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Title: Decision Analysis Framework for the Industrial Sustainability Analysis of the Surface Finishing Industry

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Abstract

Industrial sustainability is a vital issue in pursuing the long-term development of industrial systems. This paper introduces a material efficiency analysis method that extends the existing Ecological Input-Output Analysis (EIOA) method in combination with known and established sustainability metrics. This method can provide a comprehensive analysis of a large-scale industrial system and generate a system view for material efficiency improvement, which is valuable for synergistic regional efforts rather than solely for individual entity sustainability improvements.

Keywords: Industrial sustainability, input-output flow analysis

Introduction

Today, industries seek new approaches toward sustainable development, especially due to new challenges caused by industrial globalization, the increase in energy and raw material costs, the decrease in raw material availability, increased environmental and social pressures, and new technological advances. The concept of sustainability is often associated with the statement: any development should "meet the needs and aspirations of the present without compromising the ability to meet those of the future" while simultaneously achieving the triple bottom lines of sustainability (World Commission on Environment and Development, 1997). More specifically, it needs to: (i) create more value, wealth, and profits in the economically viable dimension, (ii) provide cleaner products with less raw resource consumption and waste generation in the environmentally compatible dimension, and (iii) have more socially benign products, services, and impacts in socially responsible dimension (Odum, 1996). Practically, sustainability will occur when the material and social conditions can be maintained or improved for human health and the environment *over time* without exceeding the ecological capabilities that support them (Sikdar, 2003).

Industrial sustainability, a critical level in the sustainability hierarchy, demands industries to significantly improve material and energy efficiencies, product quality and variety, and productivity, while simultaneously minimizing waste. While process systems within individual plants could be further improved, major opportunities exist within improvements among plants. That is, due to the strong interdependence among the member entities, one entity's effort to satisfy the triple bottom lines of sustainability is strongly dependent on the efforts of the other member entities as well (Singh & Lou, 2006).

This dependency extends directly to the raw material supply, waste, and product streams. As such, there is a need for a general and systematic analysis methodology that should be applicable to the study of the sustainable development of an entity, industry (composed of multiple entities), or industrial region (composed of multiple industries which work together to provide a final product). This paper introduces the use of the existing Ecological Input-Output Analysis (EIOA) methodology, as given by Bailey (2000), in combination with known and established sustainability metrics for the assessment of the state of industrial sustainability. From this type of analysis, the least sustainable industrial entities would be identified and methods toward improvement could then be suggested. Lastly, existing sustainability metrics will be used to describe the current status of sustainable development, foresee or predict a future state which they plan to reach within a given time frame, and finally, implement a path to achieve their industrial sustainability goals. As uncertainty issues arise with time, or as industrial goals change, the methodology can again be implemented and new sustainability targets can be determined.

EIOA Methodology

The authors view that the ecological IOA (EIOA) can be the mathematical core of a comprehensive methodology for industrial sustainability analysis, as it can be used to not only capture the *big picture* (the overall economic, environmental, and societal behavior of an industrial region), but also characterize the *detailed* inter relationships among the entities in the region.

EIOA Basics. The general mathematical framework for the sustainability decision-analysis methodology has been developed based on the existing EIOA method, with minor modifications. A detailed derivation of the equations is not given here, however the significant equations are discussed below.

Using the *production matrix*, ***P*** (Figure 1), we can quantitatively represent the inflows, outflows, and flows between nodes in a structured matrix format (Bailey, 2000). The *production matrix* is composed of flows at a specific time or instant and is the basis for the calculations within the context of EIOA. The general form of ***P***, assuming no accumulation within the nodes, is a 4n x 4n matrix, where n symbolizes the number of nodes in the system being analyzed.

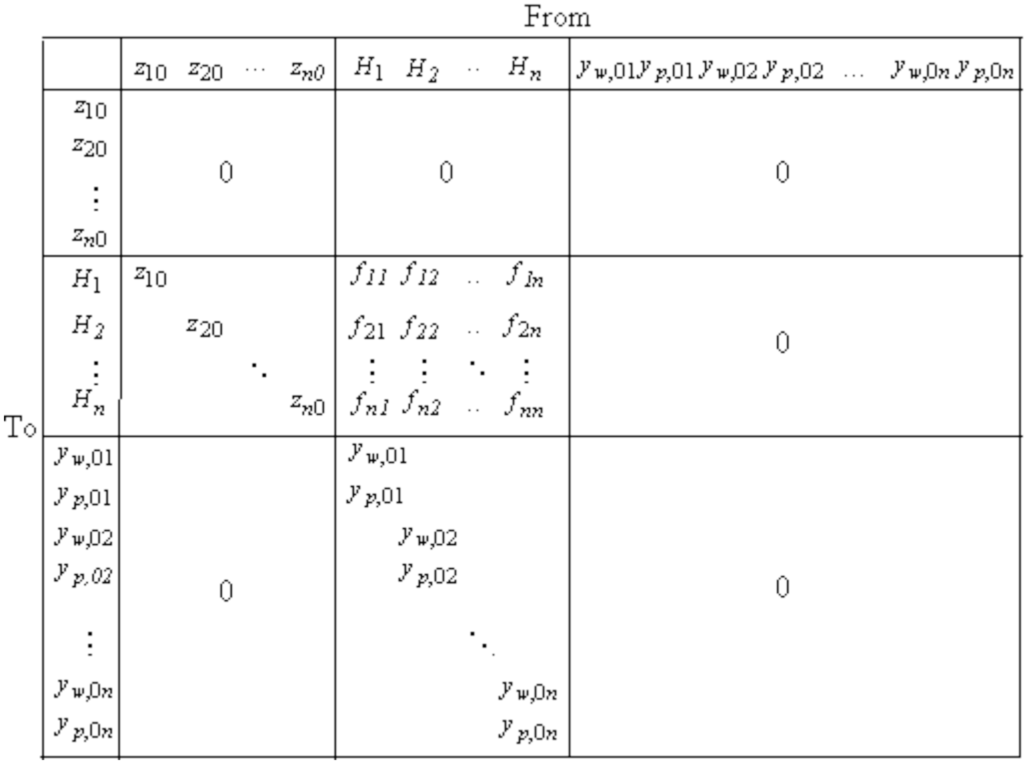
The notations used within the production matrix have the following meanings:

H_i = Node *i*, $i = 1,\cdots,n$

z_{i0} = Inflow to node *i* from outside the system

y_{0i} = Outflow from node *i* to outside the system

f_{ij} = Flow from node *j* to node *i*



From

To	$z_{10}\ z_{20} \cdots z_{n0}$	$H_1\ H_2 \cdots H_n$	$y_{w,01}\ y_{p,01}\ y_{w,02}\ y_{p,02} \ldots y_{w,0n}\ y_{p,0n}$
z_{10} z_{20} $\vdots$ z_{n0}	0	0	0
H_1 H_2 $\vdots$ H_n	z_{10} z_{20} $\ddots$ z_{n0}	$f_{11}\ f_{12} \cdots f_{1n}$ $f_{21}\ f_{22} \cdots f_{2n}$ $\vdots\ \vdots\ \ddots\ \vdots$ $f_{n1}\ f_{n2} \cdots f_{nn}$	0
$y_{w,01}$ $y_{p,01}$ $y_{w,02}$ $y_{p,02}$ $\vdots$ $y_{w,0n}$ $y_{p,0n}$	0	$y_{w,01}$ $y_{p,01}$ $y_{w,02}$ $y_{p,02}$ $\ddots$ $y_{w,0n}$ $y_{p,0n}$	0

Figure 1. Modified production matrix for a system consisting of *n* nodes, assuming no accumulation

Creaon inflow analysis. We can calculate $\boldsymbol{Q}^*$, the *instantaneous fractional inflow matrix*, by dividing each element P_{ij} of $\boldsymbol{P}$ by the sum of the i^{th} row of $\boldsymbol{P}$. If the sum of a row in $\boldsymbol{P}$ is zero, the values of all elements in that equivalent row in $\boldsymbol{Q}^*$ are set to zero to avoid division by zero. The *instantaneous fractional inflow matrix* thus takes the form:

$$Q^* = \begin{pmatrix} 0 & 0 & 0 \\ Q^*_{21} & Q^*_{22} & 0 \\ 0 & Q^*_{32} & 0 \end{pmatrix} \tag{1}$$

An element q^*_{ij} of $\boldsymbol{Q}^*$ is the *fraction* of total flow through a node, as related to P_{ij}. Defining the *transitive closure inflow matrix*, $\boldsymbol{N}^*$, as:

$$N^* = \left[I - Q^* \right]^{-1} \tag{2}$$

The *transitive closure inflow matrix*, which accounts for all direct and indirect dependency paths, is given as:

$$N^* = \begin{pmatrix} I & 0 & 0 \\ N^*_{21} & N^*_{22} & 0 \\ N^*_{31} & N^*_{32} & I \end{pmatrix} \tag{3}$$

Derivation of the input environ. The goal of input environ analysis is to determine the amount of inflow, internodal and intranodal flow, and throughflow is needed to support a unit of outflow from each node (Bailey, 2000). Although the greater part of the information needed to establish these flows (i.e. the inflows and throughflows needed to generate a unit outflow) is available through the *transitive closure inflow matrix*, $\boldsymbol{N}^*$, the internodal and intranodal flows that support a unit of outflow from each node can be determined from the following equation:

$$i_{P^*} = D_{n_i^*} Q^* \tag{4}$$

where i_{P^*}, the *normalized input environ matrix*, exists for each waste and product stream, and $D_{n_i^*}$ corresponds to a matrix whose diagonal elements are from n_i^* and whose non-diagonal elements are zero. The combination of N_{31}^*, N_{32}^*, and i_{P^*} result in a fully characterized input environ for a given system outflow. Based on these results, three separate but related environs, i.e. the traditional, actual, and percentage, can be generated. Distinctions between these environs are provided below.

> ***Traditional Environ***, E_i^T, i = waste or product stream of interest, (flow units/unit waste) – Values attained directly from N_{31}^*, N_{32}^*, and i_{P^*}.
>
> ***Actual Environ***, E_i^A, i = waste or product stream of interest, (flow units) – Values attained by multiplying the *traditional environ* by the flow magnitude of the waste stream of interest.
>
> ***Percentage Environ***, E_i^P, i = waste or product stream of interest, (%) – Values attained by dividing the *actual environ* by the magnitude of the flow rate of the stream of interest

The case study below will further elucidate the purpose and meanings of the input environs.

Quantification of Material Intensity Using Sustainability Metrics

Many sustainability indices have been proposed from different perspectives. However, the AIChE and IChemE Sustainability Metrics have become widely adopted methods in U.S. and European industries (IChemE, 2002; AIChE CWRT, 2000). AIChE's Center for Waste Reduction Technologies (CWRT) has developed a set of six baseline metrics, which are a proven, easy-to-use tool for sustainability quantification of industrial systems. This research utilizes the CWRT mass intensity metric, defined as total mass in / mass of product sold, as a method for environmental sustainability quantification. It is important to note that the smaller the material intensity metric the better, the reciprocal of the concept for "material efficiency," where the larger the better.

Additionally, IChemE has developed a set of indicators that can be used to measure the sustainable performance of an operating unit (IChemE, 2002). Our research uses the IChemE economic indicator for gross profit (gross margin), net sales minus the cost of goods sold, as a means for economic sustainability quantification.

The use of the environmental and economic indicators discussed above, in conjunction with the modified EIOA method and decision-making framework, will provide an understanding of the current state of sustainable development in the electroplating industry.

Introduction of a Decision-Making Framework

In order to provide meaningful sustainability decision-making abilities, the establishment of a second layer of analysis must be introduced. The EIOA environ calculations provide us with the basis to perform system decision analysis capabilities, by way of tracing the system inflows forward through the network. The introduction of a decision-making framework, which extends the capabilities of EIOA, will provide decision makers the ability to evaluate the current state of industrial sustainability for their given industry and be able to make systematic and strategic decisions based on their observations.

Our decision-making framework utilizes the system flow information to calculate the input environs and sustainability metrics. The data gathered from the environs and metrics are then used to identify potential areas for sustainability improvement within the network. The modified design is viable for implementation if improvements in both the environmental and economic sustainability have been achieved.

Although we have presented structures to be used as aides for the enhancement of environmental and economic sustainability, the third aspect, societal implications, is much more difficult to quantify and address from a chemical engineering viewpoint. Although metrics to quantify the societal aspects of sustainability exist, from the technology parlance, socially responsible technologies, i.e., technologies that provide quantifiable benefits for all, should be considered a satisfactory measure of social sustainability (Sikdar, 2003).

Case Study

Sustainability and the electroplating industry. Industrial globalization is exerting tremendous pressure on the electroplating industry. Low-cost imports from overseas and other globalization trends have led to changes in the industry. Recent industry estimates indicate job losses in the range of 25-30% between 2000 and 2003, with a corresponding reduction in sales of approximately 40% (EPA, 2004; USCB, 2005). In order to survive and be profitable in the future, the electroplating industry must seek ways for sustainable development. Cooperation and symbiosis efforts are also necessary between the electroplating industry and the industries it serves (i.e. automotive, airline, communications, construction, defense, electronics, etc.). Although these efforts do not presently exist, the establishment of sustainable development within industries will ultimately lead to improved profitability, efficiency, and productivity, and minimize waste.

Industrial sustainability, within the plating industry, refers to the need for a reduction in energy and raw material consumption, in addition to the need for waste minimization within the industry, all of which is critical for the future success of the electroplating industry. As such, we have examined an industrial case study that includes the electroplating and supporting industries, to clarify and demonstrate the capabilities of the generalized information flow analysis methodology for industrial sustainability assessment.

Desired information from the EIOA analysis. The generalized component-based EIOA method, as applied to industrial sustainability, allows for the examination of the dependencies between industrial suppliers, manufacturers, and end users. In the case study to follow, we look to answer questions such as how would the industry be affected environmentally and economically if the availability of a particular raw material chemical supply suddenly diminished or if more stringent governmental regulations were imposed on the amount of chemical waste that can be generated. The extended EIOA decision-making framework allows for such analysis in a concise mathematical manner.

Electroplating network description. The schematic diagram, displaying the variables used in the component based electroplating supply network, as applied to the modified EIOA, along with the initial flow values for the case, is shown in Figure 2.

This simplified electroplating network consists of two chemical suppliers to the electroplating plants (H1 & H2), two electroplating shops (H3 & H4), and two end users, in this case, two original equipment manufacturers (OEM) for the automotive industry (H5 & H6).

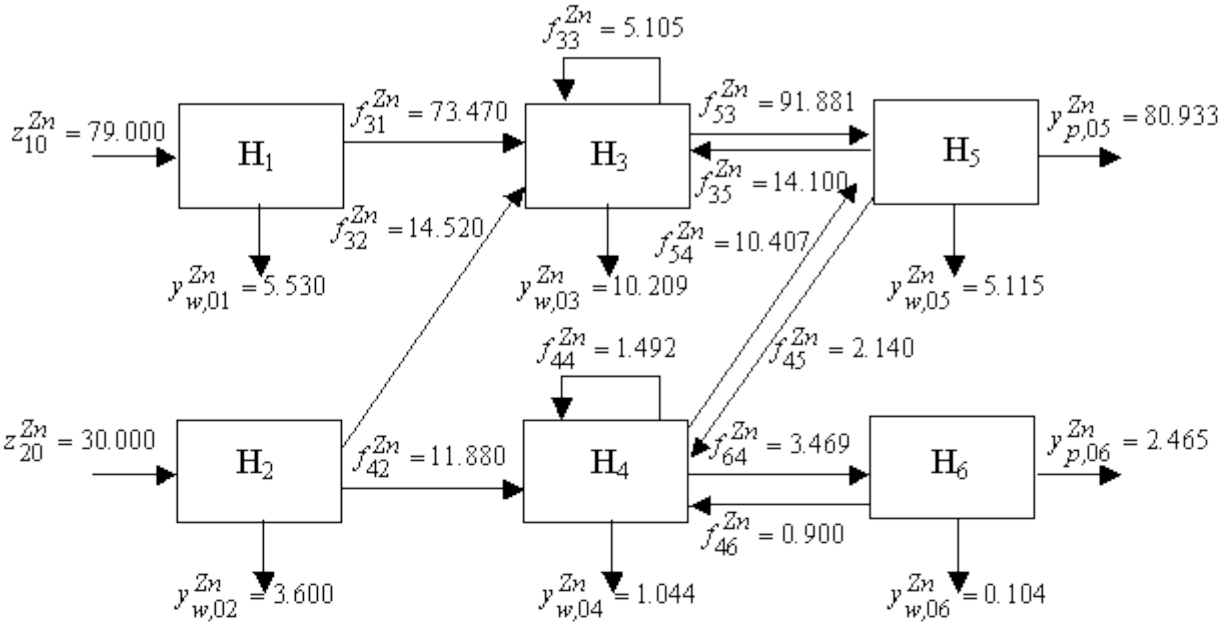


Figure 2. Schematic diagram of the variables used in the component based electroplating supply network, as applied to the modified EIOA.

EIOA calculations. Given the zinc flow information, we are able to apply the modified EIOA methodology in order to calculate the *production matrix*, ***P***, *instantaneous fractional inflow matrix*, $\boldsymbol{Q}^*$, *transitive closure matrix*, $\boldsymbol{N}^*$, and the *normalized input environ matrices*, i_{P^*}.

The combination of the *transitive closure inflow matrix* (which provides the inflow and throughflow relationships) and the *normalized input environ matrix* (which provides the intranodal and internodal flow relationships) results in the determination of the input environs for this zinc-plating network.

The input environs show us the breakdown of which flow components within a network make up a given waste or product outflow. They also allow us to trace the waste and product flows back to their origin, determine the flow needed to support a given outflow, and determine which flows an output is most dependent on. For our case study, the percentage environs show us that f_{31}^{Zn}, f_{33}^{Zn}, f_{35}^{Zn}, f_{32}^{Zn}, and z_{10}^{Zn} contribute the greatest percentage of their flow to the generation of plating shop #1's waste. Similarly, f_{54}^{Zn}, f_{53}^{Zn}, f_{32}^{Zn}, f_{33}^{Zn}, and f_{31}^{Zn} have the largest contributions to the generation of OEM #1's waste. Similar environs for each waste and product stream within the network can be generated, however are left out of this discussion for brevity.

Measurement of sustainability metrics. Additionally, as mentioned earlier, measurement of the environmental and economic metrics is needed to quantify the current level of sustainable development within the plating network. In order to measure gross profit, the economic metric of interest, we need to know the cost of zinc throughout the network.

Given the cost and the flow values from Figure 2, we are able to calculate both the economic and environmental metrics for the base case, with the results given in Table 1. It is clear from this analysis that supplier #1 and both OEM's have the best environmental sustainability within the network, however plating shop #1 has the best economic forecast, while OEM #2 is operating at a loss under the current design. Similarly, although the overall system is operating at a net profit ($354,785) the mass intensity metric suggests that there is much room for improvement.

Table 1. Zinc plating network mass intensity and gross profit metric values.

	Mass Intensity	Gross Profit ($/yr)
Overall System	1.307	354,785
Chemical Supplier #1	1.075	17,617
Chemical Supplier #2	1.136	4,668
Plating Shop #1	1.167	182,354
Plating Shop #2	1.183	21,039
Automotive OEM #1	1.053	121,581
Automotive OEM #2	1.031	(2,038)

Following the steps listed in the decision-making framework by combining the environmental and economic sustainability forecasts, suggestions for modification to the plating network can be introduced, such as the need for the plating companies to increase their internal reuse of zinc and modify their chemical supply ratios to purchase from the supplier with the lowest prices. Measurement of the environmental and economic metrics, after modifications to the system are made, would quantify the magnitude of environmental sustainability improvements that are possible and the cost associated with those modifications.

Concluding Remarks

Through the use of input environs, we are able to trace industrial waste and product outflows back to their origins, determine how much inflow, inter and intra nodal flow, and throughflow is necessary to support the outflow, and determine which flows the output is most dependent on. The combination of the EIOA modeling, the CWRT and IChemE metrics, and the extended decision-making framework presented in this work can be quite useful in evaluating the current state of industrial sustainability and in determining the potential for sustainable development, after modifications to a given network, of any topology, have been made. Also of importance, this framework introduces the synergistic use of both environmental and economic factors in the development of improved industrial sustainability.

Acknowledgments

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Literature Cited

AIChE Center for Waste Reduction Technologies (CWRT). *Collaborative Projects – Focus Area: Sustainable Development*, AIChE: New York, 2000.

Bailey, R. Input-Output Modeling of Material Flows in Industry. Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, GA. 2000.

EPA. *Toxic Release Inventory*, 2004.

IChemE. *The Sustainability Metrics – Sustainable Development Progress Metrics Recommended for use in the Process Industries*, IChemE: Rugby, UK, 2002;

Odum, H. T. *Environmental accounting: Emergy and Environmental Decision Making*; John Wiley & Sons: New York, 1996.

Sikdar, S. K. Sustainable Development and Sustainability Metrics. *AIChE J.* 2003, 49(8), 1928-1932.

Singh, A.; Lou, H. H. Hierarchical Pareto Optimization for the Sustainable Development of Industrial Ecosystems. *Ind. Eng. Chem. Res.* 2006, 45, 3265-3279.

US Census Bureau. Electroplating, Plating, Polishing, Anodizing, and Coloring: 2002, January 2005.

World Commission on Environment and Development. *Our Common Future*; Oxford University Press: New York, 1987.