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Input-Output Analysis in Laptop Computer Manufacturing

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***Abstract*—**The scope of this paper and the aim of proposed model were to apply monetary Input –Output (I-O) analysis to point out the importance of reusing know-how and other requirements in order to reduce the production costs in a manufacturing process for a laptop computer. I-O approach using the monetary input-output model is employed to demonstrate the impacts of different factors in a manufacturing process. A sensitivity analysis showing the correlation between these different factors is also presented. It is expected that the recommended model would have an advantageous effect in the cost minimization process.

***Keywords*—**Input-Output Analysis, Monetary Input-Output Model, Manufacturing Process, Laptop Computer.

I. Introduction

A manufacturing process that takes into account various different components has to deal with increasing complexity. This complexity arises from the introduction of new materials and new technologies and from the consideration of life-cycle aspects [1]. Particularly technological equipments such as computers, smart phones, electrical devices used in everyday life need significant know-how to be produced and a large proportion of the production costs of these devices comes from the know-how. In order to minimize the production costs, besides promoting recycling, reuse and recovery, costs including R&D should also be reduced.

To demonstrate interrelationships between production requirements, we used Input-output (I-O) analysis which is a method of systematically quantifying the mutual interrelationships among the various sectors of a complex economic system. In practical terms, the economic system to which it is applied may be as large as a nation or even the entire world economy, or as small as the economy of a metropolitan area or even a single enterprise [2]. Thus, an Input-Output model can be a useful tool for estimating the economy-wide effects of an initial change in economic activities.

I-O models have some major extensions in literature as a Physical IO Table (PIOT), Monetary IO Table (MIOT), Waste IO Table (WIOT) and Environmental IO Table (EIOT). The first one provides a framework in which all physical flows associated with an economy can be recorded, while the second gives an insight into the value of economic transactions between different sectors. The third represents the interdependence between the flow of goods and the flow of wastes and the last emphasizes a suitable tool for estimating the short-term response of emissions and resource usage to changes in production induced by economic growth [3].

In the study, we implement our methodology based on MIOT in order to demonstrate numerically the importance and the impact of recycling of a typical laptop and reusing the resources based on know-how during its manufacturing process.

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II. Methodology

This work is conducted by applying monetary Input-Output analysis to the manufacturing process of a laptop computer. It can be seen that both for materials used in laptop computers and for labour force or know-how required in manufacturing process, the general term must be monetary in order to be comparable, so they can't be physical quantities.

Our model is based on the equations of the static multi-sector input-output model well known in the literature [2]. Its basic notation and fundamental relationships are given by:

$$\begin{aligned} X_1 &= m_{11} + m_{12} + \ldots + m_{1n} + Y_1 \\ X_2 &= m_{21} + m_{22} + \ldots + m_{2n} + Y_2 \\ &\vdots \\ X_n &= m_{n1} + m_{n2} + \ldots + m_{nn} + Y_n \end{aligned} \tag{1}$$

where X_i $(i=1,..., n)$ denotes the total output of sector i, m_{ij} $(i=1,..., n)$ $(j=1,..., n)$ represents the flow of input from sector i to sector j, and Y_i $(i=1,..., n)$ shows the final demand for sector i's production. Equation (1) guarantees that the total output of any sector are consumed by either itself or other sectors and also used up by the demand in that economic system. Consequently, the flow of goods, products and materials are balanced in a system.

By determination a technical coefficient as $a_{ij} = m_{ij} / X_j$, (1) can be modified and rewritten respectively as follows:

$$\begin{aligned} X_1 &= a_{11}.X_1 + a_{12}.X_2 + \ldots + a_{1n}.X_n + Y_1 \\ X_2 &= a_{21}.X_1 + a_{22}.X_2 + \ldots + a_{2n}.X_n + Y_2 \\ &\vdots \\ X_n &= a_{n1}.X_1 + a_{n2}.X_2 + \ldots + a_{nn}.X_n + Y_n \end{aligned} \tag{2}$$

Hence,

$$\begin{aligned}&(1-a_{11})X_1 - a_{12}.X_2 - ... - a_{1n}.X_n = Y_1\\ &-a_{21}.X_1 + (1-a_{22}).X_2 - ... - a_{2n}.X_n = Y_2\\ &\quad\vdots \qquad\qquad \vdots\\ &-a_{n1}.X_1 - a_{n2}.X_2 + -... + (1-a_{nn}).X_n = Y_n\end{aligned} \tag{3}$$

The last equation can be transformed in a matrix form as below:

$$(I - A)X = Y \tag{4}$$

and so,

$$X = (I - A)^{-1} Y \tag{5}$$

where A is the technical coefficient matrix containing technical coefficients a_{ij} that identifies the percentage or portion of the total inputs of a sector required to be purchased from another sector irrespective of the geographic origin of this purchase, and I is the identity matrix of size n with ones on the main diagonal and zeros elsewhere. $(I - A)^{-1}$ is a square matrix commonly designated as Leontief inverse, if it exists. For an input-output model, it should be stated that each commodity has a unique input structure, irrespective of the sector of fabrication and it is also assumed that the interrelations between inputs and outputs of any sector are linear.

In order to maintain the monetary impact of manufacturing processes which have significantly different characteristic from an economic system, the classical input-output analysis should be modified. With respect to this classical method, the main difference of modified version in this study is that the inputs of a manufacturing process do not necessarily have to be equal to the outputs. For instance, some inputs are converted into different substances or components along with manufacturing process. Another chief difference is that we concentrate on MIOT. As we focus on a manufacturing process that embodies other requirements -i.e. energy, know how- besides raw materials and components, the structure of the I-O analysis needs to be modified and the factors in a matrix must be expressed in the same units. Consequently, we resorted to MIOT derived from monetary tables [4].

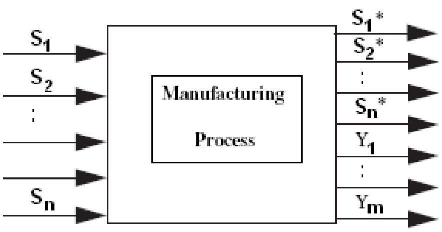

Fig. 1 Relation between Inputs and Outputs in a Manufacturing Process

Fig. 1 represents a general view of inputs and outputs of a manufacturing process based on the mass conservation. Within a process, there are n inputs, denoted by S_1 through S_n and $n+m$ outputs denoted by S_1^* through S_n^* with Y_1 through Y_n. Among the outputs, n outputs, S^*, imply the original substance form obtained by a process while m outputs, Y_n , imply the new substances referred as a waste. This transaction can be depicted as shown in the Table I where c_{ij} (arise from cost) signifies the amount of money of the substance S_i that is used for substance S_j^*, while w_{ij} (arise from waste cost) signifies the amount of money of waste Y_j that is transformed from substance S_i after the manufacturing process. It should be also noted that n does not have to e equal to m, however, the sum of the inputs in any physical unit has to be equal to the sum of all of the outputs on account of a mass conservation.

TABLE I
MONETARY INPUT – OUTPUT TABLE OF A MANUFACTURING PROCESS

Inputs	Outputs											
	S_1*	S_2*	…	S_j*	…	S_j*	Y_1	Y_2	…	Y_j	…	Y_m
S_1	c_{11}	c_{12}	…	c_{1j}	…	c_{1n}	w_{11}	w_{12}	…	w_{1j}	…	w_{1m}
S_2	c_{21}	c_{22}	…	c_{2j}	…	c_{2n}	w_{21}	w_{22}	…	w_{2j}	…	w_{2m}
…	…	…	…	…	…	…	…	…	…	…	…	…
S_i	c_{i1}	c_{i2}	…	c_{ij}	…	c_{in}	w_{i1}	w_{i2}	…	w_{ij}	…	w_{im}
…	…	…	…	…	…	…	…	…	…	…	…	…
S_n	c_{11}	c_{11}	…	c_{nj}	…	c_{nn}	w_{n1}	w_{n2}	…	w_{nj}	…	w_{nm}

Assuming that there is a linear relationship between inputs and outputs, the following equation can hold:

$$x_i = c_{i1} + c_{i2} + ... + c_{ij} + ... + c_{in} + w_{i1} + w_{i2} + ... + w_{ij} + ... + w_{im} \tag{6}$$

where x_i ($i = 1,2, ..., n$) stands for an amount of money of the substance i. In order to pass through the matrix notation for a matrix calculation, the technical coefficients assumed fixed and time-invariant (a_{ij} and b_{ij}) can be stated respectively as original outputs and as waste outputs and are indicated below:

$$a_{ij} = \frac{c_{ij}}{x_j} \tag{7}$$

and

$$b_{ij} = \frac{w_{ij}}{y_j} \tag{8}$$

where y_j ($j = 1, 2, ... m$) stands for an amount of money of waste j. Note that both x_j and y_j are computed as a total amount of money for substance j and waste j respectively.

Using the relationships from (6) through (8), following equation system can hold:

$$\begin{aligned}&x_1 = a_{11}.x_1 + a_{12}.x_2 + ... + a_{1n}.x_n + b_{11}.y_1 + b_{12}.y_2 + ... + b_{1m}.y_m\\ &x_2 = a_{21}.x_1 + a_{22}.x_2 + ... + a_{2n}.x_n + b_{21}.y_1 + b_{22}.y_2 + ... + b_{2m}.y_m\\ &\;\vdots \qquad\qquad \vdots\\ &x_n = a_{n1}.x_1 + a_{n2}.x_2 + ... + a_{nn}.x_n + + b_{n1}.y_1 + b_{n2}.y_2 + ... + b_{nm}.y_m\end{aligned} \tag{9}$$

which can be reformulated in matrix form:

$$X = AX + BY \tag{10}$$

Hence,

$$(I - A)X = BY \tag{11}$$

where $X = [x_1\ x_2\ ...\ x_n]^T$, $Y = [y_1\ y_2\ ...\ y_n]^T$.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

and

$$B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nm} \end{bmatrix}$$

A and B are technical coefficient matrices that characterize material flow in the process. For instance, a_{11} indicates the ratio of the substance S_1 which is used for the same substance as an output S_1^* and if this coefficient is less than 1, this means that any waste as an output will be formed. Note that for every i and j, the technical coefficients have to be non-negative and less or equal than 1. Since A is a square matrix and assuming that $(I – A)$ is invertible, then the inputs X can be calculated in terms of money as long as the waste outputs Y are known a priori, as below:

$$X = (I - A)^{-1}.B.Y \tag{12}$$

An input can remain unchanged in its amount during the process. In other words, in case any substance is entirely consumed, no waste will be generated as a matter of course. Hence, if this situation occurs, then $I – A$ will become singular where its inverse doesn't exist. For such a case, unchanged input can be removed from I-O Table so that invertibility is guaranteed and (12) can be computed.

Conversely, in order to convert the outputs into inputs, (12) can be modified as follows:

$$Y = B^{-1}.(I - A).X \tag{13}$$

It should be denoted that matrix B has to be square and invertible in (13). Condition that square matrix B will become singular commonly occurs by adding an output column that no waste is conducted. Therefore, there is no need to use any waste in a matrix in case it is not generated. Otherwise, we apply a new formula as

$$\overline{Y} = (B^T B)^{-1}.B^T (I - A)X \tag{14}$$

if $B^T B$ is non-singular.

III. Case Study for a Laptop Computer's Manufacturing Process

With the technological developments and the spread of electronic and electrical equipments in many different areas, the computers have dramatically penetrated into the human life and the market which has witnessed explosive growth since their introduction is also one of the fastest growing consumer markets. Today´s economy is not imaginable without computers; also the importance of computers in private life is continuously increasing. Computers are applicable in a versatile manner and part of modern life. Therefore, the number of global computer (particularly laptop computer) subscriptions is also growing.

While advances in technology give consumers the availability to upgrade to newer and more energy-efficient laptop computers, it is important to remember that older computers may not have reached the end of their useful life. On average, the original owner keeps a laptop computer for only three years. However, many computers are still in good working condition and can be recycled.

Laptop computers are even more relevant regarding sustainable development than desktop computers due to their shorter life span and their battery. Despite that they gain in popularity, the demand for notebooks increases strikingly in contrast to the demand for desktop PCs, which goes down [5]. Laptops provide users more and more advantages with respect to desktop computers. They are portable, they are becoming faster, lighter, and more powerful and the battery life is increasing. Furthermore, new technology lets users connect their desktop to their laptop from remote locations.

The notebook's pervasiveness has been fueled in part by a year-in-year fall in price (both nominal and real) to the consumer – notebooks which 10 years ago retailed for $2000 can now be purchased for as little as $300 [6]. Against this backdrop a recent report came as quite a shock: the manufacture and distribution of a 10 pound notebook computer requires an estimate 40,000 lb of materials to be processed and distilled [7]. Moreover, the average lifespan of that notebook is only 3 years, and at the end of that lifespan the device will most likely end up in a landfill alongside 55 million other computers disposed of each year [8]. It is estimated that only a small percentage of laptops is sent to recycling centers, while the remainder ends up in landfills or is stored away [9].

Laptop manufacturing is a simple process which involves assembly and packaging activities. These activities require electricity and emit air pollutants, waste water and solid waste.

The manufacturing process of a laptop computer can be covered mainly by five process: fabrication of semiconductor devices, manufacture of printed circuit boards, production of silicon wafers from raw materials, LCD manufacturing and finally assembly of the computer from component parts [5]. These parts are adapter, battery, screen, motherboard, chipset, integrated parts, inverter, CPU, fans, RAM, hard disk, keyboard, hinges, optical drive, case, operating system with software.

For simplicity, parts of a typical laptop computer are basically divided into eight input groups. Three material input groups: "Metal Components" consisting of valuable metals as copper, silver, gold, palladium; "Plastics" consisting of ABS-PC, silicon plastics and other plastics; "Other Components" consisting of tin, lead, steel, iron, nickel, glass and epoxy as a paint source. We also take into consideration five other input groups such as "Energy" that generally involves electricity, natural gas, water; "Tools" that are equipment used during the manufacturing process; "Know-How" that is needed to produce the components; "Labour" and "Software" installed in laptops. According to experts' judgements, the cost of each part is shared as sub-cost into input groups as it is shown in Table II. For a laptop computer that costs 559 $, 48 $ comes from metal components which makes 8,59 % of the total cost. The other percentages are obtained in the same way.

Based on approximate data acquired from experts, Table II depicts the inputs and outputs from a manufacturing process of a laptop. Note that the values in Table III are in terms of money per a typical laptop computer that costs 100 monetary units.

TABLE II
LAPTOP PRODUCTION COST WITH RESPECT TO THE INPUT GROUPS

	COST	Metal Components	Plastics	Other Components	Energy	Tools	Know-How (R&D)	Labour	Softwares
Adapter	**13**	5	1	1	1	2	2	1	0
Battery	**33**	2	1	16	4	4	5	1	0
Screen	**75**	5	5	35	9	7	11	3	0
Motherboard	**74**	5	2	17	7	6	33	4	0
Chipset	**16**	1	1	1	1	1	10	1	0
Integrated Parts	**28**	3	1	1	2	1	18	2	0
Inverter (LCD)	**24**	2	1	1	1	1	17	1	0
CPU	**99**	4	0	4	10	7	70	4	0
Fans - Cooling Pads	**15**	4	2	1	1	1	5	1	0
RAM	**23**	2	1	6	2	2	7	3	0
Hard disk	**40**	9	1	9	4	3	12	2	0
Keyboard	**13**	0	5	2	1	1	3	1	0
Hinges	**6**	1	0	1	1	1	1	1	0
Optical Drive	**12**	2	0	2	1	1	5	1	0
Case	**36**	3	8	4	4	4	7	6	0
Operating System + Software	**52**								52
TOTAL	**559**	48	29	101	49	42	206	32	52
PROPORTION	**1**	8,59%	5,19%	18,07%	8,77%	7,51%	36,85%	5,72%	9,30%

The explanation of the first row is given as follows. For a laptop of 100 monetary units (MU), there is 8.59 MU metal components (obtained from Table II). 6.44 MU of these metal parts can be recycled and used for the manufacturing of another laptop. 1.38 MU will be scrap and 0,77 MU will be waste chemicals.

Using the data in Table II, the coefficients matrices A and B respectively are obtained as:

$$A=\begin{pmatrix} 0,75 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0,28 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0,31 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0,19 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0,25 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0,31 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0,18 \end{pmatrix}$$

and

$$B=\begin{pmatrix} 1 & 0 & 0,06 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0,09 & 0 & 0,24 & 0 & 0 & 0 \\ 0 & 0 & 0,84 & 1 & 0,12 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0,63 & 0,16 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0,69 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0,15 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The relation between X (inputs-outputs) and Y (outputs) is given as:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{bmatrix} = \begin{pmatrix} 4 & 0 & 0,25 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1,39 & 0,13 & 0 & 0,34 & 0 & 0 & 0 \\ 0 & 0 & 1,23 & 1,46 & 0,18 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0,78 & 0,19 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1,33 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0,99 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0,15 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1,22 \end{pmatrix} \cdot \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \\ y_8 \end{bmatrix}$$

where x_1 through x_8 represent the unit cost of Metal Components, Plastics, Other components, Energy, Tools, Know-How (R&D), Labour and Software and y_1 through y_8 represent Scrap, Fuel, Waste Chemicals, Waste Paint, CO_2, Loss of Energy / Know-How / Labour, Tools Depreciation and Loss of Software Costs for a typical laptop computer manufacturing process.

Considering (12), the relationships between any output(s) and total input can be revealed. For instance, if it is desirable to reduce "Loss of Energy/Know-How/Labour", the relationship between corresponding inputs can be modified.

Table IV shows the relation between the output and the total input. As an example, the explanation of the fourth row is as follows. If we accept an increase in the loss of know-how (y6), the consumption of x4, x6, x7, x8 will be 82 %. Meanwhile, if we accept an increase in the loss of software cost (y8), then the consumption of the same inputs will be 74 %. This is a kind of sensitivity analysis which shows the correlation between the software and know-how cost. This means that if we concentrate on the y6 and y8 wastes, the consumption of the x4, x6, x7 and x8 inputs will be between 74 to 82 %.

TABLE III
INPUT - OUTPUT TRANSACTION IN MANUFACTURING PROCESS IN TERMS OF MONEY PER 100 MONETARY UNITS

	Metal Components	Plastics	Other Components	Energy	Tools	Know-How (R&D)	Labour	Softwares	Scrap	Fuel	Waste Chemicals	Waste Paint	CO2	Loss of Energy / Know-How / Labour	Tools Deprecition	Loss of Software Costs	TOTAL
Metal Components (x1)	6,44								1,38		0,77						8,59
Plastics (x2)		1,46								2,11	1,17		0,45				5,19
Other Components (x3)			5,67								10,4	1,78	0,23				18,1
Energy (x4)				1,68									1,18	5,91			8,77
Tools (x5)					1,86										5,65		7,51
Know-How (R&D) (x6)						11,5								25,4			36,9
Labour (x7)														5,72			5,72
Softwares (x8)								1,67								7,63	9,3
TOTAL	6,44	1,46	5,67	1,68	1,86	11,5	0	1,67	1,38	2,11	12,3	1,78	1,86	37	5,65	7,63	100

TABLE IV
SUMMARY OF MULTILATERAL COMPARISONS CONSISTING OF TWO OR MORE OUTPUT WITH TOTAL INPUT

Output1	Output2	Results	Inputs Consumed					Percentage Range of Consumption	Critical Percentages		
			Input1	Input2	Input3	Input4	Input5		Upper Bound	Ave. (x;x)	Lower Bound
y1	y2	Total Input	x1	x2				%71-%25	0,718	0,37	0,25
y1+y2	y3+y4	Total Input	x1	x2	x3			%65-%37	0,652	0,473	0,371
y6	y7	Total Input	x4	x5	x6	x7		%75-%74	0,752	0,747	0,742
y6	y8	Total Input	x4	x6	x7	x8		%82-%74	0,82	0,779	0,742
y7	y8	Total Input	x5	x8				%82-%75	0,82	0,785	0,752
y6	y7+y8	Total Input	x4	x5	x6	x7	x8	%78-%74	0,784	0,762	0,742

The third row shows that there is no correlation between the loss of know-how and tool depreciation (y6 and y7), since there will be a very slight change in the consumption of the inputs x4, x6, x7, x8 which is between 74-75 % in order to produce these outputs y6 and y7.

IV. CONCLUSION

Data availability is a difficult bottleneck to be conquered for compiling an IO Table. A feasible way to improve the data availability is to develop international standard for IO systems. Our model is referred as Monetary Input-Output model, since expressing everything in monetary units is much easier and the data availability for MIOT is much better than PIOT. The results showed in Table IV can be referred as an example of quantitatively sensitivity analysis. The scope of this paper and the aim of proposed model were to apply monetary I-O analysis to point out the importance of reusing know-how in order to reduce the production costs in a manufacturing process for a laptop computer. We conclude that, taking into account the information technology, the manufacturing cost is sensitive, besides other factors, to the recyclable part of know-how used. The real impact of the know-how cost on the manufacturing cost can be studied further by making significant improvement on the methodology development, because even this approach may help us to understand a complex manufacturing system, using too much simplification may also lose a lot of information.

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