Material Flows and Environmental Impacts of Manufacturing Systems via Aggregated Input-Output Models

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ABSTRACT
Manufacturing processes may be viewed as operational units in the overall manufacturing/production system. Changes in technology, production patterns, and process settings are typically made at the process (unit) level. Very often, environmental problems are apparent when the manufacturing/production system is viewed as a whole (many units joined together). However, with the units aggregated to form a system, it is often difficult to identify the source of an environmental problem or judge the singular effect of changes to a process unit; the changes become lost in the complexity of the system as a whole. Recent efforts have employed input-output modeling to describe the flow of materials and the environmental consequences associated with manufacturing processes. A method is introduced for aggregating process-level material input-output models to form a combined material input-output model for a manufacturing system. This resulting model serves as a bridge between unit-level changes and broader system behaviors. The model form permits identification of opportunities for reducing environmental impacts at the process level (e.g., reduction of emissions, waste generation, and material use) and driving the system toward zero emissions based on an examination of the aggregated manufacturing system level model. Case studies are used to illustrate the application of the aggregated material input-output model to minimizing waste and resource consumption.

Keywords: Input-Output, Material Flows, Environmental Impact, Model Aggregation, Zero Emission

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NOTATION

\( a_{ij} \) technical coefficients related to original inputs to the process

\( A \) technical coefficient matrix related to original inputs in the process, or the aggregated technical coefficient matrix in a manufacturing system

\( b_{ij} \) technical coefficients related to new generated substances in the process

\( B \) technical coefficient matrix related to new generated substances in the process, or the aggregated technical coefficient matrix in a manufacturing system

\( w_{ij} \) material flow from material \( i \) to new substance \( j \)

\( x_i \) amount of input to the process

\( X_i \) the total output, or production, of sector \( i \) in an economic system

\( X \) vector of process inputs

\( y_i \) output from the process in new substance forms

\( Y_i \) the total final demand for \( i \)'s product in an economic system

\( Y \) vector of process outputs

\( \hat{Y} \) estimate of \( Y \)

\( z_{ij} \) flow of input from sector \( i \) to sector \( j \) in an economic system, or the material flow from material \( i \) to material \( j \) in physical unit

\( \alpha \) weighting factor

\( \beta \) weighting factor

1. Introduction

Manufacturing processes in various industries, especially the chemical, automotive, electronics, and pulp and paper industries, produce adverse environmental impacts such as waste generation, energy consumption, and the release of hazardous substances. Process-centered efforts have been demonstrated to be an extremely effective means for achieving the goal of reducing the environmental impact [1]. If manufacturing process innovations are employed to achieve improved environmental performance, competitiveness will be indirectly benefited because of reduced costs associated with controlling and containing environmental impacts. Competitiveness will be directly benefited because
the innovations are likely to produce lower costs, higher productivity, and better quality products. Of course, the ultimate class of innovations are those that produce zero emissions.

One way of characterizing a manufacturing process is by materials flow analysis. Such an analysis can convert process inputs into intermediate products or final products, and can consider a range of mechanisms, e.g., mechanical and chemical. For manufacturing processes, the principal environmental impacts are associated with the process outputs, which may take the form of solid, liquid, and gaseous emissions. Materials flow analysis identifies the amounts of inputs and outputs associated with a process and then relates the inputs and outputs to provide a mathematical model that can be used to explore opportunities for reduced environmental impact. To establish an input-output relation, it is preferable to formulate a mathematical description based on physical, chemical, and other natural laws [2, 3, 4]. Unfortunately, it is often the case that there is insufficient knowledge or process information to develop a mechanistic model of a manufacturing process. However, in practice, such a mechanistic understanding of the process may not be needed; this is especially true during the beginning stages of environmental process improvement, when a simple, tractable model may be sufficient to identify opportunities for reduced environmental impact. A matrix-based input-output model represents such a model and is the focus of the effort described in this paper.

Input-output analysis has traditionally been used to analyze economic activities [5], and it has been extended to address environmental analysis at the national, industry, and product levels [6, 7, 8, 9]. These analyses have provided insight into the workings of environmental policy and the manifestation of pollution at various levels. For example, in France the emission of SO$_2$ and NO$_x$ was studied by constructing an input-output model to identify the main pollution sources and to explore the possibilities for different abatement strategies [6]. A number of the complex relations between energy, environment, and economic welfare were also investigated via a 10-sector input-output model of the UK [7]. The model was used to simulate the effects of a variety of policies and scenarios through changes in the demand levels and technical coefficients. In addition, input-output modeling has been used to characterize the environmental impacts of manufacturing processes [10].

In this paper, we develop environmental input-output models at different spatial scales for such entities as manufacturing systems, manufacturing plants, and a company. For environmental input-output models developed at
large spatial scales, e.g., at national or industry-wide levels, these models are highly aggregated and lack spatial resolution, and cannot be decomposed or disaggregated to acquire information about the manufacturing systems, manufacturing plants, and companies. Thus, there is a gap between national and process-level environmental input-output models. To bridge this gap one needs to think in terms of aggregating process-level models to obtain a larger scale system-level material input-output model. As shown in Figure 1, manufacturing systems and supply chains associated with contemporary industrial activities are very complex. Manufacturing unit operations interact with one another to form manufacturing systems, which in turn interact to form a supply chain. For each manufacturing process, it is possible to create a material input-output model. These process-level input-output models may then be aggregated to form a material input-output model for the collection of processes that form the manufacturing system or even further aggregated to establish a model for the complete supply chain.

Commonly, aggregation within input-output approaches is achieved by consolidating similar economic groups into a sector. Such an aggregation requires a homogeneous input structure. Several efforts have been made to measure the effects of aggregation of sectors in input-output models [11, 12, 13, 14, 15, 16]. This paper introduces a method for aggregating process-level material input-output models to form a combined material input-output model for a manufacturing system. The model form permits identification of opportunities for reducing environmental impacts at the process level (e.g., reduction of emissions, waste generation, and material use) based on examination of the aggregated manufacturing system level model. A case study is used to illustrate the application of the aggregated material input-output model to minimizing waste and resource consumption and provide guidance on how to drive processes toward zero emission.

2. Material Input-Output Models for Manufacturing Processes

The economic input-output model popularized by Leontief [5], can be viewed as a simple multi-input multi-output model. Traditionally, the model has been employed to relate the economic (product) flows from producer sectors to the consumer sectors. An input-output model is constructed from observed data for a particular economic area such as a nation, a region, or a state. Its basic notation and fundamental relationships are given by
\[ X_1 = z_{11} + z_{12} + \cdots + z_{1j} + \cdots + z_{1n} + Y_1 \]
\[ X_2 = z_{21} + z_{22} + \cdots + z_{2j} + \cdots + z_{2n} + Y_2 \]
\[
\vdots
\]
\[ X_i = z_{i1} + z_{i2} + \cdots + z_{ij} + \cdots + z_{in} + Y_i \]
\[
\vdots
\]
\[ X_n = z_{n1} + z_{n2} + \cdots + z_{nj} + \cdots + z_{nn} + Y_n \]

(1)

where \( X_i \) is the total output, or production, of sector \( i \), \( z_{ij} \) is the flow of input from sector \( i \) to sector \( j \), and \( Y_i \) is the total final demand for sector \( i \)'s product. Equation (1) implies that the products created in sector \( i \) are consumed by either itself or other industrial sectors and that the final demands, along with the amount of production in an underlying economic system, maintain a balance. By defining a technical coefficient \( a_{ij} = \frac{z_{ij}}{X_j} \), Equation (1) can be rewritten as:

\[
(1 - a_{11})X_1 - a_{12}X_2 - \cdots - a_{1n}X_n = Y_1
\]
\[
- a_{21}X_1 + (1 - a_{22})X_2 - \cdots - a_{2n}X_n = Y_2
\]
\[
\vdots
\]
\[
- a_{n1}X_1 - a_{n2}X_2 - \cdots + (1 - a_{nn})X_n = Y_n
\]

In matrix form, the above equation becomes

\[
(I - A)X = Y \tag{2}
\]
or

\[
X = (I - A)^{-1}Y \tag{3}
\]

where \( A \) is called the technical coefficient matrix, \( I \) is the \( n \) by \( n \) identity matrix, and \( (I - A)^{-1} \) is referred to as the Leontief inverse, if it exists. Therefore, the input-output model represents the dependent relationship between inputs and outputs within an economic system and is widely used in economics. It should be noted that the input-output model is based on two fundamental assumptions: the multi-input multi-output relation is linear, and the technical coefficient is fixed during the underlying time period for which data is available.

When the input-output analysis is used in assessing the environmental impact of manufacturing processes, the traditional input-output analysis needs to be modified. This is because manufacturing processes have significantly different characteristics from economic systems. With a traditional input-output model, the number of inputs is equal
to the number of outputs. However, when applying input-output modeling to a manufacturing process, the number of process inputs is not necessarily equal to the number of process outputs. For instance, some inputs are converted into different substance forms by the process, and other inputs maintain their original form. A second reason for modification is that the units used in a process input-output model are not monetary units but mass units associated with the material mass flows of interest. In addition to these reasons, there are no explicit final demands. Consequently, the structure of the input-output analysis needs to be modified in order to meet the requirements of environmental impact analysis of manufacturing processes.

The environment-focused input-output analysis of a manufacturing process can be illustrated via Figure 2 and Table 1. Figure 2 shows a general representation of inputs and outputs of manufacturing processes based on the mass conservation. From a materials flow viewpoint, inputs to processes generally involve raw materials, tools, and auxiliary materials, whereas outputs from processes include the product, by-products, and wastes in the form of gases, liquids, and solids. Within a process, as shown in Figure 2, there are \( m \) inputs, \( M_1 \) through \( M_m \), and \( m+n \) outputs, \( M_1^* \) through \( M_m^* \) and \( Y_1 \) through \( Y_n \). Among the outputs, \( m \) outputs, \( M_1^* \) through \( M_m^* \), maintain the original substance form, while \( n \) outputs, \( Y_1 \) through \( Y_n \), are the new substances created by the process. An input-output transaction table for such a process can be constructed as in Table 1. In the left column of the table, the process inputs are listed, and outputs are listed on the top of the table. The other elements represent the material flow from inputs to outputs. For example, \( z_{12} \) represents the amount of material \( M_1 \) going to material \( M_2 \), while \( w_{1n} \) represents the amount of material \( M_1 \) going to new substance \( Y_n \).

A graphical depiction of the input-output transaction in Table 1 is shown in Figure 3. It can be seen in Figure 3 that the material inputs to the process are distributed across the outputs. For example, \( z_{22} \) represents the amount of the material \( M_2 \) that retains the original substance form; \( z_{21} \) represents the amount of material that is transformed into substance \( M_1 \), while \( w_{21} \) through \( w_{2n} \) represent the portions of the substance that are converted into new materials \( Y_1 \) through \( Y_n \), respectively.
The development of a mathematical model that relates the inputs and outputs begins by assuming that there is a linear relationship between each output and its corresponding inputs. Based on this assumption, the following relationship holds for each input $i$ based on the principle of conservation of matter:

$$x_i = z_{i1} + z_{i2} + \cdots + z_{ij} + \cdots + z_{im} + w_{i1} + \cdots + w_{ij} + \cdots + w_{in}$$

$$= a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{ij}x_j + \cdots + a_{im}x_m + b_{i1}y_1 + \cdots + b_{ij}y_j + \cdots + b_{in}y_n$$

(4)

where $x_i (i = 1, \ldots, m)$ is the input amount, $y_i (i = 1, \ldots, n)$ is the output from the process in new substance forms, $z_{ij}$ is the material flow from material $i$ to material $j$, and $w_{ij}$ is the material flow from material $i$ to new substance $j$. All $x_i, y_i, z_{ij}$ and $w_{ij}$ are in physical units, and $a_{ij}$ and $b_{ij}$ are technical coefficients, where:

$$a_{ij} = \frac{z_{ij}}{x_j}$$

(5) and

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

(6)

It is also assumed that the technical coefficients $a_{ij}$ and $b_{ij}$ are fixed and time-invariant. This assumption is reasonable for a stable manufacturing process. Based on Equations (4) through (6), the following simultaneous equations can be established for a process:

$$x_1 = a_{11}x_1 + a_{12}x_2 + \cdots + a_{1m}x_m + b_{11}y_1 + \cdots + b_{1n}y_n$$

$$x_2 = a_{21}x_1 + a_{22}x_2 + \cdots + a_{2m}x_m + b_{21}y_1 + \cdots + b_{2n}y_n$$

$$\cdots$$

$$x_m = a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mm}x_m + b_{m1}y_1 + \cdots + b_{mn}y_n$$

(7)

Equation (7) can be rewritten in matrix form:

$$(I - A)X = BY$$

(8)

where $X = [x_1 \ x_2 \ \cdots \ x_m]^T$, \hspace{1cm} $Y = [y_1 \ y_2 \ \cdots \ y_n]^T$. 


\[ A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix}, \quad \text{and} \quad B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{bmatrix} \]

\( A \) and \( B \) are technical coefficient matrices of the underlying process and they characterize material flow in the process. Matrix \( A \) relates the process inputs to the process outputs whose substance form is unchanged, while matrix \( B \) relates the process inputs to those process outputs that are newly produced substances. Since \( A \) is a square matrix, and assuming that \((I - A)\) is non-singular, the inputs \( X \) can be solved in terms of the outputs \( Y \) as

\[ X = (I - A)^{-1} BY \] (9)

Equation (9) is of particular interest because, in general, waste materials that cause environmental impact appear in the \( Y \) vector, and one expects to reduce their impact by changing the inputs to the process. Equation (9) can be viewed as a design equation for process improvement. It can be seen from Equation (9) that if \( Y \) is specified, the corresponding inputs \( X \) can be determined, provided that the matrix \((I - A)\) is non-singular. The situation where \((I - A)\) is singular may arise if an input remains unchanged in the amount and substance form during the process operation. For such a case, however, the input (and output) could be removed from the input-output table so that \((I - A)\) invertibility is guaranteed.

On the other hand, Equation (9) can be used to solve for the outputs \( Y \) in terms of inputs \( X \) as:

\[ Y = B^{-1}(I - A)X \] (10)

provided matrix \( B \) is square and invertible; otherwise a least squares solution can be obtained as

\[ \hat{Y} = (B^T B)^{-1} B^T (I - A)X \] (11)

if \( B^T B \) is invertible.

Equations (10) and (11) relate the inputs to the process to the substances created by the process. These equations can be used to evaluate the environmental impact of the process.
3. Case Study: Chassis Manufacturing Application

To demonstrate the applications of the material input-output analysis to the environmental impact of manufacturing processes, a chassis manufacturing case study from the automotive industry is considered. The manufacturing of an automotive frame involves several processes. From the coiled steel (basic material input to the process) to the final product (i.e., chassis frame), various manufacturing processes are employed including cleaning, cutting, straightening, blanking, piercing, forming, heat treatment, shot peening, punching, and painting. The waste stream created by a series of the processes contains steel scrap, waste chemicals, waste paints, waste water, mist, and CO₂. Based on data acquired from a chassis manufacturing facility, Table 2 lists the inputs to and outputs from the system (collection of processes). The coefficient matrices \( A \) and \( B \) are given by:

\[
A = \begin{bmatrix}
0.933 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.950
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0.926 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.364 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.636 & 0 & 0 & 0 & 0 & 0 & 0.57 \\
0 & 0 & 0 & 0 & 0.857 & 1 & 0.43 & 0 \\
0 & 0 & 0.879 & 0 & 1 & 0.143 & 0 & 0 \\
0 & 0 & 0.121 & 0 & 0 & 0 & 0 & 0 \\
0.074 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

The relation between \( X \) and \( Y \) is then given by Equation (9) as

\[
\begin{bmatrix}
X_1 \\
X_2 \\
X_3 \\
X_4 \\
X_5 \\
X_6 \\
X_7 \\
X_8
\end{bmatrix} = \begin{bmatrix}
14.815 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.364 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.636 & 0 & 0 & 0 & 0 & 0 & 0.57 \\
0 & 0 & 0 & 0 & 0.857 & 1 & 0.43 & 0 \\
0 & 0 & 0.879 & 0 & 1 & 0.143 & 0 & 0 \\
0 & 0 & 0.121 & 0 & 0 & 0 & 0 & 0 \\
0.074 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 20.833 & 0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
Y_1 \\
Y_2 \\
Y_3 \\
Y_4 \\
Y_5 \\
Y_6 \\
Y_7 \\
Y_8
\end{bmatrix}
\]

where \( x_1 \) through \( x_8 \) stand for the amounts of steel, natural gas, air, water, acid, oils, tools, and paint in kilograms, and \( y_1 \) through \( y_8 \) are the amounts of scrap, CO₂, waste chemicals, waste paint, salt, mist, waste water, and steam in kilograms.
Based on Equation (12), one can explore various possibilities to reduce the waste stream and drive the process toward zero emission. For example, if it is desirable to reduce CO$_2$ emissions by changing inputs, the corresponding gas and air values can be determined from Figure 4. It also can be seen from Equation (12) that changes in several outputs may depend on the same input. Figure 5 shows the relation between the input (acid) and the outputs (mist and waste chemicals). The input acid level may then be specified to produce acceptable amounts of mist and waste chemicals. Other input-output relations can be obtained in a similar fashion.

4. Aggregation of Material Input-output Models

If input-output models have been established for several processes operating in parallel, it might be desired to combine, or aggregate, these models to understand the collective behavior of the processes. Care must be exercised in undertaking this aggregation to avoid aggregation bias. For example, technical coefficients cannot simply be averaged, since the input and output amounts may differ. To minimize or eliminate aggregation bias, aggregation should work directly with the material inputs and outputs. The system boundary must also be selected carefully for the problem under investigation so as to avoid excessive aggregation that may obscure model structures that reveal insights into the underlying processes.

Based on the foregoing discussion, a methodology for aggregating material input-output models has been created to combine process-level models. Such aggregation provides a broader region over which environmental performance improvement opportunities can be pursued. Of course, if process-level material input-output models can be aggregated to form an input-output model for a manufacturing system, further aggregation could then be performed to produce an input-output model for an entire production facility. An aggregated material input-output model at the manufacturing system, facility, or regional level can improve our ability to understand complex interactions by providing an insight into relationship between the inputs and outputs. It also provides a method for harnessing input-output knowledge at the process level to support the development of environmental input-output models at broader spatial levels.

To aggregate material input-output models into a larger model, let us consider a fundamental case where two manufacturing processes constitute a system, as shown in Figure 6. For process 1, there are $m_i$ inputs, $M_i^{(1)}$ through
Let $x_i$ be the amount of input $M_i$, $y_i$ be the amount of output $Y_i$ from the process in a new substance form, $z_{ij}$ be the material flow from material $M_i$ to material $M_j$, and $w_{ij}$ be the material flow from material $M_i$ to a new substance $Y_j$. All $x_i$, $y_i$, $z_{ij}$ and $w_{ij}$ are in units of mass. The material balance relationships for the two processes are

\[
\begin{align*}
    x^{(1)}_i &= z^{(1)}_{i1} + \cdots + z^{(1)}_{ij} + \cdots + z^{(1)}_{im} + w^{(1)}_{i1} + \cdots + w^{(1)}_{ij} + \cdots + w^{(1)}_{im} \\
    &= a^{(1)}_{ij} x^{(1)}_j + \cdots + a^{(1)}_{ij} x^{(1)}_j + \cdots + a^{(1)}_{im} x^{(1)}_m + b^{(1)}_{i1} y^{(1)}_1 + \cdots + b^{(1)}_{ij} y^{(1)}_j + \cdots + b^{(1)}_{im} y^{(1)}_n \\
\end{align*}
\]

\[
\begin{align*}
    x^{(2)}_i &= z^{(2)}_{i1} + \cdots + z^{(2)}_{ij} + \cdots + z^{(2)}_{im} + w^{(2)}_{i1} + \cdots + w^{(2)}_{ij} + \cdots + w^{(2)}_{im} \\
    &= a^{(2)}_{ij} x^{(2)}_j + \cdots + a^{(2)}_{ij} x^{(2)}_j + \cdots + a^{(2)}_{im} x^{(2)}_m + b^{(2)}_{i1} y^{(2)}_1 + \cdots + b^{(2)}_{ij} y^{(2)}_j + \cdots + b^{(2)}_{im} y^{(2)}_n \\
\end{align*}
\]

where $i = 1, 2, \cdots, m$ , $j = 1, 2, \cdots, n$ , 

\[
\begin{align*}
    a^{(1)}_{ij} &= \frac{z^{(1)}_{ij}}{x^{(1)}_j}, \\
    a^{(2)}_{ij} &= \frac{z^{(2)}_{ij}}{x^{(2)}_j}, \\
    b^{(1)}_{ij} &= \frac{w^{(1)}_{ij}}{y^{(1)}_j}, \\
    b^{(2)}_{ij} &= \frac{w^{(2)}_{ij}}{y^{(2)}_j}. \\
\end{align*}
\]

By defining an aggregated input vector $X$ and an aggregated output vector $Y$:

\[
X = \begin{bmatrix} x_1 & x_2 & \cdots & x_m \end{bmatrix}^T
\]

(15)

and

\[
Y = \begin{bmatrix} y_1 & y_2 & \cdots & y_n \end{bmatrix}^T
\]

(16)

where $m$ is the number of unique inputs in both processes, and $n$ is the number of unique outputs that involve new substances from both processes. Combining Equations (13) and (14) yields
\[ x_i = z_i^{(1)} + z_i^{(2)} + \ldots + z_i^{(k)} + \ldots + z_y^{(1)} + z_y^{(2)} + \ldots + z_y^{(k)} + \ldots + z_{im}^{(1)} + z_{im}^{(2)} + \ldots + w_i^{(1)} + w_i^{(2)} + \ldots + w_i^{(k)} + \ldots + w_j^{(1)} + w_j^{(2)} + \ldots + w_j^{(k)} + \ldots + w_{im}^{(1)} + w_{im}^{(2)} + \ldots + w_{im}^{(k)} \]

\[ = a_{i1}x_1 + a_{i2}x_2 + \ldots + a_{im}x_m + b_{i1}y_1 + b_{i2}y_2 + \ldots + b_{in}y_n \]

where

\[ x_i = x_i^{(1)} + x_i^{(2)} \], and \[ y_j = y_j^{(1)} + y_j^{(2)} \].

The aggregated technical coefficients can be defined as follows:

\[ a_{ij} = \alpha_j^{(1)}a_{ij}^{(1)} + \alpha_j^{(2)}a_{ij}^{(2)} \quad (18) \]

and

\[ b_{ij} = \beta_j^{(1)}b_{ij}^{(1)} + \beta_j^{(2)}b_{ij}^{(2)} \quad (19) \]

where \( \alpha_j^{(1)}, \alpha_j^{(2)}, \beta_j^{(1)}, \beta_j^{(2)} \) are weighting factors, \( \alpha_j^{(1)} = \frac{x_j^{(1)}}{x_j}, \quad \alpha_j^{(2)} = \frac{x_j^{(2)}}{x_j}, \quad \beta_j^{(1)} = \frac{y_j^{(1)}}{y_j}, \quad \text{and} \quad \beta_j^{(2)} = \frac{y_j^{(2)}}{y_j} \). It can be seen that model aggregation does not introduce any bias. From Equations (13) through (19), an aggregated material input-output model can be built with the following form:

\[ X = (I - A)^{-1} BY \], or \[ Y = B^{-1}(I - A)X \]

where \( I \) is an \( m \) by \( m \) identity matrix, \( X \) is the aggregated input vector, and \( Y \) is the aggregated output vector defined by Equation (15) and (16). \( A \) is the aggregated technical coefficient matrix, and \( B \) is the aggregated technical coefficient matrix related to new substances from the underlying system.

The approach described above can be applied to aggregate material models for situations involving more than two processes. Consider \( k \) manufacturing processes to be aggregated, and there are \( m_1, m_2, \ldots, m_k \) inputs and \( m_1+n_1, m_2+n_2, \ldots, m_k+n_k \) outputs within process 1 through \( k \), respectively. The following relation holds for the underlying system.

\[ x_i = z_i^{(1)} + z_i^{(2)} + \ldots + z_i^{(k)} + \ldots + z_y^{(1)} + z_y^{(2)} + \ldots + z_y^{(k)} + \ldots + z_{im}^{(1)} + z_{im}^{(2)} + \ldots + w_i^{(1)} + w_i^{(2)} + \ldots + w_i^{(k)} + \ldots + w_j^{(1)} + w_j^{(2)} + \ldots + w_j^{(k)} + \ldots + w_{im}^{(1)} + w_{im}^{(2)} + \ldots + w_{im}^{(k)} \quad (20) \]
where \( M \) is the number of unique inputs in all \( k \) processes, and \( N \) is the number of unique outputs that involve new generated substances from all \( k \) processes.

Correspondingly, aggregated technical coefficients are

\[
a_{ij} = \alpha_j^{(1)} a_{ij}^{(1)} + \alpha_j^{(2)} a_{ij}^{(2)} + \cdots + \alpha_j^{(q)} a_{ij}^{(q)} + \cdots + \alpha_j^{(k)} a_{ij}^{(k)}
\]

and

\[
b_{ij} = \beta_j^{(1)} b_{ij}^{(1)} + \beta_j^{(2)} b_{ij}^{(2)} + \cdots + \beta_j^{(q)} b_{ij}^{(q)} + \cdots + \beta_j^{(k)} b_{ij}^{(k)}
\]

where \( \alpha_j^{(q)} \) and \( \beta_j^{(q)} \) are weighting factors and have the following forms.

\[
\alpha_j^{(q)} = \frac{x_j^{(q)}}{x_j}
\]

\[
\beta_j^{(q)} = \frac{y_j^{(q)}}{y_j}
\]

\( q = 1, 2, \ldots, k \).

As suggested by the above development, Equations (20) through (24) can be used to form a material input-output model for a manufacturing system based on models for the individual processes. Using these relations, models for all the production facilities operated by a company can be aggregated to form an input-output model for the company. Similarly, the above methodology can support the aggregation of input-output models to create models at the industry sector level, regional level, etc.

5. Application of the Aggregated Models in Steel-making

To illustrate the aggregation of material input-output models at the process level to form a model for a manufacturing system, two steelmaking processes that operate in parallel within a production facility are used as an example. The two steelmaking processes have different inputs and process operation control, and therefore the material outputs from the two processes are different. The simplified material input-output transaction tables for the two processes are shown in
Tables 3 and 4, respectively [17]. The inputs to the process consist of hot metal, flux, and oxygen gas, while the outputs from the process include steel, slag, fume, and gas. Fe, C, Si, P and O\textsubscript{2}, which form the \( \mathbf{X} \) vector, are considered inputs to the process. The new substances created by the process include FeO, Fe\textsubscript{2}O\textsubscript{3}, CO, CO\textsubscript{2}, SiO\textsubscript{2}, and P\textsubscript{2}O\textsubscript{5}, which form the \( \mathbf{Y} \) vector. In examining the table, CO and CO\textsubscript{2} gases are significant discharges that have an adverse environmental impact. The aim of the analysis presented here is to establish a linear multi-input multi-output relationship through which opportunities to drive the process toward zero emission may be identified.

The aggregated input vector \( \mathbf{X} \) and output vector \( \mathbf{Y} \) are as follows.

\[
\mathbf{X}^T = [\text{Fe}, \text{ C}, \text{ Si}, \text{ P}, \text{ O}_2], \text{ and } \mathbf{Y}^T = [\text{FeO}, \text{ Fe}_2\text{O}_3, \text{ CO}, \text{ CO}_2, \text{ SiO}_2, \text{ P}_2\text{O}_5].
\]

It may be noted that the vector \( \mathbf{X} \) includes all the unique material inputs while the vector \( \mathbf{Y} \) includes all the unique material outputs from the two processes. Then technical coefficient matrices of the two processes, based on Equations (5) and (6), are

\[
A_1 = \begin{bmatrix}
0.9739 & 0 & 0 & 0 & 0 \\
0 & 0.0886 & 0 & 0 & 0 \\
0 & 0 & 0.3492 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.0071
\end{bmatrix}, \quad B_1 = \begin{bmatrix}
0 & 0.7087 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.4287 & 0.2735 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.4694 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.2913 & 0.5713 & 0.7265 & 0.5306 & 0
\end{bmatrix},
\]

\[
A_2 = \begin{bmatrix}
0.9663 & 0 & 0 & 0 & 0 \\
0 & 0.0411 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.1125 & 0 \\
0 & 0 & 0 & 0 & 0.0032
\end{bmatrix}, \quad B_2 = \begin{bmatrix}
0.7774 & 0.6993 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.4288 & 0.2730 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.4676 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.4383 \\
0.2226 & 0.3007 & 0.5712 & 0.7270 & 0.5324 & 0.5617
\end{bmatrix}.
\]

Using Equations (17) through (24) and \( A_1, B_1, A_2, \text{ and } B_2 \), the aggregated technical coefficient matrices \( \mathbf{A} \) and \( \mathbf{B} \) can be calculated as follows.

\[
\mathbf{A} = \begin{bmatrix}
0.9703 & 0 & 0 & 0 & 0 \\
0 & 0.0639 & 0 & 0 & 0 \\
0 & 0 & 0.1726 & 0 & 0 \\
0 & 0 & 0.1125 & 0 & 0 \\
0 & 0 & 0 & 0.0050
\end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix}
0.7774 & 0.7051 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.4288 & 0.2732 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.4683 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.4383 \\
0.2226 & 0.2949 & 0.5712 & 0.7268 & 0.5317 & 0.5617
\end{bmatrix}.
\]
Using Equation (9), it is possible to identify opportunities for reducing waste gases such as CO and CO₂. For example, assume that it is desirable to reduce the generation of CO and CO₂ by 25 and 20 percent, respectively, i.e., the vector $\mathbf{Y}$ is to be changed from $[21.29\ 55.10\ 170.47\ 24.60\ 28.69\ 1.62]^T$ to $[21.29\ 55.10\ 127.85\ 19.68\ 28.69\ 1.62]^T$. Using Equation (9), the vector $\mathbf{X}$ should be changed from $[1865.22\ 85.26\ 15.79\ 0.80\ 153.54]^T$ to $[1865.22\ 64.30\ 16.20\ 8.00\ 125.10]^T$. According to the I/O representation, the amount of input C should be reduced from 85.26 to 64.30 kg. The result shows that the amount of carbon input into the process should be decreased. In modern steelmaking practice, carbon is introduced in the form of coke in the blast furnace process. The carbon then reduces FeO to produce elemental Fe and waste CO and CO₂. Introducing more coke/carbon into the process, and oversaturating the process with carbon, produces excessive levels of CO and CO₂. Therefore, to implement an environmentally friendly steelmaking process, control of the blast furnace process must avoid oversaturating the iron with carbon. In this case, the input-output model has provided insight into how to improve the environmental performance of the process. Of course, to implement the carbon reduction suggested by the input-output model requires a careful technical analysis to assess the feasibility of the proposed change.

6. Discussion and Conclusions

Material input-output models provide a method to closely examine environmental impacts of manufacturing activities at the process level. An aggregated material input-output model permits identification of opportunities to improve the environmental performance and drive manufacturing systems toward zero emissions at larger spatial scales (e.g., the facility level). However, care should be exercised when responding to changes suggested by input-output models, as the feasibility of the changes must be carefully assessed for the process or system under study. For example, an input-output model may suggest that it is mathematically possible to determine the process input $\mathbf{X}$, using the design equation, if a desired material output vector, $\mathbf{Y}$, is specified. The model indicates that if the material inputs are changed, the desired outputs will be obtained. However, further investigation must be undertaken to assess the feasibility/efficacy of such changes. If such an investigation reveals that such changes are not feasible or will be ineffective, it is very likely that the investigation will reveal alternative approaches like substitute processes, process layout improvements, process control, and alternative processing materials [18, 19] that will produce environmental benefits within the underlying manufacturing process/system. Of course structural changes in the process will change elements of the technical coefficient matrices $\mathbf{A}$ and $\mathbf{B}$, which in turn change the behavior of the underlying system.
There are several opportunities for reducing the environmental impact associated with manufacturing processes and systems:

• changes in inputs to processes when desirable outputs are specified, provided that the specified process conditions are feasible.

• changes in the technical coefficients of the underlying process.

It should be noted that while the input-output analysis provides a tractable method of identifying opportunities to reduce the environmental impact, a more complex model may be necessary for those manufacturing processes with nonlinear input-output relations. In addition, not all manufacturing process may be best modeled with an input-output format [20]. Based on the analysis of process characteristics, an appropriate modeling strategy should be employed. It should also be pointed out that process changes may affect material yield, productivity, and product quality characteristics. As noted above, manufacturers must thoroughly investigate consequences and side-effects when input-output analysis identifies promising opportunities for emission reduction/elimination.

Some conclusions can be drawn from the above analysis and discussion:

• The proposed environmental input-output analysis of manufacturing processes is helpful in understanding the dependence of the environmental impact on the process inputs. It tracks material flow in the entire process and provides clues as to how to drive the manufacturing processes and systems toward zero emission.

• Opportunities for reducing the environmental impact of manufacturing processes may include changes to the inputs of the process, and changes in the technical coefficients of the processes. The implementation of the latter needs to use specific process knowledge and techniques.

A methodology for aggregation of material input-output models at the process level has been developed. Material input-output models of manufacturing processes can be aggregated into a system model without bias. It is possible to further aggregate such models into a material input-output model for systems at larger spatial scales. The aggregated material input-output model provides a means to support improvement opportunity analysis of the environmental performance of manufacturing systems and production facilities.
7. Acknowledgement

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8. References


Author Vitae

Dr. Huanran Xue was born in China. He received his B.S. and M.S. degrees from the Huazhong University of Science and Technology, China, and Ph.D. degree in the Department of Mechanical Engineering - Engineering Mechanics from Michigan Technological University. He currently works for Ford Motor Company Manufacturing Design Center as a system analyst. He works in the CAD/CAM area for stamping engineering.

Vishesh Kumar is a Ph.D. candidate in the Department of Mechanical Engineering - Engineering Mechanics at Michigan Technological University and a Graduate Scholar of the Michigan Tech Sustainable Futures Institute. He received his B.Tech in Mechanical Engineering from IIT Kanpur in 2000. Prior to coming to Michigan Tech, he worked as a research engineer for an Indian automotive manufacturer. Mr. Kumar has published numerous papers in various journal and conference proceedings. His research is focused on the economic sustainability of the automotive recycling infrastructure and value recovery at the end-of-use stage of the product life cycle.

Dr. John W. Sutherland holds the Henes Chair Professorship within the Department of Mechanical Engineering – Engineering Mechanics and serves as the Co-Director of the Sustainable Futures Institute at Michigan Technological University. He received his Ph.D. from the University of Illinois at Urbana-Champaign in 1987. Prior to joining the faculty at Michigan Tech in 1991, he served as Vice President of a small manufacturing consulting company. His research and teaching interests are focused on design and manufacturing for sustainability. He has mentored over 60 students to the completion of their degrees and has authored/co-authored over 200 publications. Dr. Sutherland and his students are the recipients of numerous awards for education and research.
Figure 1: Manufacturing Processes, Production Facilities, and Supply Chain Network
Figure 2: Input-Output Relation of a Manufacturing Process
Figure 3: Material Flows in Manufacturing Processes
Figure 4: Output CO$_2$ vs. Inputs Natural Gas and Air
Figure 5: Outputs Mist and Waste Chemicals vs. Input Acid
Figure 6: Aggregation of Multiple Manufacturing Processes
Table 1: Input-Output Transaction for a Process

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<td>$z_{21}$</td>
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Table 2: Input-Output Transaction for Manufacturing of Frame (kg)

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<th>Acid</th>
<th>Oils</th>
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<th>Waste chem.</th>
<th>Waste paint</th>
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Table 3: Material Input-Output Transaction in Process 1 (kg)

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