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The economic theory of environmental Life Cycle Inventory models

T. Pento

University of Jyväskylä, School of Business and Economics, P.O.Box 35, FIN-40351 Jyväskylä, Finland

Email: pento@clinet.fi

Abstract

This paper shows that Life Cycle Inventory theory can be derived directly from the theories of production functions and methods of Input-Output analysis of economics. Linear Economic-Environment (EEP) production functions are formed into a Leontief Input-Output matrix A, which shows the transition of physical quantities of materials through the processes and flows along a product's life cycle. The Life Cycle Inventory E* is then calculated as = $\{ [I - A]^{-1} \times Y \} \times E$ = the total quantity vector of effluents produced, where Y is the functional unit vector, I an identity matrix, and E the amount of effluents emitted per unit quantity of a product produced. This formulation is usable with both one product and multi-product functional units. Construction principles of dynamic LCI and material flow models are then discussed. Examples and results of dynamic LCI scenarios are given of the material flows of printing papers in Germany between 1993 – 2000.

1 Production functions of life cycle inventories

The life cycle of a product consists of processes, which transform or transport virgin raw materials from the environment or products into other products or locations. The flows of printing papers in Figure 1 begin at hard- and softwood forests and limestone quarries, and continue to pulp

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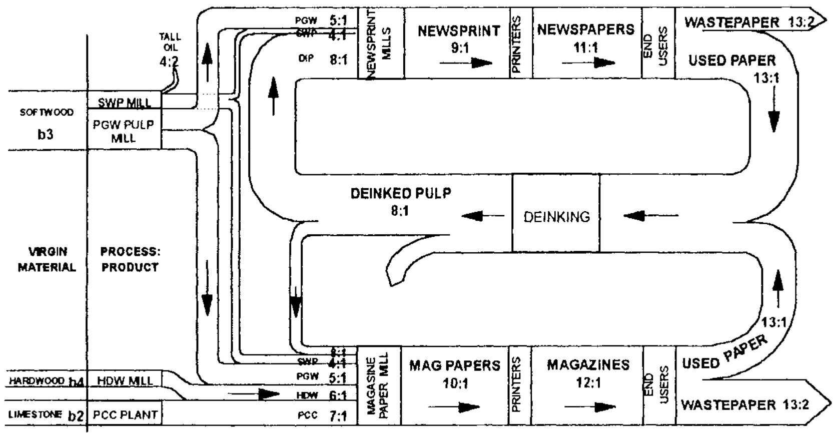
mills to paper mills to printers, consumption, waste or paper collection, and through de-inking back to paper making. One or more products may be generated at each process, and each product may be a part of one or more life cycles. In the figure, the mechanical grinding of softwoods produces only pressurised groundwood (PGW), while the kraft pulping of softwood yields both softwood pulp (SWP) and tall oil; and post-consumer paper may end up as collected used paper or as waste paper.

Figure 1. Life Cycles of Printing Papers, Pento[11]



A short-term production function of economics models a process, which transforms physical quantities of input products and materials into physical quantities of output products, Mansfield[10]. If D_i and D_o are the quantity vectors of input and output products, the production function is:

$$G_k \{ D_o \} = F_k \{ D_i \} \qquad (1)$$

The analysis of both economic and environmental outcomes of a process requires the expansion of (1) to include environmental variables, and such functions have to be nested over the life cycle of the product. Let vector D_{ok} denote quantities of output products of the process k, D_{ik} the quantities of input products from the earlier processes, R_k quantities of materials derived directly from the environment, and H_k the amounts of effluents which are emitted by the process to the natural environment. The short run economic - environment production (EEP) function of a process is then:

$$G_k \{D_{ok}, H_k\} = F_k \{ D_{ik}, R_k\} \tag{2}$$

This function shows the maximal quantities of outputs D_{ok}, which can be made from the inputs $\{ D_{ik}, R_k \}$ and the minimal emissions H_k which are generated by the process in this conversion. Most current LCI applications simplify (2) with *ceteris paribus*, and consider long-term production factors fixed, and ignore their inputs and emissions, Mansfield[10], Reeve[13]. The functions G_k and F_k are thus reduced to linear and homogeneous relations between separable input and output variables.

Let D be a vector of all products made or used in all processes of the life cycle. Each of the k = 1 ... K processes inputs products from the other processes and/or virgin materials from the natural environment, and makes n = 1 .. N_k output products, many of which are used as inputs by the other processes. The process ok produces the quantity $d_{ok:n}$ of the output product n and uses $d_{ik:s;\, ok}$ of the input product s from the process ik, the amount of $r_{m,ok}$ of the virgin material m, m = 1 ... M, and emits the quantity $h_{p,ok}$ of effluent p. Following the boundary principle of microeconomics, the EEP function of this <u>process</u> is given as a material balance equation, Ayres[2]:

$$\sum_{n}^{Nk} d_{ok:n} = \sum_{ik}^{K} \sum_{s}^{Nk} d_{ik:s;\, ok} + \sum_{m}^{M} r_{m,ok} - \sum_{p}^{P} h_{p,ok} \tag{3}$$

This function shows the material balance of products, virgin materials and emissions of a process. In LCI work, it is transformed to product functions by allocating all input and emission quantities of the process to the output product quantities. This is done with scalars so that the EEP function of a <u>product</u> can be given as a material balance equation:

$$d_{ok:n} = \sum_{ik}^{K} \sum_{s}^{Nk} z_{ik:s,\, ok:n} d_{ik:s,\, ok:n} + \sum_{m}^{M} u_{m,\, ok:n} r_{m,\, ok:n} - \sum_{p}^{P} w_{p,\, ok:n} h_{p,\, ok:n} \tag{4}$$

The scalars $z_{ik:s,ok:n}$, $u_{m,ok:n}$, $w_{p,ok:n} \geq 0$, and for every input product $d_{ik:s}$, material r_m, and emission h_p of every process:

$$\sum_{n}^{Nk} z_{ik:s,ok:n} = 1 \ , \ \sum_{n}^{Nk} u_{m,ok:n} = 1 \ , \text{ and } \sum_{n}^{Nk} w_{p,ok:n} = 1$$

1.1 Allocation and Boundaries

The vector D contains far too many products to be usable in practical work. Products are eliminated from the vector by applying established boundary rules. The allocation scalars z and u are a first-order decision rule for excluding side-products from the life cycle, typically when:

$$\sum_{ok}^{K}\sum_{n}^{Nk} z_{ik:s,ok:n} \cong 0 \ , \text{ or when } \sum_{ok}^{K}\sum_{n}^{Nk} u_{m,ok:n} \cong 0 \qquad (5)$$

These rules are often augmented with others, such as if the cradle to the end of the process ik life cycle of the product ik:s does not give rise to noteworthy toxic or acidifying or ozone depleting etc. emissions, or if the natural environment contains large reserves of the material m.

2 LCI as an Input-Output Model

Leontief Input-Output (I-O) models have been applied mostly for the economic analysis of sectors of national economies, Leontief [9]. Environmental I-O modelling in money terms has gained momentum recently Lave[8], Koninj[6]. Life Cycle Inventories may also be formulated into the format of physical quantity input-output matrices. Define the technical coefficients:

$$a_{ik:s,ok:n} = \frac{z_{ik:s,ok:n}\, d_{ik:s,ok}}{d_{ok:n}} \qquad (6)$$

which indicate the quantity of input product s which is needed to make one quantity unit of output product n. These coefficients make up the Leontief structural matrix A in which the columns correspond to the z • d term of the linearised EEP function (4), so that the outputs are in the columns and inputs in the rows of the matrix. The virgin material input coefficients $b_{m,ok:n}$ and the emission coefficients $e_{p,ok:n}$ are defined as:

$$b_{m,ok:n} = \frac{u_{m,ok:n}\, r_{m,ok}}{d_{ok:n}} \qquad e_{p,ok:n} = \frac{w_{p,ok:n}\, h_{p,ok}}{d_{ok:n}} \tag{7}$$

and show the amount of virgin material input m which is needed to make, and the quantity of effluent p which is generated by the manufacture of one unit of product n. These form the matrices B for calculating virgin material use and E for emissions.

Matrices A and B, which define the boundaries of the life cycle, are typically sparse because each process inputs only a few of the virgin materials and/or products. Table 1 shows non-zero elements of the matrices A, B and E for Figure 1, with the exception of output product 4:2, which would be excluded on the basis of (5). In most practical LCI work, many products of A are independent inputs which utilize none of the other products in A, and can be separated from A to make an input matrix in the style of the matrix B.

Table 1. Life Cycle Inventory as a Static Input-Output Table

Process:Product — Input / Output	1:1 Fuel	2:1 Electricity	3:1 Transport	**4:1 SW pulp**	**4:2 Tall Oil**	5:1 PGW	6:1 HDW pulp	7:1 Prec. CC	8:1 De-ink pulp	9:1 Newsprint	10:1 Magas pap	11:1 Newspaper	12:1 Magasine	**13:1 Used paper**	**13:2 Waste pap**	Total output	Emission: e1 BOD	e2 COD	e3 SOX	e4 NOX
13:2 Waste paper																	X	X	X	X
13:1 Used paper		X							X										X	X
12:1 Magasines														X	X				X	X
11:1 Newspapers														X	X				X	X
10:1 Mag. papers													X				X	X	X	X
9:1 Newsprint												X					X	X	X	X
8:1 De-Inked Pulp										X	a8:1,10:1					d8:1	X	X	e8:1,3	X
7:1 Precip. CC											a7:1,10:1						X	X	X	X
6:1 Hardwood pulp											a6:1,10:1						X	X	X	X
5:1 Pressur.grwood										X	a5:1,10:1						X	X	X	X
4:2 Tall Oil																				
4:1 Softwood pulp										X	a4:1,10:1						X	X	X	X
3:1 Transport				X	X	X	X	X	X	X	a3:1,10:1	X	X	X	X		X	X	X	X
2:1 Electricity				-X	X	X	-X	X	X	X	a2:1,10:1	X	X				X	X	X	X
1:1 Fuel			X														X	X	X	X
Virgin material																				
b4 Hardwood							X													
b3 Softwood				X	X	X														
b2 Limestone								X												
b1 Oil	X	X									b1,10:1									

Traditional LCI studies specify a functional unit of one product, such as a ton of 45 g/m^2 newsprint produced and delivered at the printer's gate. The above I-O formulation makes it possible to have a functional unit of one or more products of an industry, and determine environmentally (and economically) best production structures.

In the I-O formulation, final demand Y is the functional unit. It shows the externally specified amounts of products and services for which the (economic and) environmental outcomes are calculated. Traditional LCI's would have only one positive element in Y, but wider industry-level models have already been made which work with many-product functional units, Kärnä[7], Virtanen[15]. The quantities of products D* which have to be made to get the functional unit, and the corresponding virgin material use and emissions are given by:

$$D^* = [I - A]^{-1} \times Y \ , \ B^* = B \times D^* \ , \text{and } E^* = D^* \times E \qquad (8)$$

3 Dynamic Life Cycle Inventories

Static LCI's are a poor tool for planning future environmental policies. Comparisons of products, which satisfy the same functional units but have different life cycles are notoriously debatable. In addition, static LCI's exclude the continuous changes in technical and environmental conditions of consumption and production and disregard the positive and negative effects of capital investments, Pento[12].

Dynamic models employ matrices A^t, B^t and E^t, and functional unit vectors Y^t for successive time periods $t = 1 \ldots T$, and enable time path analyses of each variable d^{*t}, b^{*t},and e^{*t} within different scenarios of demand, permit policies, investments and like. The matrices of the time periods are used to calculate:

$$D^{*t} = [I - A^t]^{-1} \times Y^t \ , \ B^{*t} = B^t \times D^{*t} \ , \ E^{*t} = D^{*t} \times E^t \qquad (9)$$

The analysis of the functions in (9) can be made with the Joined Time Projection (JTP) technique; Pento[11], Gronow,[3], in which all of the vectors and matrices of different time periods are first estimated, then calculated, and elements d^{*t}, b^{*t},and e^{*t} of interest of the time periods are collected and joined in time sequence for a projective analysis.

4 Applications of Dynamic I-O LCI's

Dynamic input-output LCI models produce greatest advantages over static LCI's when they are applied to the environmental analysis and planning of an industry. Most environmental policies concentrate on changing production rather than consumption. The rows and columns of the I-O matrix show the actors, who are to implement a planned policy in practice. What if - analyses with the dynamic model illuminate the effects on the material flows of different scenarios in which the varying elements may be policies, or developments in technologies, markets, investments, or other aspects of the industry. The I-O approach also enables the incorporation of both economic and environmental analyses in the same framework. This is made by multiplying the physical units by the price vector.

Data and allocation problems have made static LCI's a somewhat notorious tool, Klöppfer[5], Pento[12]. Dynamic models appear to be less sensitive to errors in data, and allocation and boundary methods, because they study time paths and changes in the quantities of materials and emissions rather than absolute values. The focus on changes tends to eliminate a large part of variability caused by data errors and the choice of particular allocation and boundary rules.

These capabilities of dynamic models satisfy the needs for LCA-method development outlined by the European Network for Strategic Life-Cycle Assessment Research and Development: "Today's LCA *sensu strictu* are valid for incremental changes of the product of interest only. The *ceteris paribus* condition is no longer valid, if LCA's are used to deliver answers to long-term planning issues.", Udo de Haes[14], p. 13.

A dynamic LCI model is applied below to study two policy scenarios of the flows of printing papers in Germany between 1993 and 2000. The model was developed to study both environmental and economic effects, Pento[11], Gronow[3]. Scenario A assumes that no policy changes will be made. This scenario shows the results of demand growth, when production capacities are adapted to satisfy the demand while keeping the proportions of imports and exports fixed. Scenario B is based on a policy, which raises paper recovery rates from 50 percent to 70 percent by the year 2000. The increased mass of recovered papers is mainly de-inked and re-used in the domestic manufacture of newsprint, and the rest is incinerated. Import proportion of newsprint is allowed to decline.

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The two scenarios were construed into models with the JTP technique, which was solved with a heuristic procedure, because some of the functions contained non-linearities. De-inking yield $a_{13:1,\ 8:1}$, for example, was defined as a function of the proportion of newspapers and magazines in the incoming stock of used papers, and the proportion of the de-inked pulp which was used as a raw-material of newsprint, and the number of recycling rounds which the wood fibres had gone through, Huuhtanen[4]. The functional unit was:

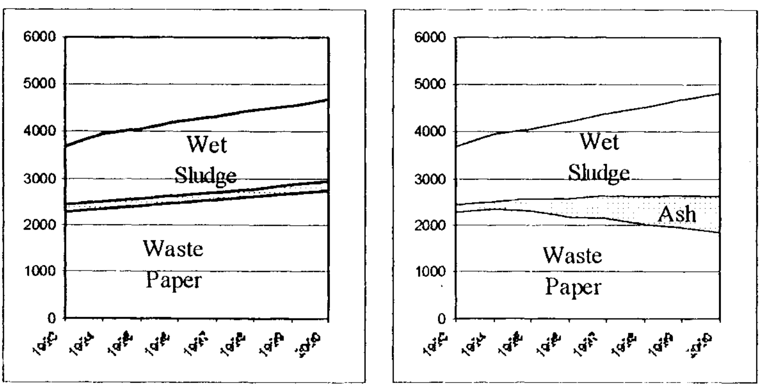
Table 2. The functional unit of the dynamic model = demand forecasts of the products in 1000 tons

	1993	1994	1995	1996	1997	1998	1999	2000
Fine Paper	1690	1741	1793	1847	1902	1959	2018	2078
Newsprint	2100	2142	2185	2229	2273	2319	2365	2412
Magaz. paper	2500	2550	2627	2705	2786	2870	2956	3045

Scenario A in Figure 4 shows that if nothing is done, amounts of all solid wastes and all materials produced grow with the demand growth. The results of Scenario B show that the total amount of waste, which is produced does not decrease regardless of the markedly higher rates of recycling. The amount of waste paper, which is landfilled decreases, but the amounts of de-inking sludge (60 % solid content) and incineration ash increase. The amount of waste is almost unchanged, but the composition of waste changes from the relatively benign used papers to the much more difficult to handle de-inking sludge.

Figure 4. Annual waste quantities of printing papers in Germany between 1993 – 2000, in 1000 tons / year

A. No policy change B. With a recycling policy



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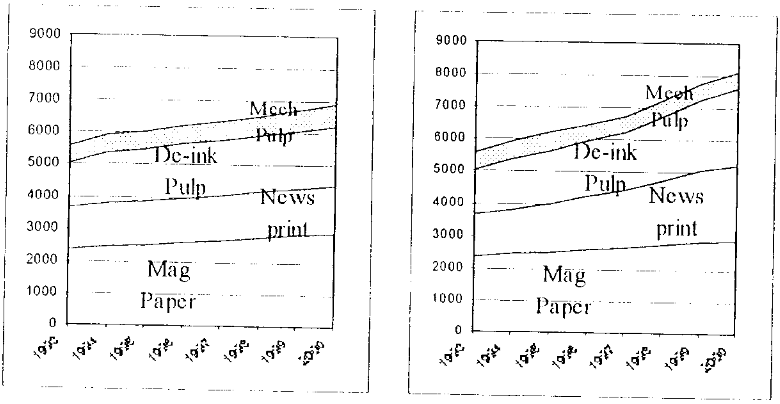
The economic consequences of the recycling policy are also visible as a rapid increase in the amounts of de-inked pulp and newsprint, which are produced in Germany, Figure 5. A policy of increasing recovery and recycling requires that the pulp and paper industry must construct sufficient capacity in Germany to make the fast growth possible. The very large investments into new de-inked content newsprint in Germany between 1993-1995 did produce this capacity, and domestic production has since increased markedly. The projections indicate large shifts in the market shares of suppliers of newsprint, with the importers losing markets to the producers in Germany.

Figure 5. Annual production quantities in Germany between 1993 – 2000, in 1000 tons / year

A. No policy change B. With a recycling policy



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