

Incorporating costs in LCA applying an Input-Output computational structure

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Keywords: Life Cycle Costing, Input-Output Analysis, Supply Chains.

ABSTRACT

This paper addresses the emerging issue of incorporating costs into Life Cycle Assessment (LCA) by developing a computational structure of Life Cycle Costing (LCC) which is grounded in the well-established one for Life Cycle Inventories. Production processes linked by both materials and cost flows are modelled as a Supply Chain and the Life Cycle Cost is defined as a vector that shows how the costs accrued in each stage according to the process costing principles. The algebra of environmentally extended Input-Output Analysis provides with an analytical support to control internal production costs, environmental burdens and their drivers according to proper cause-effect relationship along the supply chain.

Introduction

Although a lively debate has taken place in order to outline a more uniform meaning for LCC within the framework of Life Cycle Management [1], the parallel implementation of LCC and LCA as complementary tools seems to exclude any formal integration of the former into the latter [2]. Most of the proposed models, indeed, usually combine some discounted cash flow analysis with LCA. Our aim, instead, is to investigate to what extent LCA and LCC could actually share a similar computational structure. Yet, at this stage the discussion has focused mainly on the theoretical foundations.

Life Cycle Costing and the Supply Chain

Economic figures often diverge from the environmental ones. In the extent one tries to integrate LCA with considerations about costs, it seems that, so far, such a limitation cannot be overcome unless not easily quantifiable cost issues are included or a discount rate is quite arbitrarily chosen. Despite these computational contrivances, one will be finally forced to set either environmental or economic priorities anyway. Inasmuch sustainable development will not just happen on its own, it is herein assumed, instead, that those organizations which actually interact to jointly reduce environmental burdens may require cost management tools to turn out figures that support decisions on how to cooperate [3]. This is not just a matter of environmental costs, as doing environmental management accounting (EMA) is doing more comprehensive management accounting [4].

Integrated SC management shares the conceptual basis and the physical backbone of LCA [5]. Furthermore, in the extent that the resource consumption counts, cash flows are inappropriate for costing purposes [6]. Thus, a method for cost accounting in an SC perspective [7] seems more consistent with the LCA's "physical" life-cycle than asset management tools like conventional LCC [8]. Otherwise, the parallel implementation of LCA and LCC would be theoretically feasible so far as capital budgeting for durable assets is concerned, and the scope of the latter would then be narrower.

Since it is crucial to integrate physical and monetary issues, the herein proposed accounting scheme is dual, that is the assignment of production costs relies on data about the linked material flows along the SC. The latter has been modelled through enterprise input-output accounts [9] as a set of interrelated production processes which may belong to different actors, from the raw materials supplier to the final user, then to the end-of-life actors. These physical input-output relationships are then turned into financial transactions among different units processes and between the processes and the outside market [10]. Both cost drivers and environmental interventions should be identified to know which can be actually controlled in order to put the outcomes of an LCA into operation and to gain insights on how this would cost as well. Like the interorganizational cost management [11], the proposed scheme is intended to help reduce the information asymmetry between the buyer and the supplier – whether they are organizations or processes within the same organization – regarding the relationship between the specifications established by the former and the resulting costs to the latter, in order to identify opportunities for joint cost reduction.

Input-Output Supply Chain Modeling

System boundaries are set once the $n \in \aleph$ (where \aleph stands for the set of natural numbers) reciprocally linked unit production processes are selected and characterized in terms of $m \in \aleph$ economic flows, *i.e.* commodities, which are produced by the economic system and either serve as intermediate inputs or meet the market demand. Flows are listed in a definite order, each one is labelled univocally and its unit is specified. Economic flows include $n \in \aleph$ main outputs, which are both supplied and required within the above defined system boundaries. Also $n_w \in \aleph$ waste types, or secondary products, are included which either undergo some end-of-pipe treatment or serves as secondary inputs. Besides economic flows, also the environmental interventions of unit processes have been taken into account within this scheme as $n_e \in \aleph$ environmental flows, *i.e.* those from and into the natural environment.

It often happens that $(m - n_w) > n$, since there are $n_M \in \aleph$ commodities supplied by “black box” processes which cannot be controlled and, consequently, are not described in detail within the scheme. In other words, as purchased externally, such flows are *cut off*. This is an important point when trying to include cost management issues in LCA. Indeed, as far as the latter is concerned, the less economic flows are cut off, the more is the *depth* of the analysis. Macroeconomic IOA merged with LCA has mainly served that aim [12]. It is instead not always useful nor possible to gain further insight into suppliers’ cost structure when neither a joint effort to achieve cost savings beyond the influence of a single organization is feasible, nor is it the management of drivers to control cost propagation through the SC.

Each process operates according to parameters like its own capacity, run size and cycle time. Different batches of products may require different interrelated processes to operate according with different parameters, due to design specifications. Resources and time consumption thus vary accordingly, as stated in the Bill of Materials. Assuming there is only one product, the $m \times n$ use table \mathbf{U} gives the inputs which feed the j -th unit process as listed in the j -th column. Its u_{ij} element describes the requirement of intermediate economic flow i by process j to produce a certain amount of outputs as described in another table, the $n \times m$ make table \mathbf{V} . The latter represents the list of all outputs per production unit, as its v_{ji} element describes the production of the economic flow i by the process j . It is assumed that the main output of process j is listed as the j -th commodity. Within the transpose of the make table, \mathbf{V}^T , the outputs which come from the j -th production unit are listed in the j -th column. Both \mathbf{U} and \mathbf{V}^T are positive semi-definite. The $m \times n$ system’s net output matrix $\mathbf{Z} = (\mathbf{V}^T - \mathbf{U})$ is defined. A $n_e \times n$ matrix $\underline{\mathbf{R}}$ and a $n \times n_e$ matrix $\overline{\mathbf{R}}$ are defined. Within the former, the inputs from the environment which feed the j -th unit process are listed in the j -th column, whereas $\overline{\mathbf{R}}^T$ shows in that column the releases into the environment from that production unit.

If all the economic flows were produced by the n manufacturing processes included within the boundaries, \mathbf{Z} would be $n \times n$ – just as it conventionally happens for macroeconomic IOA. Yet, this is not the case, since SC perspective is not comprehensive. A *cut off* algorithm is helpful since it provides criteria to organize the collected data about economic flows.

Assume that just the production and the intermediate consumption of main products shall result in a $n \times n$ technology matrix \mathbf{Z} . If processes are multifunctional, one will decompose the $n \times n$ make matrix into its on-diagonal and off-diagonal elements, *e.g.* $\mathbf{V} = \widehat{\mathbf{V}} + \widetilde{\mathbf{V}}$. Only the former, $\widehat{\mathbf{V}}$, should be considered when calculating the system’s net output, *i.e.* $\mathbf{Z} = (\widehat{\mathbf{V}}^T - \mathbf{U})$, whereas, by assumption, $\widetilde{\mathbf{V}}$ would rather trigger some demand for waste treatment than compete with the corresponding primary output.

Economic flows within the $n_M \times n$ purchased inputs matrix \mathbf{M} are those absorbed by one or more processes but not produced by any of them. Their contribution to the overall manufacturing cost, given the market price paid to suppliers, can only be influenced by resource consumption rates. Secondary outputs, instead, are due to both waste/scrap generation and processes being multifunctional. They are assumed not to be released into the environment: if closed-loop recycling within the SC does not take place, producing these flows will call for some treatment process. Thus, a $n_w \times n$ matrix $\overline{\mathbf{N}}^T$ is defined, whose element \overline{n}_{kj}^T represent the net generation of waste k by process j , whereas the element \underline{n}_{kj} of the $n_w \times n$ matrix $\underline{\mathbf{N}}$ represents the input of waste k into process j . Each process is assumed either to produce a given waste k or to use it as an input, *i.e.* $\forall j \in n, \forall k \in n_w : \overline{n}_{jk} \times \underline{n}_{kj} = 0$ [13]. Waste outflows are thus netted out from intra-process recycling. Although this may not always be the case in literature, it seems most convenient for cost accounting purposes.

Applying costs

In order to apply monetary values to the physical amounts, the SC of relevant unit processes must be seen as a vertically-integrated business. Inputs and outputs respectively entering and leaving the system are described for each individual step in production. Direct materials costs should then be traced and conversion costs (*i.e.* labour and production overheads) should be allocated to each process according to drivers which are to be available in such an input-output scheme. The latter should be structured so that the cost of manufacturing the main output of a unit process is *transferred* to the downstream processes receiving it, as a separate category of direct material costs [14]. This recalls how prices are computed within leontevian macroeconomic IOA, where the primary factors' costs are incurred by each producing sector in addition to payments for input purchased from other producing sectors [15]. The analogous of IOA's value added vector is to be obtained, although it cannot be intended as a "value added" properly. Indeed, the cost of producing the main outputs is assumed to offset the *transfer price* for all the inputs supplied by the other processes and the costs related to (a) externally purchased inputs, (b) waste/by products treatment and (c) inter-process recycling, (d) labour and overheads.

A number of drivers is thus required besides the material flows considered so far. Provided that overhead rates had been estimated, the $n_L \times n$ \mathbf{L} matrix and the $n_H \times n$ \mathbf{H} matrix are thus defined whose entries are the cost drivers which have been chosen to assign $n_L \in \aleph$ distinct direct labour issues and $n_H \in \aleph$ overhead cost issues to processes. These drivers shall be determined as non unit-based factors that can be observed which cause a change in a cost object's consumption of resources. An example could be those parameters at which processes operate, like the required machine hours (cycle time). Although utility costs, like electricity, are overheads, their drivers will be recorded in \mathbf{M} , unless these flows are supplied within the SC. A kind of such driver could be obtained multiplying the adjusted installed power by the working hours required to run the process. Environmental flows, on the other hand, could be recorded also in \mathbf{H} , as far as they serve the purpose of allocating those overheads which are assumed as proportional to some releases into the environment (*e.g.* environmental taxes or fees).

One may also be interested into the assignment of *both* the incurred disposal/treatment costs and the production cost of scraps/by-products [4]. To fulfil these cost accounting purposes *simultaneously* within an input-output computational structure, one should first carry out an *allocation* procedure, just as in LCI [16], in order to apply some joint product costing [14]. A unit process is thus split into two independent unit processes, one producing the same output as before and one producing the former by-product as a main output. The entries of the new vectors are obtained once the allocation factors λ and $(1-\lambda)$, where $0 < \lambda < 1$, has been determined according to proper criteria and multiplied by the entries of the former vector. Unit processes, as well as the main outputs, are now $n_I \in \aleph$, where $n_I > n$. Yet, due to the aim of cost allocation, the following is required: (a) within the process vector producing the former by-product, the same flow is entered twice, as both a main output and as a by-product, exactly as before; (b) the downstream processes using the former main output shall also use the economic flow obtained after the allocation has been carried out. The procedure described so far allows one to know the cost of producing a given by-product, whereas the issues of waste management cost and of using wastes as secondary input will be discussed in the next section.

Implementing the integrated model

Given the above described computational issues, equation (1) displays in compact matrix notation how the different matrices are stacked.

$$\begin{bmatrix} \underline{Z} \\ \underline{W} \\ -\underline{M} \\ -\underline{L} \\ -\underline{H} \\ \underline{R} \end{bmatrix} = \begin{bmatrix} \underline{\tilde{V}}^T \\ \underline{\tilde{N}}^T \\ 0 \\ 0 \\ 0 \\ \underline{R}^T \end{bmatrix} - \begin{bmatrix} \underline{U} \\ \underline{N} \\ \underline{M} \\ \underline{L} \\ \underline{H} \\ \underline{R} \end{bmatrix} \quad (1)$$

So far, collected data refers to unit processes according to their own technical specifications, as if they were "cooking recipes". Yet, the system's net output must meet an exogenous set of economic flows, or final demand (an example would be the batch size of a given finished product), represented by the $n_I \times 1$ reference flow vector y_I . To the purpose, a balancing procedure is required which yields, provided that the net output matrix \mathbf{Z}

is square and invertible, the $n_j \times 1$ scaling vector s_j whose entries represent the activity levels at which processes are required to operate [16]:

$$(\tilde{V}^T - U) \times s_j = y_j \Rightarrow s_j = (\tilde{V}^T - U)^{-1} y_j \quad (2)$$

It is then useful to aggregate waste flows according to the kind of waste treatment they undergo. The aim is to turn the net waste generation of each production process into its demand for treatment processes, provided that the latter are $n_{II} \in \mathfrak{N}$, where $n_w > n_{II}$ [13]. The computational principle for turning waste flows into the demand for waste treatment as additional n_{II} economic flows and for determining their cost have been followed as described in [17],[18] although it has been adapted for an SC perspective and the make-use matrix. Provided that the $(n_m + n_L + n_H) \times n$ matrix \mathbf{B} stands for the stacked \mathbf{M} , \mathbf{L} and \mathbf{H} ones, the following must hold:

$$\begin{bmatrix} \tilde{V}^T - U \\ 0 \\ \tilde{N}^T \\ -B \\ \tilde{N}^T \\ -\tilde{N} \\ R \end{bmatrix} \hat{s}_j e = \begin{bmatrix} \tilde{V}^T - \tilde{U} \\ 0 \\ \tilde{N}^T \\ -\tilde{B} \\ \tilde{N}^T \\ -\tilde{N} \\ \tilde{R} \end{bmatrix} e = \begin{bmatrix} y_j \\ 0 \\ \varepsilon \\ v \\ \varepsilon \\ \rho \\ g \end{bmatrix} \quad (3)$$

Matrices have been stacked in a different way from equation (1). The superscript “~” indicates that a matrix has been multiplied by the diagonalized scaling vector \hat{s} , i.e. “scaled up”, and e is a unity column vector of appropriate dimensions. The $n_e \times 1$ vector $g = R s_j$ gives the total amount of each type of environmental intervention which is due to the activity level. The $(n_m + n_L + n_H) \times 1$ vector $v = B s_j$ gives the total amounts for each kind of cost driver, which will be used as an allocation basis.

The $n_w \times 1$ vector $\varepsilon = \tilde{N}^T s_j$ gives the total amount of each waste type which has been produced. A $n_w \times 1$ vector r is defined whose element $r_k = \sum_{j=1}^n \tilde{n}_{kj} / \sum_{j=1}^n \tilde{n}_{kj}^T$ gives the amount of waste which has been sold as a secondary input within the SC, the so called *sale of waste*. The amount of waste sold is obtained as follows:

$$\forall k, k = 1..n_w : \sum_{j=1}^n \tilde{n}_{kj} = \rho = \sum_{j=1}^n \tilde{n}_{kj}^T r_k = \varepsilon_k r_k \quad (4)$$

A $n_{II} \times n_w$ matrix \mathbf{Q} is then defined, whose element q_{lk} , where $0 < q_{lk} < 1$, indicates the amount of k -th waste type which undergoes the l -th treatment. It should be noted that $e^T \mathbf{Q} = e^T$. In order to account for waste treatment as economic flows, the following must hold:

$$\begin{bmatrix} I & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & I & Q(I - \hat{r}) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & I & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \hat{r} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I \end{bmatrix} \times \begin{bmatrix} \tilde{V}^T - \tilde{U} \\ 0 \\ \tilde{N}^T \\ -\tilde{B} \\ \tilde{N}^T \\ -\tilde{N} \\ \tilde{R} \end{bmatrix} = \begin{bmatrix} \tilde{V}^T - \tilde{U} \\ -Q(I - \hat{r}) \tilde{N}^T \\ -\tilde{B} \\ \hat{r} \tilde{N}^T \\ -\tilde{N} \\ \tilde{R} \end{bmatrix} \quad (5)$$

At this point, treatment processes may enter the formal scheme or not, according to the same criteria adopted so far. Those which enter the scheme serve mainly two purposes: the end-of-pipe pollutant abatement and the system's end-of-life. In the latter case, it is like adding a dedicated unit processes whose main output is a certain quantity of “disposed” system. As to the former case, one adds n_{II} column vectors to the matrix yielded in equation (5). Yet, it is assumed that neither the treatment processes produce the same output of the other processes nor *vice versa*. It is also assumed that treatment processes (a) are not being supplied with production processes' main outputs, (b) are not required to meet any reference flow and (c) do not require each other treatment services.

Economic flows (rows) which refer to production and abatement activities are grouped and indicated

respectively by subscript “I” and “II”. Treatment processes’ output is measured by the amount (expressed as weight) of the wastes they have treated. Given that \mathbf{Z} is now $n \times n$, where $n = n_I + n_{II}$,

$$\begin{bmatrix} e \\ s_{II} \end{bmatrix} = \begin{bmatrix} \tilde{V}_{I,I}^T - \tilde{U}_{I,I} & 0 \\ -Q(I - \hat{r})\tilde{N}_{\bullet,I}^T & \tilde{V}_{II,II}^T \end{bmatrix}^{-1} = \begin{bmatrix} y_I \\ 0 \end{bmatrix} \quad (6)$$

where subscript “•” indicates all the components of the relevant row or column. Flows are then re-scaled:

$$\begin{bmatrix} \tilde{V}_{I,I}^T - \tilde{U}_{I,I} & 0 \\ -Q(I - \hat{r})\tilde{N}_{\bullet,I}^T & \tilde{V}_{II,II}^T \\ -\tilde{B}_{\bullet,I} & -\tilde{B}_{\bullet,II} \\ \hat{r}\tilde{N}_{\bullet,I}^T & 0 \\ -\tilde{N}_{\bullet,I} & 0 \\ \tilde{R}_{\bullet,I} & \tilde{R}_{\bullet,II} \end{bmatrix} \left\langle \begin{bmatrix} e \\ s_{II} \end{bmatrix} \right\rangle = \begin{bmatrix} \tilde{V}_{I,I}^T - \tilde{U}_{I,I} & 0 \\ -Q(I - \hat{r})\tilde{N}_{\bullet,I}^T & \tilde{V}_{II,II}^T \\ -\tilde{B}_{\bullet,I} & -\tilde{B}_{\bullet,II} \\ \hat{r}\tilde{N}_{\bullet,I}^T & 0 \\ -\tilde{N}_{\bullet,I} & 0 \\ \tilde{R}_{\bullet,I} & \tilde{R}_{\bullet,II} \end{bmatrix} \quad (7)$$

Costing will be carried out according to physical driver amounts, other than environmental interventions, as resulting from the right side of equation (7). To the purpose, the analogous of IOA’s value added vector is obtained by applying monetary values to cost drivers:

$$\begin{bmatrix} I & 0 & 0 & 0 & 0 \\ 0 & I & 0 & 0 & 0 \\ 0 & 0 & p_M^T & \bar{p}^T & \bar{p}^T \end{bmatrix} \times \begin{bmatrix} \tilde{V}_{I,I}^T - \tilde{U}_{I,I} & 0 \\ -Q(I - \hat{r})\tilde{N}_{\bullet,I}^T & \tilde{V}_{II,II}^T \\ -\tilde{B}_{\bullet,I} & -\tilde{B}_{\bullet,II} \\ \hat{r}\tilde{N}_{\bullet,I}^T & 0 \\ -\tilde{N}_{\bullet,I} & 0 \end{bmatrix} = \begin{bmatrix} \tilde{Z}_{I,I} & \tilde{Z}_{I,II} \\ \tilde{Z}_{II,I} & \tilde{Z}_{II,II} \\ \omega_{\bullet,I} & \omega_{\bullet,II} \end{bmatrix} \quad (8)$$

where \mathbf{I} is the identity matrix of proper dimensions.

The $(n_M + n_L + n_H) \times 1$ vector p_M provides with (a) the unit cost of direct materials and (b) the predetermined overhead rates for each production overhead considered. Attention must be paid in the choice of the cost drivers. Even if subjective, the allocation of conversion costs should indeed avoid *cross subsidizing*.

It should be noted that a waste will be *sold* at an exogenous price \bar{p} which is not its “manufacturing cost”; it could also happen, indeed, that $\bar{p} \leq 0$.

The $1 \times n$ vector $\omega = [\omega_I \ \omega_{II}]$ such that $\omega = -p_M^T \tilde{B}_{\bullet,\bullet} + \bar{p}^T \hat{r}\tilde{N}_{\bullet,\bullet}^T - \bar{p}^T \tilde{N}_{\bullet,\bullet}$ recalls the leontevian IOA’s value added vector. Thus, the following

$$[p_I \ p_{II}] \times \begin{bmatrix} \tilde{V}_{I,I}^T & 0 \\ 0 & \tilde{V}_{II,II}^T \end{bmatrix} = [p_I \ p_{II}] \times \begin{bmatrix} -\tilde{U}_{I,I} & 0 \\ -Q(I - \hat{r})\tilde{N}_{\bullet,I}^T & 0 \end{bmatrix} + [\omega_I \ \omega_{II}] \Rightarrow [p_I \ p_{II}] = [\omega_I \ \omega_{II}] \times \begin{bmatrix} \tilde{V}_{I,I}^T - \tilde{U}_{I,I} & 0 \\ -Q(I - \hat{r})\tilde{N}_{\bullet,I}^T & \tilde{V}_{II,II}^T \end{bmatrix}^{-1} \quad (9)$$

yields the $n \times 1$ vector $p = [p_I \ p_{II}]^T$, whose partitions show, respectively, how manufacturing cost has been accumulated in each stage of the unit processes SC, including those cost incurred to run the treatment processes internally.

Conclusion

Economic issues form one of the sustainability pillars. Yet, while trying to extend the environmental life-cycle view to also address economic aspects within sustainability, LCA is still striving to close the gap between existing methodologies and tools and practical implementation [19]. The proposed method thus focuses on the SC to combine the perspectives of those partners which are actually concerned with jointly reducing, where possible, costs and impacts at the same time, even in the use and disposal phases of the commodities they produce. From a cost accounting perspective, the LCA’s aim of reducing cut-off flows as much as possible (using databases or merging with IOA) would not necessarily improve the analysis. It seems most important,

instead, that data and methods which offer a solution to the individual problem that has to be tackled by a certain actor or firm are used. Within the proposed scheme there could theoretically be as many processes as commodities. Yet, it is not always meaningful to gain insight into the cost of producing all of them: unless buyers can cooperate with their suppliers to jointly reduce costs, they just act as price takers. Thus, the first goal to achieve is to make the focus company aware of both the physical flows which characterize its manufacturing processes and the way they drive its production costs, as well as the cost of process inefficiencies such as wastes. The model could then be gradually extended to link supplier to customers in the value chain and the value chain to the ecological product chain.

The outcomes of the formal model depend upon the processes' operating parameters, the costs related to externally purchased direct materials, the conversion costs and the environmental "internal failure" costs. This allows one to determine and manage the contribution of physically driven costs, as well as the material flows that cause them, according to actual relationships along the supply chain and to avoid relying solely on discounted cash flows.

Since chasing accuracy of past figures as an apparent reduction in uncertainty can increase risk, the model is not intended to be a deterministic one [6]. Thus, further developments should address managing uncertainty issues within the model's parameters, so that the proposed method can serve as both a backcasting and a forecasting tool in order to let the analysis lead to some action.

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