it is "not necessarily better than any other suggested method. It does, however, ensure that information on "key issues" is not lost in cascade coupled recycling systems. It is therefore recommended for "key issue identification" LCAs, however not necessarily for other types of application."

General recommendations

The following criteria for a good allocation procedure have been presented. [5,8,10] The procedure should be:

- in accordance with the goal of the LCA;
- acceptable to the people using the LCA results;
- easy to apply;

Moreover, the allocation procedure should have a consistent internal logic, avoid double counting, be possible to perform at a low level of information about the actual use or origin of scrap materials, and give incentives for both use of secondary materials and recycling of materials after use.

Most likely, there is not a single allocation method that fulfils all the criteria listed above. Instead, certain criteria may be more important in different kinds of LCA studies.

Recommendations for different kinds of LCA studies

It has been argued that the choice of allocation method must be consistent with the goal of the LCA. [5] It has been recognised that there are two types of LCAs, with respect to the goal: cause-oriented or retrospective, and goal-oriented or prospective. In cause-oriented LCAs, the main objectives are to describe the environmental impacts of a system as correct as possible and to find the causes of its most significant impacts to the environment. In a goal-oriented LCA, on the other hand, the primary objective is to find out the consequences of a decision or a change in the system.

Product improvement, key issue identification

The 50/50 method was recommended for "key issue identification" LCAs in the "Nordic Guidelines on Life-Cycle Assessment". [11] Perhaps an allocation method based on relations between market prices could serve this purpose equally well.

Comparison of different disposal and recycling options

In this case, system expansion is preferred. By expanding the system boundaries in an appropriate way, the effects of different options could be explored. "If the goal of the LCA is to support decisions that affect inflows or outflows of cascade material, it is important that the procedure be based on effect-oriented causalities." [5]

Marketing and benchmarking

For comparison of products and marketing, the most important thing is that the allocation method used is accepted by all involved parties. [5,10] The parties may, for instance, be a producer and a customer of a product. In practice, the need for a mutually acceptable allocation method may favour the use of the procedures given in the ISO 14041 standard. In some cases, however, the parties could agree on other allocation methods. A manipulative use of allocation methods in order to make the company's product look better is, of course, strongly discouraged. Such manipulation could seriously damage the status and reputation of LCA.

Environmental product declarations (EPD)

Environmental product declarations (EPD), which are sometimes referred to as Type III ecolabels, are based on product LCAs. The ISO 14025 standard for EPDs is not yet issued, however, there are some guidelines for how EPDs should be prepared. [9,10,12,15] In these guidelines, it is recommended that no allocation or system expansion is performed for open-loop recycling. Instead, inflows and outflows of recycled materials to/from the life cycle of the product should be accounted as such. The reason for avoiding open-loop recycling allocation is that the data should be as unperturbed or "pure" as possible, in order to facilitate the use of EPD data in LCA studies of other product systems.

According to the guidelines, the production of all raw materials used in the manufacture of the product, using either virgin raw materials or scrap, should be entirely included in the present life cycle. The waste treatment after use should also be included, but not the downstream recycling process, in which the scrap is upgraded to new raw material. However, the transport of scrap to the recycling site should be included. [9]

Comments: The procedure described is essentially the cut-off method.

Further reading

For further information about principles for allocation at cascade recycling, see Ekvall (1994) [17] and Rydberg [19], which also provides calculated results to illustrate the consequences of different choices.

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