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Ecological Input−Output Analysis-Based Sustainability Analysis of Industrial Systems

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Industrial sustainability is a vital issue in pursuing the long-term development of industrial systems. This paper utilizes the existing Ecological Input−Output Analysis (EIOA) method, in combination with known and established environmental (mass intensity) and economic (gross profit) sustainability metrics, to (i) create a systematic analysis methodology capable of evaluating various decisions, which are made by individual plant management for the benefit of their own company, and (ii) determine which option results in the best route for improving sustainable development, at the plant, industry, and regional levels. Such information will be valuable for the synergistic sustainability improvements of both individual entities as well as industrial regions. To demonstrate the efficacy of this methodology, a case study involving a network of different industries is presented. Sustainability of the base case and two modified cases is assessed. The one with the highest positive environmental and economic sustainability impact is recommended.

Introduction

The concept of sustainability is often associated with the following 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.[1] More specifically, it must (i) create more value, wealth, and profits in the economically viable dimension; (ii) provide cleaner products with less raw material consumption and waste generation in the environmentally compatible dimension; and (iii) have more socially benign products, services, and impact in the socially responsible dimension.[2] 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.[3]

To work toward improved industrial sustainability, which is a critical level in the sustainability hierarchy, industries must significantly improve their material and energy efficiencies, product quality and variety, and productivity, while simultaneously minimizing waste. A multitude of methods have been developed and utilized to assess the environmental impact that material flows have on a system. One such assessment method includes Material Flow Analysis (MFA), which refers to a family of different techniques, each focusing on various aspects of inlet material flows.[4] Specific MFA methods include Total Material Requirement (TMR), which concentrates on the study of material inputs into a society at the national level; Material Intensity Per Unit Service (MIPS), which focuses on the material flow of a specific product or service; and substance flow analysis (SFA), which concentrates on the flows of specific substances within a region or from "cradle-to-grave."[5] A second type of flow analysis method is Input−Output Analysis (IOA), which dates back to 1758 and Quesnay's *Tableau Economique*, which modeled the interdependencies between economic activities at a company level.[6] The most significant step in bringing the IOA into its current form was taken almost two centuries later, when Leontief applied input−output economics to study the U.S. economy.[7] The significance of Leontief's work was his ability to expand IOA to the study of a large-scale system. Although IOA was traditionally applied for the macroeconomic study of monetary flows through various economic sectors, it has more recently been applied to the modeling of material and energy flows and their environmental impact analysis on various ecosystems.[8−14] Furthermore, recent work by Bailey and coworkers provided a comprehensive review of the traditional sector-based input-output approaches that are integrated with materials, energy, and/or environmental impacts.[15,16]

Today, industries seek new approaches toward sustainable development, especially because of new challenges caused by industrial globalization, increased energy and raw material costs, decreased raw material availability, increased environmental and social pressures, and new technological advances. Although process systems within individual plants could be further improved, major opportunities exist within improvements among plants. That is, an industrial regional synergistic effort on material and energy use efficiency and waste reduction is more critical for sustainable development.

Note that, because of the strong interdependence among the member entities, one entity's effort to satisfy the triple bottom lines of sustainability also is strongly dependent on the efforts of the other member entities.[17] The convoluted inter-relationships must be quantified, and they should reflect both spatial and temporal aspects. 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 final products).

The methodology should be predictive in nature, addressing uncertain issues that may arise in the future (i.e., enhanced government regulations, change in consumer demand, etc.), thus allowing for a comprehensive analysis of the industry's current and predicted future state of sustainability. As such, this paper

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employs the existing Ecological IOA (EIOA) method, as introduced by Bailey et al.,[16] in conjunction with the use of established environmental (mass intensity) and economic (gross profit) sustainability metrics, to develop a methodology capable of analyzing the current and future state of industrial sustainability within an industrial region composed of chemical suppliers, plating companies, and automotive OEM manufacturers.

As a result of the analysis, by way of the decision-analysis framework to be introduced, industrial entities and overall networks will be able to evaluate and assess various decisions, which are made by individual plant management for their own benefit, and how the proposed modifications will affect the industrial network as a whole. In addition, the framework allows industrial zones to (i) describe their current status of sustainable development, (ii) identify changes to the system that must be made to realize an improved future state of sustainable development, and finally, (iii) evaluate various potential future production schedules, which they plan to reach within a given time frame, to determine which option provides the best route toward improved industrial sustainable development, at the plant, industry, and regional levels. As uncertainty issues arise with time, or as industrial goals change, the methodology can again be implemented and new sustainability targets can be determined for the synergistic sustainability improvements of the industrial region.

EIOA Methodology

The core of IOA is the input−output mathematical framework, which allows a modeler to fully consider direct and indirect relationships among conserved flows, which could include either material or energy flows, in a system. Previous works have implemented the input−output mathematics to model material and energy flows in the characterization of physical flows in an industry.[15,16] The mathematics are presented from an ecological perspective, culminating in the capacity to trace flows with environs. [Environs represent all direct and indirect flows necessary to produce a specific outflow.] The addition of existing sustainability metrics is the central link in connecting input−output flow *analysis* to *synthesis*, as demonstrated by connecting the flow metrics to both environmental objectives and controllable aspects of flow models. Thus, changes to the existing flow systems could be synthesized to predict a future flow system, advising areas for improved system behavior.

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

EIOA Limitations. Input−output flow analysis has been shown to be a powerful tool in tracing flows forward through a system through the use of environs.[15] To apply this tool toward the industrial sustainability analysis and decision making of a given industry, some modifications to EIOA must be addressed. Currently, the EIOA methodology does not differentiate between waste and product output from a node; rather, all outputs from the system are lumped into a single term. From a sustainability point of view, specifically for environmental analysis, it is extremely important for a distinction to be made regarding the output being waste to the environment or product sold to consumers. This allows one to trace the waste streams back to their origins, without including the product output in the calculations.

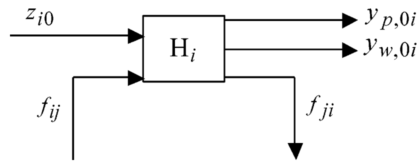

Figure 1. Basic elements of input−output flow analysis.

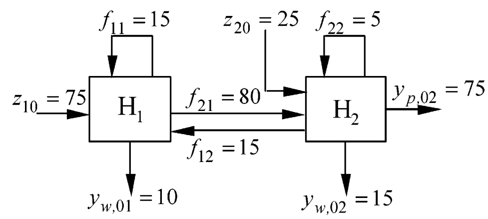

Figure 2. Two-node example case (flows are given in units of 10^3 lbs/yr).

Moreover, the EIOA provides the ability for decision analysis regarding the origins of each outflow and the fate of each inflow to the system. However, to provide meaningful sustainability decision-analysis abilities, a second layer of analysis must be introduced. The combination of the EIOA calculations, along with the decision-analysis methodology, will provide an all encompassing measure and evaluation of the current state of industrial sustainability for a given industry.

EIOA Basics. EIOA consists of the analysis of a system's nodes and flows, where a node represents any processing unit, industrial entity, or individual subsystem of interest and a flow characterizes an interested material, energy, or other conservative input and output from a node. Figure 1 shows a representation of the basic elements of input−output flow analysis. We see that the raw material input to a node i is denoted as z_{i0} (i.e., from the environment, which is denoted as 0, to node i). Similarly, the streams that run from a node to the environment, where a distinction has been made between a waste or product stream, are denoted as $y_{w,0i}$ or $y_{p,0i}$ respectively. Last, internodal flows from node j to node i are symbolized as f_{ij}. A simple two-node example, as shown in Figure 2, will be utilized throughout this section to aid in clarifying the mathematical concepts to be introduced. This example problem consists of two plants (H_1 and H_2), each consisting of a raw material input (z_{10} and z_{20}), internal recycle (f_{11} and f_{22}), internodal flow (f_{21} and f_{12}), and waste output streams ($y_{w,01}$ and $y_{w,02}$). In addition, node H_2 generates a product stream ($y_{p,02}$). Using the production matrix, **P** (Figure 3), we can quantitatively represent the inflows, outflows, and flows between nodes in a structured matrix format.[15] 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 $4n \times 4n$ 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 is the ith node ($i = 1, 2, ..., n$); z_{i0} is the inflow to the ith node from outside the system; $y_{w,0i}$ (or $y_{p,0i}$) is the waste (or product) outflow from the ith node to outside the system; and f_{ij} is the flow from the jth node to the ith node.

For simplification, we can divide **P** into submatrices, as shown below in eqs 1−4:

$$\mathbf{P} = \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{P}_{21} & \mathbf{P}_{22} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_{32} & \mathbf{0} \end{pmatrix} \tag{1}$$

where

From

$$
\text{To}\quad
\begin{array}{c|c|c|c}
 & z_{10}\ \ z_{20}\ \ \cdots\ \ z_{n0} & H_1\ \ H_2\ \ \cdots\ \ H_n & y_{w,01}\ y_{p,01}\ y_{w,02}\ y_{p,02}\ \cdots\ y_{w,0n}\ y_{p,0n} \\
\hline
\begin{array}{c} z_{10} \\ z_{20} \\ \vdots \\ z_{n0} \end{array} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\
\hline
\begin{array}{c} H_1 \\ H_2 \\ \vdots \\ H_n \end{array} &
\begin{array}{cccc} z_{10} & 0 & \dots & 0 \\ 0 & z_{20} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & z_{n0} \end{array} &
\begin{array}{cccc} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1} & f_{n2} & \cdots & f_{nn} \end{array} & \boldsymbol{0} \\
\hline
\begin{array}{c} y_{w,01} \\ y_{p,01} \\ y_{w,02} \\ y_{p,02} \\ \vdots \\ y_{w,0n} \\ y_{p,0n} \end{array} & \boldsymbol{0} &
\begin{array}{cccc} y_{w,01} & 0 & \dots & 0 \\ y_{p,01} & 0 & \dots & 0 \\ 0 & y_{w,02} & \dots & 0 \\ 0 & y_{p,02} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & y_{w,0n} \\ 0 & 0 & \dots & y_{p,0n} \end{array} & \boldsymbol{0}
\end{array}
$$

Figure 3. Modified production matrix for a system consisting of *n* nodes, assuming no accumulation.

$$\mathbf{P}_{21} = \mathrm{diag}(z_{i0}) \qquad (i = 1, ..., n) \tag{2}$$

$$\mathbf{P}_{22} = [f_{ij}]_{n\times n} \qquad (i, j = 1, ..., n) \tag{3}$$

$$\mathbf{P}_{32} = \mathrm{diag}(y_{k,0i}) \qquad (i = 1, ..., n;\ k = w, p) \tag{4}$$

Furthermore, the throughflow (T_k) of node H_k is defined as the rate of energy or material flow through node k.[15] Mathematically, the throughflow is defined as follows.

$$T_k = \sum_{j=1}^{n} f_{kj} + z_{k0} \qquad (k = 1, ..., n) \tag{5}$$

$$T_k = \sum_{i=1}^{n} f_{ik} + y_{p,0k} + y_{w,0k} \qquad (k = 1, ..., n) \tag{6}$$

Simply stated, throughflow is either the sum of all inflows to a node (eq 5, which equals the sum of the rows in **P**) or the sum of all outflows from a node (eq 6, which equals the sum of the columns in **P**) and the two throughflows are equal to each other.

Given the production matrix **P** and throughflows, we can perform an inflow analysis, which allows us to trace system outputs back to their origins by determining the amount of direct and indirect flows within the system needed to generate that outflow.[15]

Referring back to the example problem, it is clear that node H_1 requires 75 × 10^3 lbs/yr of raw material input, along with 15 × 10^3 lbs/yr of recycle from node H_2 and 15 × 10^3 lbs/yr of internal recycle to generate 80 × 10^3 lbs/yr of product to be sold to H_2 and 10 × 10^3 lbs/yr of waste to the environment. Similarly, node H_2 requires 20 × 10^3 lbs/yr of raw material input, along with the 80 × 10^3 lbs/yr of product from H_1 and 5 × 10^3 lbs/yr of internal recycle to generate 70 × 10^3 lbs/yr of product to be sold to society and 15 × 10^3 lbs/yr of waste to the environment. The production matrix **P** for this case can be created and is supplied in Table 1. Furthermore, the throughflow for each node can be calculated using either eq 5 or eq 6, resulting in T_1 = 105 × 10^3 lbs/yr and T_2 = 110 × 10^3 lbs/yr.

Table 1. Production Matrix (P) for the Two-Node Example Case

P	z_{10}	z_{20}	H_1	H_2	$y_{w,01}$	$y_{p,01}$	$y_{w,02}$	$y_{p,02}$
z_{10}	0	0	0	0	0	0	0	0
z_{20}	0	0	0	0	0	0	0	0
H_1	75	0	15	15	0	0	0	0
H_2	0	25	80	5	0	0	0	0
$y_{w,01}$	0	0	10	0	0	0	0	0
$y_{p,01}$	0	0	0	0	0	0	0	0
$y_{w,02}$	0	0	0	15	0	0	0	0
$y_{p,02}$	0	0	0	75	0	0	0	0

Inflow Analysis. To begin the inflow analysis, Bailey and co-workers[15,16] referred to this inflow analysis as a creaon inflow analysis, we must first express the flow from node H_j to node H_i (denoted as f_{ij}) as a proportion (q^*_{ij}) of the total throughflow of node H_i (T_i), i.e.,

$$f_{ij} = q^*_{ij} T_i \tag{7}$$

Substitution of eq 7 into eq 6 allows us to express the throughflow of H_j (T_j) as

$$T_j = \sum_{i=1}^{n} q^*_{ij} T_i + y_{w,0j} + y_{p,0j} \qquad (j = 1, ..., n) \tag{8}$$

Converting eq 8 into matrix form, we find

$$\mathrm{T}' = \mathbf{Q}^*_{22}\mathrm{T}' + \mathrm{y}'_{w} + \mathrm{y}'_{p} \tag{9}$$

Here, $\mathbf{Q}^*_{22}$ is an $n \times n$ submatrix of $\mathbf{Q^*}$, the instantaneous fractional inflow matrix, which is similar to the submatrices of **P** (see eq 10 below). We can calculate $\mathbf{Q^*}$ by dividing each element P_{ij} of **P** by the sum of the ith row of **P** (which is equal to T_i). If the sum of a row in **P** is zero, the values of all elements in that equivalent row in **Q*** are set to zero, to avoid division by zero.

$$\mathbf{Q}^* = \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{Q}_{21}^* & \mathbf{Q}_{22}^* & \mathbf{0} \\ \mathbf{0} & \mathbf{Q}_{32}^* & \mathbf{0} \end{pmatrix} \tag{10}$$

An element q_{ij}^* of **Q*** is the fraction of T_i that is related to P_{ij}. Each element q_{ij}^* of $\mathbf{Q}_{22}^*$ is the proportion of T_i attributable to f_{ij}. Similarly, each element q_{ij}^* of $\mathbf{Q}_{21}^*$ is the proportion of T_i attributed to z_{j0}, and each q_{ij}^* of $\mathbf{Q}_{32}^*$ is the proportion of outflow y_{0i} stemming from node H_j.

Solving eq 9 for $\mathbf{T}'$ results in the following expression:

$$\mathbf{T}' = [\mathbf{y}_w' + \mathbf{y}_p'][\mathbf{I} - \mathbf{Q}_{22}^*]^{-1} \tag{11}$$

Defining $\mathbf{N}_{22}^*$ as

$$\mathbf{N}_{22}^* = [\mathbf{I} - \mathbf{Q}_{22}^*]^{-1} \tag{12}$$

Equation 11 can be written as

$$\mathbf{T}' = [\mathbf{y}_w' + \mathbf{y}_p']\mathbf{N}_{22}^* \tag{13}$$

Again, the basis for the inflow analysis was to determine the origins of each outflow from the system. Equation 13 tells us just that, as the throughflow for each node is divided up among its contribution to the waste and product outflows. This is more clearly seen in eq 14, because each throughflow is expressed mathematically as the sum of contributions to each outflow:

$$T_k = \sum_{j=1}^{n} y_{w,0j}\, n_{jk}^* + y_{p,0j}\, n_{jk}^* \qquad (k = 1, ..., n) \tag{14}$$

Because **N*** is equal to the inverse of (**I** − **Q***), the configuration of the transitive closure inflow matrix (**N***) is given as

$$\mathbf{N}^* = \begin{pmatrix} \mathbf{I} & \mathbf{0} & \mathbf{0} \\ \mathbf{N}_{21}^* & \mathbf{N}_{22}^* & \mathbf{0} \\ \mathbf{N}_{31}^* & \mathbf{N}_{32}^* & \mathbf{I} \end{pmatrix} \tag{15}$$

The transitive closure inflow matrix is a matrix that accounts for all direct and indirect nodal inter-relationships.[15] Each element n_{ij}^* of $\mathbf{N}_{22}^*$ is the throughflow in H_j (T_j) necessary to produce a unit of flow terminating in node H_i. Similarly, each element n_{ij}^* of $\mathbf{N}_{21}^*$ represents the inflows (z_{j0}) necessary to produce a unit of flow terminating in node H_i, each n_{ij}^* of $\mathbf{N}_{31}^*$ represents the amount of inflow (z_{j0}) needed to produce a unit of outflow ($y_{w,0j}$ or $y_{p,0j}$), and each n_{ij}^* of $\mathbf{N}_{32}^*$ is the throughflow in H_j (T_j) necessary to produce a unit of outflow ($y_{w,0j}$ or $y_{p,0j}$) from H_i.[15]

The following paragraphs refer back to the example problem introduced earlier. As mentioned above, to calculate the instantaneous fractional inflow matrix (**Q***), each element P_{ij} of **P** must be divided by the sum of the ith row of matrix **P** (which is equal to T_i). For example, element q_{34}^* of **Q*** is calculated by dividing element P_{34} (which is equal to 15) by the sum of the third row (which is equal to 105). Therefore q_{34}^* = 15/105 = 0.143. The complete instantaneous fractional inflow matrix for the example problem is provided in Table 2.

Furthermore, from eq 12, **Q*** can be used to compute the transitive closure inflow matrix, **N***, which is displayed in Table 3. To clarify the meaning of the values contained within the transitive closure inflow matrix, the specifics of the third row will be considered. The third row indicates that inflows of 0.954 and 0.045 flow units (n_{31}^* and n_{32}^*, respectively) and throughflows of 1.337 and 0.200 (T_1 and T_2, respectively) are necessary to produce one unit of flow ending up in H_1. Although a similar analysis can be performed for the remaining rows, they are left out of this discussion, for the sake of brevity.

Table 2. Instantaneous Fractional Inflow Matrix (Q*) for the Two-Node Example Case

Q*	z_{10}	z_{20}	H_1	H_2	$y_{w,01}$	$y_{p,01}$	$y_{w,02}$	$y_{p,02}$
z_{10}	0	0	0	0	0	0	0	0
z_{20}	0	0	0	0	0	0	0	0
H_1	0.714	0	0.143	0.143	0	0	0	0
H_2	0	0.227	0.727	0.045	0	0	0	0
$y_{w,01}$	0	0	1.000	0	0	0	0	0
$y_{p,01}$	0	0	0	0	0	0	0	0
$y_{w,02}$	0	0	0	1.000	0	0	0	0
$y_{p,02}$	0	0	0	1.000	0	0	0	0

Table 3. Transitive Closure Inflow Matrix (N*) for the Two-Node Example Case

N*	z_{10}	z_{20}	H_1	H_2	$y_{w,01}$	$y_{p,01}$	$y_{w,02}$	$y_{p,02}$
z_{10}	1.000	0	0	0	0	0	0	0
z_{20}	0	1.000	0	0	0	0	0	0
H_1	0.954	0.045	1.337	0.200	0	0	0	0
H_2	0.727	0.272	1.018	1.120	0	0	0	0
$y_{w,01}$	0.954	0.045	1.337	0.200	1.000	0	0	0
$y_{p,01}$	0	0	0	0	0	1.000	0	0
$y_{w,02}$	0.727	0.272	1.018	1.120	0	0	1.000	0
$y_{p,02}$	0.727	0.272	1.018	1.120	0	0	0	1.000

Below, a discussion of the construction of the input environs, as described by Bailey,[15] is given. Also note that Bailey[15] also derived a second type of environ—namely, the output environ—which determines how much outflow, internodal and intranodal flow, and throughflow are generated by a unit of inflow to each node. Although this information also could prove to be useful in an industrial sustainability analysis, it is not the focus of this paper and, hence, will not be discussed further. The input environ terminology will be used throughout the remainder of this paper, to maintain consistency with previous works.

Derivation of the Input Environ. The goal of the input environ analysis is to determine the amount of inflow, internodal and intranodal flow, and throughflow needed to support a unit of outflow from each node.[15] 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, **N***, the internodal and intranodal flows that support a unit of outflow from each node are yet to be identified. However, eq 7 provides an approach to do just that.

Let $\mathbf{D}_{n_i^*}$ correspond to a matrix whose diagonal elements are from n_i^* of an outlet stream and whose nondiagonal elements are zero. Equation 7 can then be rearranged with $\mathbf{D}_{n_i^*}$ replacing the throughflow and a normalized input environ matrix ($\boldsymbol{i}_{\mathbf{P}*}$) being substituted for the internodal and intranodal flows (f_{ij}), resulting in

$$\boldsymbol{i}_{\mathbf{P}*} = \mathbf{D}_{n_i^*}\mathbf{Q}^* \tag{16}$$

To clarify these calculations, we will again refer back to the two-node example problem. To calculate the input environs for $y_{w,01}$, which is the fifth row in **N*** (Table 3), the first step is to determine the structure of the $\mathbf{D}_{n_5^*}$ and $\mathbf{5}_{\mathbf{P}*}$ matrices. Again, $\mathbf{D}_{n_5^*}$ corresponds to the matrix whose diagonal elements are from the fifth row of **N***, whose results are given in Table 4. From eq 16, we can then calculate $\mathbf{5}_{\mathbf{P}*}$ (see Table 5). Again, similar calculations can be performed for the remaining output

Table 4. Two-Node Example Case, Matrix $\mathbf{D}_{n_5^*}$

$\mathbf{D}_{n_5^*}$	z_{10}	z_{20}	H_1	H_2	$y_{w,01}$	$y_{p,01}$	$y_{w,02}$	$y_{p,02}$
z_{10}	0.954	0	0	0	0	0	0	0
z_{20}	0	0.045	0	0	0	0	0	0
H_1	0	0	1.337	0	0	0	0	0
H_2	0	0	0	0.200	0	0	0	0
$y_{w,01}$	0	0	0	0	1.000	0	0	0
$y_{p,01}$	0	0	0	0	0	0	0	0
$y_{w,02}$	0	0	0	0	0	0	0	0
$y_{p,02}$	0	0	0	0	0	0	0	0

Table 5. Waste Stream $y_{w,01}$ Normalized Input Environ Matrix for the Two-Node Example Case

$\mathbf{5}_{\mathbf{P}^*}$	z_{10}	z_{20}	H_1	H_2	$y_{w,01}$	$y_{p,01}$	$y_{w,02}$	$y_{p,02}$
z_{10}	0	0	0	0	0	0	0	0
z_{20}	0	0	0	0	0	0	0	0
H_1	0.955	0	**0.191**	**0.191**	0	0	0	0
H_2	0	0.045	**0.145**	**0.009**	0	0	0	0
$y_{w,01}$	0	0	1.000	0	0	0	0	0
$y_{p,01}$	0	0	0	0	0	0	0	0
$y_{w,02}$	0	0	0	0	0	0	0	0
$y_{p,02}$	0	0	0	0	0	0	0	0

Table 6. Plant H_1 Waste Stream ($y_{w,01}$) Traditional, Actual, and Percentage Environs for the Two-Node Example Case

variable	$E^{T}_{w,01}$	$E^{A}_{w,01}$	$E^{P}_{w,01}$
z_{10}	0.954	9.540	12.720
z_{20}	0.045	0.450	1.800
f_{11}	0.191	1.910	66.667
f_{21}	0.145	1.450	0.000
f_{22}	0.009	0.090	0.000
f_{12}	0.191	1.910	12.733
$y_{w,01}$	1.000	10.000	14.500
$y_{w,02}$	0.000	0.000	0.600
$y_{p,02}$	0.000	0.000	2.547
T_1	1.337	13.370	N/A[a]
T_2	0.200	2.000	N/A[a]

[a] Calculation not performed.

streams (namely, $y_{w,02}$ and $y_{p,02}$); however, they are omitted from this discussion, for the sake of brevity.

The combination of $\mathbf{N}^*_{31}$, $\mathbf{N}^*_{32}$, and $\boldsymbol{i}_{\mathbf{P}^*}$ results in a fully characterized input environ for a given system outflow. Based on these results, three separate but related environs (i.e., traditional, actual, and percentage) can be generated. Distinctions between these environs are provided below.

Traditional Environ. In the traditional environ, represented as E_i^{T}, i denotes the waste or product stream of interest (flow units/unit waste), and the values are attained directly from $\mathbf{N}^*_{31}$, $\mathbf{N}^*_{32}$, and $\boldsymbol{i}_{\mathbf{P}^*}$.

Actual Environ. In the actual environ, represented as E_i^{A}, i denotes the waste or product stream of interest (flow units), and the values are attained by multiplying the traditional environ by the flow magnitude of the waste stream of interest.

Percentage Environ. In the percentage environ, represented as E_i^{P}, i denotes the waste or product stream of interest (expressed as a percentage), and the values are attained by dividing the actual environ by the magnitude of the flow rate of the stream of interest.

The traditional, actual, and percentage environs for the waste stream from plant H_1 ($y_{w,01}$), from the working example problem, are provided in Table 6. The traditional environs are taken directly from **N*** (Table 3) and $\mathbf{5}_{\mathbf{P}^*}$ (Table 5), and the actual environs are calculated by multiplying the traditional environ by the flow value for $y_{w,01}$, which is equal to 10×10^3 lbs/yr. The percentage environ for z_{10}, for example, is calculated by dividing the actual environ (9.540) by the magnitude of the flow rate of the stream of interest ($z_{10} = 75.0$) and then multiplying by 100. Therefore, the percentage environ for stream z_{10} is $(9.540/75) \times 100 = 12.720$.

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

Quantification of Environmental and Economic Sustainability

With the triple-bottom-line concerns of the economy, environment, and society, the development of sustainable technologies has attracted great attention.[18,19] Many sustainability indices have been proposed from different perspectives. However, usage of the AIChE and IChemE Sustainability Metrics have become widely adopted methods in U.S. and European industries.[20,21] 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 the sustainability quantification of industrial systems. The CWRT mass intensity metric is utilized (which is defined as the ratio of the total mass in per mass of product sold) as a method for environmental sustainability quantification. It is important to note that the smaller the mass intensity metric, the better, which is the reciprocal of the concept for "material efficiency," where the larger the metric the better.

In addition, IChemE has developed a set of indicators that can be used to measure the sustainable performance of an operating unit.[20] 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.

This sustainability decision analysis methodology, which implements the use of these environmental and economic indicators, in conjunction with the modified EIOA method, will provide an understanding of the current state of sustainable development in an industrial zone, identify changes to the system which must be made to improve the environmental and economic sustainability, and implement the required modifications to achieve the improved industrial sustainability goals.

Although currently, the only CWRT sustainability metric that is directly applicable to our case study is the mass intensity metric, it is important to note that the use of existing metrics, in conjunction with the EIOA methodology, provides a systematic industrial sustainability modeling and analysis technique. Future case studies can easily be extended to include the analysis of energy, water usage, pollutants, human health, and ecotoxicity metrics as well.

Decision-Analysis Framework

As discussed previously, to provide meaningful sustainability decision-analysis 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 outflows back to their origins. The introduction of a decision-analysis 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 allow them to make systematic and strategic decisions, based on the calculations.

Although this paper does not discuss the optimization of a network to achieve the optimal design with regard to the triple bottom lines of sustainability, the introduction of the decision-analysis methodology (i) provides a systematic industrial sustainability analysis tool that is capable of assessing the current state of sustainable development within an industrial region, (ii) identifies changes to the system that must be made to realize

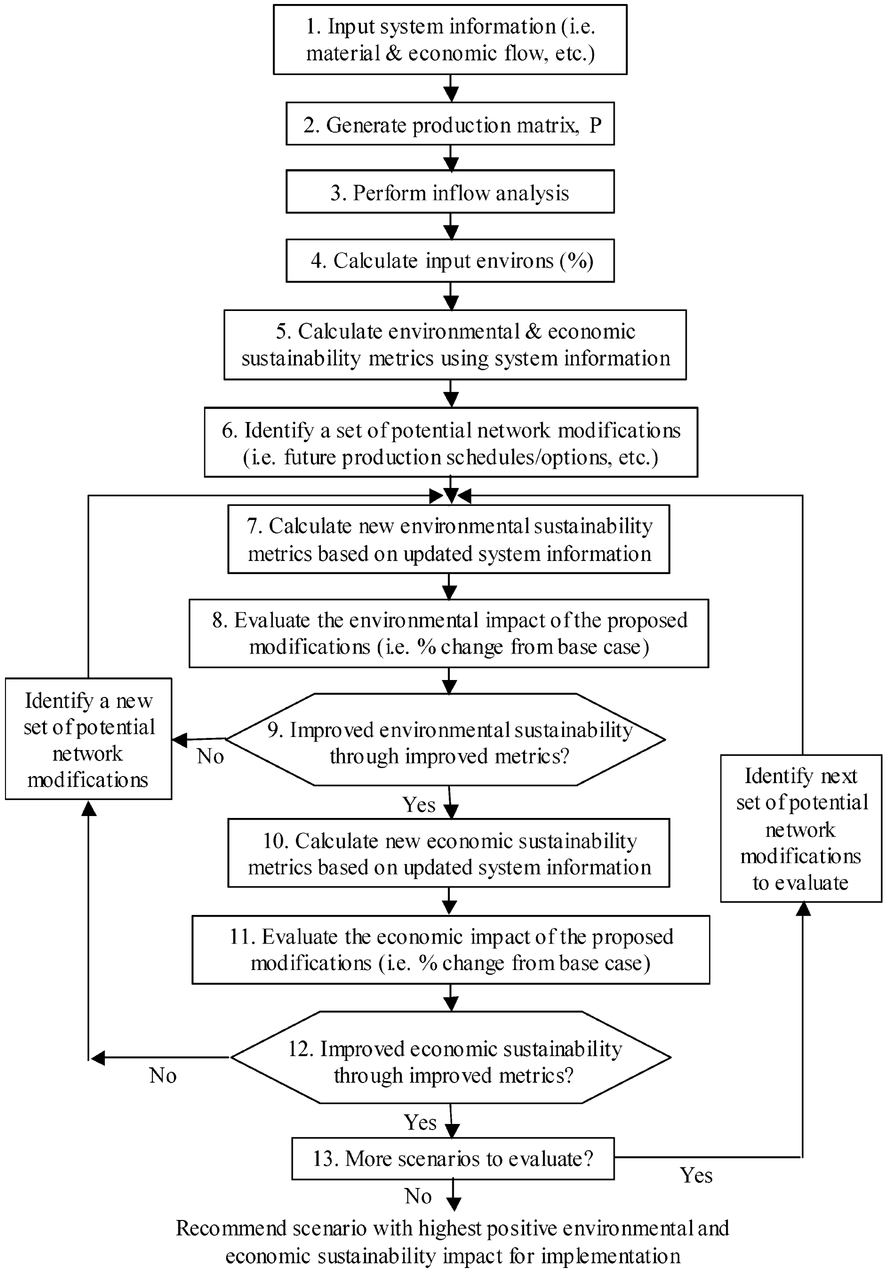

Figure 4. Flow diagram displaying the proposed modeling methodology and analysis.

an improved future state of sustainable development, and finally, (iii) evaluates various future plant production schedules, to determine which option provides the best route toward improved industrial sustainable development, at the plant, industry, and regional levels.

Figure 4 lays out the 14 steps required for the decision-analysis framework. To begin, all available system information must be collected, which may include material, energy, and monetary flows, at the plant, industry, and zone levels. Once this information has been obtained, the material flow information can be used to initiate the EIOA analysis, by way of generating the production matrix **P**. As discussed previously in the EIOA Methodology section, the matrix **P** is used as the basis for the inflow analysis, which leads to the calculation of the percentage input environs. The fifth step in the analysis methodology requires the use of the original system information (i.e., the material and monetary flow data) to calculate the environmental and economic sustainability metrics, as discussed previously in the Quantification of Environmental and Economic Sustainability Using Sustainability Metrics section, for each individual entity within the industrial zone and the overall zone. The quantification of the metrics at this point provides the first piece of valuable information, namely, the quantification and assessment of the current state of sustainable development within an industrial region.

Furthermore, the percentage environs for each waste stream within the industrial zone provides a quantification of the direct and indirect contribution each stream within the zone has on a given waste stream. Therefore, the percentage environs identify which streams within the network must be modified to realize an improved future state of sustainable development by reducing the environmental impact of the waste streams. It is important to note that the decision-analysis framework does not suggest which streams should be modified and to what extent: these decisions belong to the individual plant managers. However, the analysis framework does provide a systematic assessment of various planning options. For instance, management for each plant within the industrial zone of interest would analyze the percentage environs and determine which of the suggested streams for modification they have control of, and as such, each

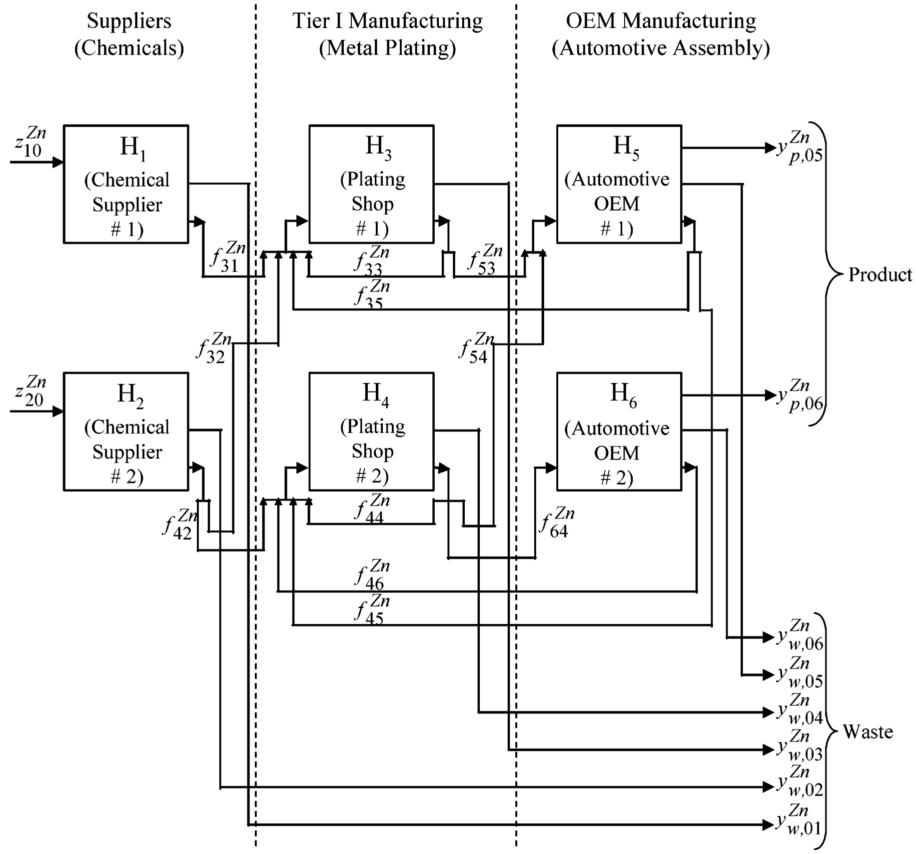

Figure 5. Schematic diagram of the variables used in the component-based electroplating supply network.

develop a variety of future planning options. The analysis of a single plant would not be particularly difficult to analyze; however, the interest of this work is to analyze an industrial zone, which is highly integrated and complex, thus making the sustainability analysis of the various planning options much more difficult.

Once management has decided on the various planning options, Step 7 of the decision-analysis framework can be implemented. As such, new environmental sustainability metrics can be calculated, based on the updated system information. Step 8 requires the evaluation of the environmental impact of the proposed modifications. (In other words, determine if the environmental sustainability metric has improved at the plant and zone levels from the original case or not. If the answer is no, this option is discarded and a new set of network modifications is identified.)

If an environmental improvement has been made, the economic viability of the option is assessed. Step 10 requires the recalculation of the economic sustainability metric, again based on the updated economic data for the case of interest. A similar approach was performed for the environmental evaluation; Step 11 requires the evaluation of the economic impact of the proposed modifications. (In other words, determine if the economic sustainability metric has improved at the plant and zone levels from the original case or not. If the answer is no, this option is discarded, despite the fact that environmental performance at the plant and zone levels has improved, and a new set of network modifications is identified.)

If the case results in an improved state of economic sustainability, this option is retained as a potential recommendation. Step 13 determines whether or not there are more scenarios to be evaluated. If the answer is yes, the process is repeated, to ascertain whether or not better options exist. If there are no more scenarios to evaluate, the scenario with the highest positive environmental and economic sustainability impact is recommended for system-wide implementation.

Structures that are to be used as aides for the enhancement of environmental and economic sustainability have been presented. 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 to be a satisfactory measure of social sustainability.[3] The usefulness of the decision-analysis framework will be further clarified in the case studies to follow.

Case Studies

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 the years 2000 and 2003, with a corresponding reduction in sales of ∼40%.[22,23] To survive and be profitable in the future, the electroplating industry must seek ways to accomplish sustainable development. Cooperation and symbiosis efforts are also necessary among the electroplating industry and its entire supply chain, i.e., the industries it serves (automotive, airline, communications, construction, defense, electronics, etc.) and the industry suppliers (chemicals, materials, energy, etc.). Although these efforts do not presently exist, the establishment of sustainable development within industries will ultimately lead to improved profitability, efficiency, productivity, and waste minimization.

Table 7. Zinc Plating Network Flow Information

	Flow Information ($\times 10^3$ lbs/yr)		
variable	Base Case	Modification 1	Modification 2
z_{10}^{Zn}	50.000	50.000	50.000
z_{20}^{Zn}	70.000	70.000	70.000
f_{31}^{Zn}	46.500	46.500	46.500
f_{32}^{Zn}	27.720	29.295	29.295
f_{42}^{Zn}	33.880	35.805	35.805
f_{33}^{Zn}	4.044	8.732	8.842
f_{44}^{Zn}	4.025	5.726	5.874
f_{53}^{Zn}	68.746	73.352	74.276
f_{35}^{Zn}	2.614	2.796	3.786
f_{54}^{Zn}	18.373	19.864	20.379
f_{45}^{Zn}	1.742	1.864	2.840
f_{64}^{Zn}	15.033	16.253	16.674
f_{46}^{Zn}	0.601	0.650	0.667
$y_{w,01}^{Zn}$	3.500	3.500	3.500
$y_{w,02}^{Zn}$	8.400	4.900	4.900
$y_{w,03}^{Zn}$	8.088	5.239	5.305
$y_{w,04}^{Zn}$	2.817	2.202	2.259
$y_{w,05}^{Zn}$	4.356	4.661	2.840
$y_{p,05}^{Zn}$	78.407	83.895	85.189
$y_{w,06}^{Zn}$	0.601	0.650	0.667
$y_{p,06}^{Zn}$	13.830	14.953	15.340

Table 8. Zinc Plating Network Economic Flow Information

	Base Case		Modification 1		Modification 2	
variable	\$/lb	\$/yr	\$/lb	\$/yr	\$/lb	\$/yr
z_{10}^{Zn}	0.58	29000	0.58	29000	0.58	29000
z_{20}^{Zn}	0.55	38500	0.55	38500	0.55	38500
f_{31}^{Zn}	0.89	41367	0.89	41367	0.89	41367
f_{32}^{Zn}	0.88	24415	0.86	25293	0.86	25293
f_{42}^{Zn}	0.88	29841	0.86	30913	0.86	30913
f_{33}^{Zn}	0.40	1618	0.42	3667	0.42	3714
f_{44}^{Zn}	0.45	1811	0.46	2654	0.46	2723
f_{53}^{Zn}	2.93	201672	2.92	213852	2.89	214995
f_{35}^{Zn}	0.35	915	0.35	979	0.33	1249
f_{54}^{Zn}	2.51	46139	2.49	49388	2.47	50244
f_{45}^{Zn}	0.37	645	0.37	690	0.35	994
f_{64}^{Zn}	2.51	37751	2.49	40410	2.47	41110
f_{46}^{Zn}	0.42	252	0.42	273	0.42	280
$y_{w,01}^{Zn}$	0.25	875	0.25	875	0.25	875
$y_{w,02}^{Zn}$	0.27	2268	0.25	1244	0.25	1244
$y_{w,03}^{Zn}$	0.29	2346	0.27	1415	0.27	1432
$y_{w,04}^{Zn}$	0.29	817	0.27	596	0.27	610
$y_{w,05}^{Zn}$	0.35	1525	0.35	1631	0.34	974
$y_{p,05}^{Zn}$	5.93	464574	5.88	493398	5.83	496765
$y_{w,06}^{Zn}$	0.35	210	0.35	228	0.35	233
$y_{p,06}^{Zn}$	2.93	40585	2.91	43499	2.89	44297

Industrial sustainability, within the plating industry, refers to the need for a reduction in energy and raw material consumption and providing quality products, 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, an industrial case study that includes the electroplating and supporting industries will be examined, to clarify and demonstrate the capabilities of the generalized information flow analysis methodology for industrial sustainability assessment.

Desired Information from the Decision-Analysis Framework. As discussed previously, the decision-analysis framework allows individual entities and overall industrial zones/networks to be able to (i) describe their current status of sustainable development (through the use of established sustainability metrics), (ii) identify changes to the system that must be made to realize an improved future state of sustainable development (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), and finally, (iii) evaluate various potential future production schedules, which the entities and industries plan to reach within a given time frame, to determine which option provides the best route toward improved industrial sustainable development, at each the plant, industry, and regional levels. In the case studies below, we use the decision-analysis framework to evaluate the current state of sustainability within an industrial region and analyze the impact that two future production plans will have on the sustainable development of both the individual entities and the overall industrial zone.

Electroplating Network Description. Figure 5 displays the variables used in the component-based simplified electroplating supply network, whereas the initial flow values for the base case are supplied in Table 7. This electroplating network consists of two chemical suppliers to the electroplating plants (H_1 and H_2), two electroplating shops (H_3 and H_4), and two end users (in this case, two original equipment manufacturers (OEM) for the automotive industry (H_5 and H_6)). The following section will use the decision-analysis methodology to evaluate the existing sustainability situation within the given industrial network, as well as assess the efficacy of various planning options, to determine the best option that will benefit not only the individual entities within the zone, but also the overall industrial network as a whole.

Decision-Analysis Methodology. Application of the introduced methodology is illustrated step by step in this case study.

Step 1: Gather System Information. The first step of the decision-analysis methodology requires the gathering of the available system information for the base case, which, in this case, includes the zinc material flows (Table 7) and the costs associated with each flow (Table 8).

Step 2: Generate a Production Matrix. Given the zinc flow information for the base case, we are able to apply the modified EIOA methodology to calculate the production matrix, **P**. The nonzero submatrices in **P** are given in eqs 17−19.

$$\mathbf{P}_{21} = \begin{pmatrix} 50.000 & 0 \\ 0 & 70.000 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \tag{17}$$

$$\mathbf{P}_{22} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 46.500 & 27.720 & 4.044 & 0 & 2.614 & 0 \\ 0 & 33.880 & 0 & 4.025 & 1.742 & 0.601 \\ 0 & 0 & 68.746 & 18.373 & 0 & 0 \\ 0 & 0 & 0 & 15.033 & 0 & 0 \end{pmatrix} \tag{18}$$

$$\mathbf{P}_{32} = \begin{pmatrix} 3.500 & 0 & 0 & 0 & 0 & 0 \\ 0 & 8.400 & 0 & 0 & 0 & 0 \\ 0 & 0 & 8.088 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.817 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4.356 & 0 \\ 0 & 0 & 0 & 0 & 78.407 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.601 \\ 0 & 0 & 0 & 0 & 0 & 13.830 \end{pmatrix} \tag{19}$$

Step 3: Perform Inflow Analysis. As discussed previously, matrix **P** is the basis for the third step of the framework, the inflow analysis, which results in the calculation of both the instantaneous fractional inflow matrix (**Q***) and the transitive closure matrix (**N***). In a manner similar to that observed for the production matrix, the nonzero submatrices in **N*** are provided in eqs 20−23.

$$\mathbf{N}^*_{21} = \begin{pmatrix} 1.000 & 0 \\ 0 & 1.000 \\ 0.622 & 0.378 \\ 0.024 & 0.976 \\ 0.496 & 0.504 \\ 0.024 & 0.976 \end{pmatrix} \tag{20}$$

$$\mathbf{N}^*_{22} = \begin{pmatrix} 1.000 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.000 & 0 & 0 & 0 & 0 \\ 0.622 & 0.378 & 1.082 & 0.008 & 0.035 & 0.000 \\ 0.024 & 0.976 & 0.042 & 1.142 & 0.051 & 0.017 \\ 0.496 & 0.504 & 0.863 & 0.248 & 1.039 & 0.004 \\ 0.024 & 0.976 & 0.042 & 1.142 & 0.051 & 1.017 \end{pmatrix} \tag{21}$$

$$\mathbf{N}^*_{31} = \begin{pmatrix} 1.000 & 0 \\ 0 & 1.000 \\ 0.622 & 0.378 \\ 0.024 & 0.976 \\ 0.496 & 0.504 \\ 0.496 & 0.504 \\ 0.024 & 0.976 \\ 0.024 & 0.976 \end{pmatrix} \tag{22}$$

$$\mathbf{N}^*_{32} = \begin{pmatrix} 1.000 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.000 & 0 & 0 & 0 & 0 \\ 0.622 & 0.378 & 1.082 & 0.008 & 0.035 & 0.000 \\ 0.024 & 0.976 & 0.042 & 1.142 & 0.051 & 0.017 \\ 0.496 & 0.504 & 0.863 & 0.248 & 1.039 & 0.004 \\ 0.496 & 0.504 & 0.863 & 0.248 & 1.039 & 0.004 \\ 0.024 & 0.976 & 0.042 & 1.142 & 0.051 & 1.017 \\ 0.024 & 0.976 & 0.042 & 1.142 & 0.051 & 1.017 \end{pmatrix} \tag{23}$$

Step 4: Calculate the Input Environs. The next stage of the decision-analysis framework requires calculation of the percentage input environs for each of the six waste streams included in the industrial zone case study. The combination of the transitive closure inflow matrix (**N***), which provides the inflow and throughflow relationships, and the normalized input environ matrix ($\boldsymbol{i}_{\mathbf{P}^*}$), which provides the intranodal and internodal flow relationships, results in determination of the input environs for this zinc-plating network. Table 9 provides the resulting traditional, actual, and percentage environs results for the waste stream from plating shop 1 ($y^{\mathrm{Zn}}_{\mathrm{w},03}$). Again, it is important to note that the remaining analysis is based on the percentage environs; however, because the percentage environ is directly related to both the traditional and actual environs, they are also provided for clarification.

Similar environs for each waste and product stream within the network can be generated; however, they are left out of this discussion, for the sake of brevity. As mentioned previously, the traditional environs are retrieved directly from the transitive closure inflow and the normalized input environ matrices. The actual environs are calculated by multiplying the traditional environs by the magnitude of the waste flow of interest from Table 7 (i.e., $y^{\mathrm{Zn}}_{\mathrm{w},03}$ in this case). Finally, the percentage environs are determined by dividing the actual flow environ by the magnitude of the original flow. The following paragraphs are included to elucidate the process of environ calculation.

Table 9. Base Case Zinc Plating Network Traditional, Actual, and Percentage Environs

variable	$E^T_{w,03^{\mathrm{Zn}}}$	$E^A_{w,03^{\mathrm{Zn}}}$	$E^P_{w,03^{\mathrm{Zn}}}$
z^{Zn}_{10}	0.622	5.032	10.063
z^{Zn}_{20}	0.378	3.057	4.366
f^{Zn}_{31}	0.622	5.032	10.821
f^{Zn}_{32}	0.371	2.999	10.819
f^{Zn}_{42}	0.007	0.057	0.170
f^{Zn}_{33}	0.054	0.438	10.820
f^{Zn}_{44}	0.001	0.007	0.161
f^{Zn}_{53}	0.028	0.226	0.328
f^{Zn}_{35}	0.035	0.283	10.829
f^{Zn}_{54}	0.007	0.060	0.326
f^{Zn}_{45}	0.0004	0.003	0.186
f^{Zn}_{64}	0.0001	0.001	0.005
f^{Zn}_{46}	0.0001	0.001	0.135
$y^{\mathrm{Zn}}_{\mathrm{w},01}$	0.000	0.000	0.000
$y^{\mathrm{Zn}}_{\mathrm{w},02}$	0.000	0.000	0.000
$y^{\mathrm{Zn}}_{\mathrm{w},03}$	1.000	8.088	100.000
$y^{\mathrm{Zn}}_{\mathrm{w},04}$	0.000	0.000	0.000
$y^{\mathrm{Zn}}_{\mathrm{w},05}$	0.000	0.000	0.000
$y^{\mathrm{Zn}}_{\mathrm{p},05}$	0.000	0.000	0.000
$y^{\mathrm{Zn}}_{\mathrm{w},06}$	0.000	0.000	0.000
$y^{\mathrm{Zn}}_{\mathrm{p},06}$	0.000	0.000	0.000

The percentage environ divides the actual environ (which has units of flow), for the waste or product stream of interest, by the magnitude of the total flow rate of the stream of interest (which also has units of flow), which is then multiplied by 100. The percentage environ is a measure of the percentage of a specific stream's mass flow that contributes to the generation of a waste or product flow from a node. For instance, to calculate the base case percentage environ for z^{Zn}_{10}, we take the actual environ for z^{Zn}_{10} (see Table 9, column 3), which is 5.032, and divide it by the magnitude of the total flow rate for z^{Zn}_{10} from Table 7, which is 50.0. The calculation gives us a percentage environ value of 10.063, as shown in Table 9, column 4, row 2. For the sake of space and brevity, Table 9 does not show all the percentage environs: only those for the waste stream of plating shop 1 ($E^{\mathrm{P}}_{\mathrm{w},03^{\mathrm{Zn}}}$). Again, the percentage environ relates to a specific stream of interest; therefore, if you were to sum a column within Table 9, it would not add up to 100%, because that calculation involves multiple streams. For instance, sticking with z^{Zn}_{10} for the stream, we are given one percentage environ, 10.063%. The remaining seven environs in the base case account for the remaining 89.937% (the set of eight percentage environs for z^{Zn}_{10} are 7.000%, 0%, 10.063%, 0.137%, 4.321%, 77.780%, 0.029%, and 0.672%). These values were not included in the discussion, for the sake of brevity.

Again, the percentage environs for each waste stream within the industrial zone allow us to trace the waste and product flows back to their origin, determine the flow needed to support a given outflow, and determine the flows for which an output is most dependent, or more specifically, the breakdown of which flow components within a network comprise a given waste or product outflow. These percentage environs identify which streams within the network must be modified (i.e., which streams have the highest percentage environs), to realize an improved future state of sustainable development by reducing the environmental impact of the waste streams.

For this case study, the percentage environs in Table 9 show us that f^{Zn}_{33}, f^{Zn}_{32}, f^{Zn}_{31}, f^{Zn}_{35}, and z^{Zn}_{10} contribute the greatest percentage of their flow to the generation of waste from plating shop 1. As such, to improve the sustainable development of plating shop 1, these streams in particular should be considered for modification. It is important to note that plating shop 1 does

Table 10. Zinc Plating Network Mass Intensity and Gross Profit Metric Values

system type	Mass Intensity			Gross Profit ($/yr)		
	Base Case	Modification 1	Modification 2	Base Case	Modification 1	Modification 2
overall system	1.301	1.214	1.194	429619	463410	468194
chemical supplier 1	1.075	1.075	1.075	11492	11492	11492
chemical supplier 2	1.136	1.075	1.075	13488	16462	16462
plating shop 1	1.118	1.071	1.071	131013	141133	141941
plating shop 2	1.084	1.061	1.061	50524	54674	55834
automotive OEM 1	1.053	1.053	1.031	216798	230194	232795
automotive OEM 2	1.042	1.042	1.042	2876	3134	3234

Table 11. Zinc Plating Network Mass Intensity and Gross Profit Metric Comparisons to Base Case

system type	Mass Intensity Improvement from Base Case (%)		Gross Profit Improvement from Base Case (%)	
	Modification 1	Modification 2	Modification 1	Modification 2
overall system	6.69	8.22	7.87	8.98
chemical supplier 1	0.00	0.00	0.00	0.00
chemical supplier 2	5.37	5.37	22.05	22.05
plating shop 1	4.20	4.20	7.72	8.34
plating shop 2	2.12	2.12	8.21	10.51
automotive OEM 1	0.00	2.09	6.18	7.38
automotive OEM 2	0.00	0.00	8.97	12.45

not have direct control of all of these streams; therefore, management must first determine which streams they can improve in-house and which streams would require symbiotic efforts among the other member entities within the industrial region. Similar environs for each waste and product stream within the network can be generated; however, they are left out of this discussion, for the sake of brevity.

Step 5: Calculate the Environmental and Economic Sustainability Metrics. The fifth step in the analysis methodology requires the use of the original system information (i.e., the material and monetary flow data) to calculate the environmental (mass intensity) and economic (gross profit) sustainability metrics, for each individual entity within the industrial zone, as well as for the overall zone. The quantification of the metrics at this point provides the first piece of valuable information, namely, the quantification and assessment of the current state of sustainable development within an industrial region.

The results for both the environmental and economic sustainability metrics for the individual entities and overall industrial zone for this base case are given in Table 10 (columns 2 and 5, respectively). These values will provide a basis for comparison against the future planning options to be evaluated in the upcoming steps of the decision-analysis framework.

Step 6: Identify a Set of Potential Network Modifications. This phase of the analysis requires the identification of various potential network modifications. For instance, after the management for each plant within the industrial zone has analyzed the percentage environs from Step 4 and determined which of the suggested streams for modification they have control of, they will determine a variety of future planning options. It is again important to note that the decision-analysis framework does not suggest which streams should be modified and to what extent: these decisions belong to the individual plant managers. The analysis framework provides the systematic assessment of various planning options and evaluates the impact that various network modifications will have on the sustainable development of both individual plants and the overall industrial region.

For this particular case study, two potential network modifications, which were determined by various plant managements, are further analyzed.

Modification 1: Chemical supplier 2 improves process efficiency and thus reduces waste generation by 5%, from 12% zinc waste generation to 7% zinc waste generation. In addition, both plating shops 1 and 2 enhance their in-plant zinc recycling technologies, thereby improving their internal recycle capabilities by 5% (now 10%) and 3% (now 13%), respectively. Because of these process improvements, both plating shops have also reduced their zinc waste generation by 4% (now 6%) and 2% (now 5%), respectively.

Modification 2: In addition to the adjustments made in Modification 1, Modification 2 includes a few more adjustments. OEM 1 improves plant efficiency and slightly increases recycle back to both plating companies, thus reducing zinc waste generation by 2%, from 5% to 3%. OEM 1 is willing to increase the amount of recycle to the plating companies, because of the fact that the plating companies have improved their process technologies in such a way that allows them to use some of the would-be waste stream of OEM 1 as input to their plating processes. As such, OEM 1 pays less in zinc remediation costs by being able to sell off a portion of their waste and the plating shops are willing to receive the would-be waste, because it costs less than raw materials supplied directly from the chemical suppliers. These modifications result in the flow values for streams f_{35}^{Zn} and f_{45}^{Zn} both increasing by 1%.

Also, it is important to note the fact that, because of these proposed network modifications, the cost data associated with the processing of the various streams within the industrial zone will also change. These updated material flows, as well as cost modifications, can be seen from Tables 7 and 8, respectively.

Step 7: Calculate New Environmental Metrics. Given management's proposed planning Modification 1, Step 7 of the decision-analysis framework can be performed. Updated environmental sustainability metrics, for both the individual plant and the overall industrial zone, can be calculated, based on the updated system information from Table 7. The results of the new mass intensity metric values are provided in Table 10.

Step 8: Evaluate the Environmental Impact. After the updated mass intensity metrics for the industrial zone have been determined, the next step requires the evaluation of the environmental impact of the proposed modifications (i.e., determine if the environmental sustainability metric has improved at the plant and zone levels from the original case or not). For the case of Modification 1, Table 11 displays the percentage improvement over the base case for all entities. In fact, each of the entities that made process modifications (i.e., chemical supplier 2, plating shop 1, and plating shop 2) resulted in improving their mass intensity metrics by 5.37%, 4.20%, and 2.12%, respectively. As expected, the plants that did not have any modifications scheduled did not change their respective mass intensity metrics. As a result of Modification 1, the overall network would result in a mass intensity improvement of 6.69%.

Referring back to Figure 4 and the decision-analysis framework, because this set of proposed network modifications has improved the environmental sustainability of the member entities, as well as the overall network, the "Yes" route is followed, thus moving our analysis onward to Step 10 for an economic evaluation.

Step 10: Calculate New Economic Metrics. Given the fact that Modification 1 has resulted in improved environmental sustainability for both the individual entities and the overall industrial region, Step 10 of the decision-analysis framework begins the evaluation of the economic viability of the proposed modifications. Updated economic sustainability metrics, for both each individual plant and the overall industrial zone, are calculated, based on the updated system information from Table 8. The results of the new gross profit metric values are provided in Table 10.

Step 11: Evaluate the Economic Impact. A similar approach was performed for the environmental evaluation in Step 8. Step 11 requires evaluation of the economic impact of the proposed modifications (i.e., determine if the economic sustainability metric has improved at the plant and zone levels from the original case or not). Again, these calculations have taken into account the increased capital and operating costs that would be incurred by the plants making the process modifications. For the case of Modification 1, Table 11 displays the percentage improvement over the base case for all entities. Again, as expected, each of the entities that made process modifications (i.e., chemical supplier 2, plating shop 1, and plating shop 2) resulted in improving their gross profit metrics by 22.05%, 7.72%, and 8.21%, respectively. Also noteworthy is the fact that both OEMs also improved economically, by 6.18% and 8.97%, respectively, from the base case, because of the modifications made by the other network entities. As expected, chemical supplier 1 did not see any economic improvement from the base case, because no modifications were scheduled in Modification 1. As a result of Modification 1, the overall network would see a gross profit improvement of 7.87%.

Referencing the decision-analysis framework in Figure 4, because this set of proposed network modifications has improved the economic sustainability of the member entities as well as the overall network, the "Yes" route is followed, thus moving the analysis onward to Step 13.

Step 13: More Scenarios to Evaluate. The next phase of the analysis framework looks to determine whether or not there are more alternatives to evaluate. For this case study, the answer is "Yes," because we have yet to evaluate the results of Modification 2. From here, Steps 7−13 would be repeated. The environmental and economic data for Modification 2 are supplied in Tables 7 and 8, respectively, while the environmental and economic results are supplied in Tables 10 and 11. The results in Table 11 clearly show that Modification 2 would result in higher positive environmental and economic sustainability for both the member entities and the industrial zone as a whole.

At this point, at Step 13, because there are no more potential scenarios left to evaluate, the "No" route is followed.

Recommendations. The scenario with the highest positive environmental and economic sustainability impact, in this case Modification 2, is recommended for system-wide implementation.

Concluding Remarks

The decision-analysis framework introduced in this work provides a systematic methodology for industrial entities and overall networks to implement, to describe their current status of sustainable development, and to evaluate various potential future production schedules, which they plan to reach within a given time frame, to determine which option provides the best route toward improved industrial sustainable development, at the plant, industry, and regional levels. The framework allows for the evaluation and assessment of various decisions, which are made by individual plant management for their own benefit, and how the proposed modifications will affect the industrial network as a whole. As uncertainty issues arise with time, or as industrial goals change, the methodology can again be implemented and new sustainability targets can be determined for the synergistic sustainability improvements of the industrial region. An industrial case study was evaluated to display the efficacy of the analysis framework.

Future analysis will look to further extend the methodology to analyze the dynamic, time-dependent behaviors within an industry and how one company or industry's future plans will influence the future sustainability of the industry and its dependents, thus providing a picture of the current and future states of industrial sustainability.

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