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A flowsheeting approach to integrated life cycle analysis

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Abstract

The objective of life cycle analysis is to determine the total environmental impact of any given product. The paper addresses the problem of branched production chains incorporating multi-product plant and inter-process recycle (or reuse). We show that in such chains no product can be assigned an unambiguous environmental impact. Furthermore, the traditional approaches to LCA can lead to some environmental impacts being assigned multiple times and others omitted altogether. The paper introduces the important mass-balance principle that the sum total of all actual environmental impacts should equal the sum total of impacts assigned to the range of products. We describe a method for ensuring material balance in integrated LCA over a multi-product branched production chain. The method is illustrated by application to a desulphurization process. The method allows operators to assign environmental cost to any product according to their own judgement. The judgement is akin to assigning costs to individual products from a multi-product facility. Nevertheless, no matter how the judgement is applied, material balance must be maintained. It is noted that nearly all production chains include multi-product facilities. Environmentally, multi-product facilities are frequently superior because they minimize waste production. However, in traditional LCA, such processes may score badly because their full environmental cost is assigned to more than one product stream. The methods put forward correct the imbalance.

A note on recycle and reuse. The chemical industry differentiates between recycle and reuse. “Recycle” is applied to reuse within the same process. For example, unconverted raw material recycled to a reactor. The process design ensures that the recycled material is used on site without transportation, and that the production is exactly balanced with the use. “Reuse” is use of the waste from one process as an input to another process. Reused material may need to be transported and may need preliminary processing before it can be reused. Under this definition, domestic recycled waste is actually reused waste (such as reused waste paper). We follow the convention of differentiating between reuse and recycle.

Keywords: LCA; Multi-objective optimization; Design; Analysis

1. Introduction

Traditional life cycle analysis methods [1,2] find difficulty in assigning environmental costs to individual products from multi-product processes. There is a similar problem in assigning costs to streams that are partly reused and partly sent to waste. Multi-product processes are frequently environmentally efficient processes because materials that would otherwise be waste become useful co-products or by-products. The challenge for life cycle analysis is to determine how to distribute environmental costs between the product streams. For example, how are energy costs divided in the process to manufacture chlorine and sodium hydroxide from electrolysis of brine? Unless the same person conducts the LCA, the LCA for glass (that uses sodium carbonate made from sodium hydroxide) may take all or none of the energy cost for the sodium hydroxide production step. Similarly, the LCA for a chlorinated dry-cleaning fluid, or the chlorinated domestic water supply, may take all or none of the energy cost for the chlorine production step. There is a similar problem with reused material. What environmental credits, if any, are assigned to the reuse? What environmental costs in transportation and pre-processing are charged? The calculation is straightforward if we count only one environmental cost, such as energy, and there is only one source of the waste. However, if the waste is multi-sourced from quite distinct processes and carries a range of environmental costs (global warming gases, acid gases, heavy metals, etc.), the problem cannot be solved for any one facility in isolation.

The problem can be solved if the whole production network of inter-linked products and processes is considered in an

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integrated way. The principle is developed in Section 2 below. A logical outcome of Section 2 is that no LC cost can be assigned to one product without assigning a LC cost to every product and process. The task clearly becomes impossible on a product-by-product basis. Nevertheless, the section shows how environmental costs can be accumulated incrementally, process by process. It enables total life cycle costs to be accumulated without knowledge of more than one process at a time. Section 3 illustrates a practical application of the mass-balance approach. In Section 4, we outline how the approach could be adapted for an integrated programme for pollution minimization.

2. An integrated approach to estimation of environmental costs

In this section, we consider the conditions under which unambiguous environmental costs can be derived for products, and those conditions under which it is impossible to assign environmental costs unambiguously. In Section 2.1, we consider production chains in which each process has a single product. For such production chains, material balance enables environmental costs to be assigned unambiguously. Section 2.2 considers production chains including multi-product plant. It is shown that environmental costs cannot be assigned unambiguously to individual products. However, material balance enables us to assign environmental impacts consistently. A general formulation is presented together with specific assignment formulae. Section 2.3 shows that the consistent mass-balance approach applies equally for recycle between processes. Section 2.4 considers pollutants as products and Section 2.5 considers the special cases of reused waste, stored waste and fuel products. Section 2.6 summarizes the "cradle-to-grave" applicability of the approach. We emphasize that there are many arbitrary choices that must be made, but these have a marginal impact on the assessment of environmental impact over the whole range of products.

2.1. Processes with single product streams

Fig. 1 illustrates a production chain in which traditional LCA can be applied successfully. Raw materials R_1 enter a process for conversion to an intermediate product S_1. The process releases materials E_1 to the environment. The vector of materials E_1 is made up of an array of individual pollutants $\{e_{11}, e_{12}, e_{13}, \ldots\}$ which have harmful environmental impacts. The product S_1 goes as raw material to a second process in which it reacts with a second intermediate S_2 to produce a product P.

The life cycle cost of product P is computed as follows. Assume that the flows S_1, e_{11}, e_{12}, etc., are measured in tonnes/h. We assign the environmental cost of pollutant "i" (in tonnes of pollutant/tonnes of product) the value:

$$c_{1i} = \frac{e_{1i}}{S_1}$$

The costs are similarly assigned for process 2. The total environmental burden carried by process 3 is then the sum of the input burdens and the pollution directly caused by the current process, namely:

$$t_{3i} = S_1 c_{1i} + S_2 c_{2i} + e_{3i}$$

The resulting environmental cost of the product P for pollutant "i" is

$$c_{3i} = \frac{t_{3i}}{S_3}$$

It immediately follows that the total environmental burden assigned to product P is the sum of the actual pollution rates caused by all the processes in the production chain to make P. This mass-balance characteristic is valuable to product users. If users compare two products, they can be assured that the life cycle impacts assigned to each fairly reflect the relative burden that each places on the environment.

Using the same approach, it is readily shown that the mass-balance characteristic extends to more complex production chains. Thus, we can extend the proof to any chain in which each process has only one output and the output either is a final product, or goes exclusively as input to another process. Furthermore, we can include any process in which the single output is divided amongst several other processes or sold directly as a final product. In all these cases, every intermediate stream and product can be assigned an unambiguous environmental cost.

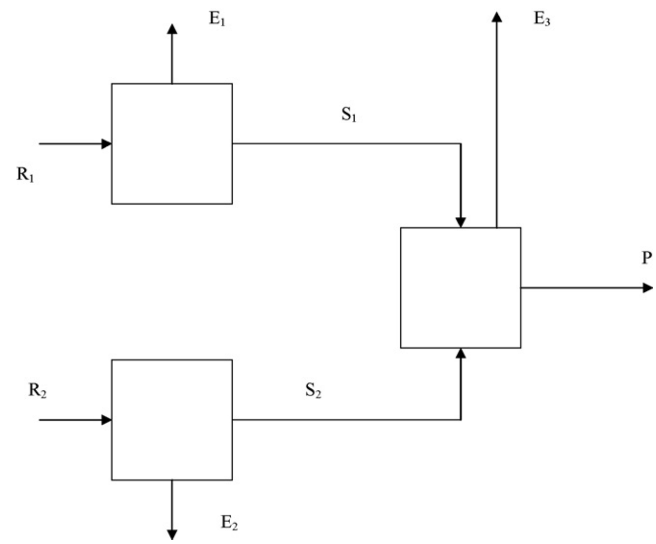

Fig. 1. Production chain with single-product processes.

2.2. Multi-product processes

There is no unambiguous environmental cost for supply chains as illustrated in Fig. 2. Consider the process with feed R_2. The environmental impact of pollutant "i" is e_{2i}. There are an infinite number of ways of dividing this impact between the two product streams. We could assign all impacts to stream S_2. The corresponding environmental costs are then:

$$c_{2i} = \frac{e_{2i}}{S_2} \quad (1a)$$

$$c_{3i} = 0 \quad (1b)$$