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A Proposed LCA Model of Environmental Effects With Markovian Decision Making

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ABSTRACT

As the pool of existing non-renewable natural resources continues to shrink, it will be necessary for government and industrial leaders to achieve a workable strategy for the intelligent allocation of scarce resources. In this paper, a method of quantifying the environmental and resource impacts of product redesign is proposed. This new method utilizes Input Output Analysis coupled with the Markovian decision making into a single matrix-based tool. The benefit of a fully developed tool would be the ability to make informed pre-production decisions leading to optimum product and process designs with minimal environmental impact. This paper illustrates this technique with an example based upon real industry data and extrapolated effects.

INTRODUCTION

The next century will become an age of diminishing natural resources as population and its demands increase. In the past, resource development and production either matched or outpaced the growth of population. Shortages were rare and usually brought about by war or other social maladies. Little thought was given to depletion of the natural resources as the supply seemed endless. Study groups consisting of scientists, businessmen and national leaders have indicated that we cannot sustain our rate of development based on exploitation of raw materials [Milbraith, 1989]

Efficient utilization of materials and energy requires the means of evaluating current usage and any intended changes. When used in the context of sustainability, efficient utilization also implies maintaining usages rates to those levels which can be provided for indefinitely. The concepts of life cycle analysis and assessment (LCA) are fundamental to this evaluation. No single manufacturer can control the rate of material usage for the nation or the world. However, a manufacturer can insure that their requirements for a material do not exceed what is reasonably necessary by the technology available. In addition, a manufacturer has the ability to design products which make use of renewable materials, those materials in relative abundance and avoid those materials which are environmentally hazardous. This paper extends LCA to allow manufacturers to better quantify their inventories and to provide pathways to reducing material usage where desired.

LITERATURE REVIEW-Input Output Analysis was first developed by Wassily Leontief [1966]. For his work in this effort, he was awarded the Nobel Prize in Economics in 1973. IOA is used extensively in the analysis of economics of nations. For example, the Department of Commerce prepares a data base of information (usually lagging by several years) each year for use with IOA [1994]. This information is also available in part on the World Wide Web through the Economics Department of the University of Michigan. Dr. Leontief made recommendations for expanded use of IOA in engineering[1987]; however, little has
been done. Breuil applied IOA to quantify pollutant emissions in France [1992]. IOA has been applied to the LCA framework by Lave, et. al. [1995]. The Society for Environmental Toxicology and Chemistry (SETAC) established the technical framework for Life Cycle Analysis and Assessment beginning in January 1991 [Fava, 1991].

Life Cycle Assessment as a technique has been documented in two Environment Protection Agency (EPA) publications: Life-Cycle Assessment: Inventory Guidelines and Principles, EPA/600/R-92/245, and Life Cycle Design Guidance Manual, EPA/600/R-92/226. Several industrial investigators have tried to implement this procedure and have had problems. A critical review of LCA was published by Keoleian and Menerey in 1994 [Keoleian and Menerey, 1994]. In particular, they found that the LCA suffered from several methodological maladies including excessive costs to conduct, lack of standards, inappropriate boundary setting (i.e., the scoping problem), incommensurable data, etc. Other researchers, most notably, Allenby and Graedel [1995], have extended LCA through the use of matrix evaluations. These qualitative tools have relied upon the skill and the knowledge of the analyst to arrive at conclusions for resource planning and pollution prevention.

Markovian analysis is a well established methodology [Hillier & Lieberman, 1986]. For example, Malhame and Boukas have applied Markovian decision processes to improving manufacturing effectiveness [1991]. However, to the extent of our knowledge, no one has coupled IOA and LCA with Markovian decision processes to find optimal solutions for solving environmental problems.

LCA METHODOLOGY: The ideal LCA technique should quantitatively predict where material originates, how it is used and how the material is transformed by the usage. In addition this LCA methodology should include the environmental impact of each stage in the material transformation. The LCA methodology can be divided into three steps, namely inventory analysis, impact analysis and improvement analysis.

The first step of any LCA is the Inventory Analysis, which tells how much quantity of a particular material will go into a particular system, and how much of it comes out. For example, in the turning process, the inputs include the raw material, such as steel round stock, the carbide cutting tool, the cutting fluids and the input energy. Outputs from this process include finished parts, scrap parts, used cutting fluid, chips, used tools, spent energy in the form of heat, vibration and noise. In the long term, the machine tool will also exit the system as a waste stream. These inputs and outputs are quantified in Input/Output Matrix tables.

The second step of LCA, Impact Analysis, is more complex. It focuses on the type of material and how they affect the environment. This analysis can be further extended to find the effect of using different materials on concerned industries. For example, it is known that many of the polymers that are in use today have their origins in the by-products of the petroleum industry. If we were to convert vehicles to use only electrical energy, what would be the impact on the plastics industry? We have assumed that reduction of toxic materials is beneficial. But what happens when an industry replaces a known hazard usage with materials of an unknown hazard? In several cases, it was later found that the replacement was more environmentally damaging than the material replaced. The problem seems to be that effective tools for evaluating collateral effects have not been developed yet.

The third step of LCA, Improvement Analysis, is really Design for the Environment (DFE). The drafters of LCA hoped that designers would make use of the results from the first two steps to design products that are more efficient with materials and energy usage. In theory, there is no reason why designers would not do this. Efficient products should be cheaper to produce and more desirable to consumers. But current technology does not provide designers with enough information to make effective environmentally conscious design decisions. The lack of tools to evaluate collateral effects of design decisions and the overwhelming amount of data prevents designers from quickly establishing the impact of a given design decision.

CORRELATION BETWEEN LCA, IOA AND THE MARKOVIAN METHODOLOGIES: The goal of this paper is to describe a mathematical computational tool which, when used within the framework of Life Cycle Analysis, provides a quantitative Impact and Improvement Analysis. The paper shows that Input Output Analysis (IOA) provides a quantitative state space model of a product (or process) that either exists or has been proposed. It further demonstrates that by constructing the model for use as a discrete finite Markov chain, we can quantitatively predict the impact of product or process design decision and optimize that decision for its impact upon both sustainable development and the environment. Using historical industry data, a multivariate data dependent system (DDS) can be developed to further refine the Input Output Analysis [Pandit, 1991]. The objective of this paper is to create a methodology that constructs a state space model of a product or process which when used as a Markovian chain predicts the long term
usage and flow of materials as well as the transient effects of changes made to the system. A second but critical element of this paper is the use of Markovian decision making to make optimal environmental decisions. These concepts can be recognized in figure 1.

DEMONSTRATION OF CONCEPT

The methodology presented above is outlined with the help of an example. The Input Output table represents estimated data based on manufacturer's information on production of medium truck-frames. However, the Markovian analysis and dynamic programming solution are hypothetical.

The technique has the potential to be extremely powerful in reaching product and process material levels which implement the concepts of both sustainability and life cycle analysis. The method demonstrated by the example is readily amenable to computer solutions; the example was completely solved using a program written in Mathematica. Research is needed to fully explore the concepts presented and to demonstrate that it is applicable to full scale industry.

As previously stated the data obtained from a manufacturer of automotive frames will be used for the methodology application. The basic frame material is a steel which is procured in coils from steel mills. The thickness of the steel sheet is 0.4 inches, which is wrapped in a coil 5 feet in diameter weighing 40,000 lbs. The coil is unwound by the frame manufacturer and cleaned with either a soap or acid bath depending on the steel. Following cleaning, the steel is sheared into three parts with the mill edges being scrapped. The steel strips are again sheared into divided sheets. Because of the coiling, the sheets have camber which is removed by hydraulic pressing. The next operation is blanking and punching. The sheet is then rolled or press formed into the structural 'C' shape needed for the frame element. Heat treatment is performed to increase the yield stress of the material to 110,000 psi. The steel frame is then shot peened to improved the fatigue life of the frame. A final hole punching operation is performed to gain precision controlled holes. Then the rails are painted and prepared for shipment to assembly. This process is illustrated in Figure 2.

Since Input Output Analysis was developed for economics, dollars are traditionally used as the unit of transfer. The units used for the method do not matter as long as the they are commensurate. In this analysis, mass in pounds is used as the unit of transfer. The first step in any IOA is to build the transaction table. The Example Transaction Table, below, has been constructed to represent the frame manufacturer's flows. The leftmost columns are inputs from the outside while the top row are the system outputs to the external world. This table has been normalized to one coil of steel of weight 40,000 lbs. To convert this table to a transaction matrix, T, a row and a column are assigned to each input and each output. An entry of T, $t_{ij}$, represents the conversion from an input on row i to an output in column j. For this example, the 16 $\times$ 16 matrix that results is constructed by the first 7 rows and first 7 columns representing the inputs. Since there is no transfer of material weights between the inputs, the entries are zero. The last 9 rows and columns are for the outputs which also are zeros. The top 7 rows and the last 9 columns are
presented in Table 1. The last 9 rows and first 7 columns are again zeros. A vector, $Y$, can be constructed such that for any element of $Y$, $y_i$, represents the conversion of the material $i$ to another form either used internally in the model or to a final output:

```
STEEL COIL
   ├── ACID
   │    └── CLEANING
   │        ├── CUTTING OPERATION (CUTTING SAW)
   │                └── MILL EDGE
   │                    └── MILL SCALE
   │                        └── SCRAP METAL
   │                                        └── STRAIGHTENING (PRESS DIES)
   │                                                └── BLANKING AND PIERCING (BLANKING DIES)
   │                                                        └── ROLL FORMING/PRESS FORMING (FORMING DIES/ROLL)
   │                                                                 └── NATURAL GAS
   │                                                                            └── WATER
   │                                                                                     └── HEAT TREATMENT
   │                                                                                                    └── STEAM
   │                                                                                                                  └── HOT WATER
   │                                                                                                                        └── MIST
   │                                                                                                                                 └── EXHAUST GAS
   │                                                                                                                                      └── SHOT PEENING (CAST STEEL SHOTS)
   │                                                                                                                                                └── PUNCHING (PUNCHING DIE)
   │                                                                                                                                                    └── SCRAP
   │                                                                                                                                                      └── TRUCK FRAME
```

Figure 2. Process Block Diagram
Table 1: Example Transaction Table

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Inputs</th>
<th>Frame</th>
<th>Scrap</th>
<th>CO₂</th>
<th>Waste</th>
<th>Steam</th>
<th>Mist</th>
<th>Salts</th>
<th>Waste</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H₂O</td>
<td></td>
<td></td>
<td></td>
<td>Chem</td>
<td>Paint</td>
</tr>
<tr>
<td>Steel</td>
<td>40000</td>
<td>37500</td>
<td>2500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1650</td>
<td>0.62</td>
</tr>
<tr>
<td>Gas</td>
<td>2000</td>
<td></td>
<td></td>
<td>5500</td>
<td></td>
<td>2250</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>30000</td>
<td></td>
<td></td>
<td></td>
<td>28000</td>
<td>1700</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acid</td>
<td>1700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50</td>
<td>200</td>
<td>1450</td>
<td></td>
</tr>
<tr>
<td>Oils</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Tools</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paint</td>
<td>12.93</td>
<td>12.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ y_i = \sum_{j=1}^{16} f_{ij} + z_i \]

The term \( z_i \) represents the final outputs of the system under the terms and notation used by Leontief. Essentially, the Z vector formed from \( z_i \) is the external outputs from the system. Since none of the inputs are sent outside of the system, \( z_i \) for the inputs are zero, with one exception, natural gas, which will be discussed below. The outputs of this system are not used internally and therefore all have \( z_i \) reflecting their weights of total production.

One can evaluate the output vector \( Y \) for steel of which 40,000 lbs is produced by an input and converted internally into frames and scrap:

\[ y_1 = t_{18} + t_{19} = 37500 + 2500 = 40000 \]

Similarly for frames, since there is no internal conversion, all \( t_j \) are zero; therefore,

\[ y_8 = z_8 = 37512.31 \]

With respect to natural gas, a stoichiometric relationship is used to convert it to heat, CO₂ and steam. The mass of air used has not been included; therefore to balance the transaction matrix, \( z_2 \) has been set to -5750.

The next step forms the matrix of technical coefficients which represent the fraction of the input usage to the total output of column. Defining \( a_{ij} \) as the technical coefficient, it is constructed by

\[ a_{ij} = \frac{t_{ij}}{y_j} \]

In the example problem, the technical coefficient of steam from water is

\[ a_{3,12} = \frac{1700}{3950} = 0.4304 \]

suggesting, of course that only 43% of the steam in this facility is produced by input water being used. The remainder is from the conversion of natural gas to heat.

The objective now is to determine what set of inputs and outputs will be required for forcing the final outputs to a given state. In terms of the environment, this is the problem of reducing a pollutant which is found in the final output of a facility. In terms of sustainability, what we wish to do is to reduce the overall material weight of a final output. The formulation above can answer these questions by rearranging the equations to yield the vector \( Y \) when \( Z \) is known:

\[ y_i = \sum_{j=1}^{9} t_{ij} + z_i = a_{i1} y_1 + a_{i2} y_2 + \ldots + a_{i9} y_9 \cdot \]

Rewriting this matrix notation and solving for \( Y \), we arrive at

\[ (I - A)Y = Z \]

\[ Y = (I - A)^{-1}Z \]

In this example, if we wish to reduce the amount
of mist generated from 350 lbs. to 50 lbs, we find that the input of water into the system decreases by 257 lbs (0.85% of the original) and that amount of acid is reduced by 42 lbs (2.52% of the original).

The results above are based upon the structure of the system and ignores whether or not the process can tolerate these changes. In the example above, the selection of the final output vector Z was arbitrary. However, in practice changes are made incrementally. It is ludicrous to believe that all changes to be made can be forecasted at any one time. In addition, even if the changes could be forecasted, a prudent executive would not allow the changes to be made at once. In our example above, we may know that to be environmentally friendly, we must reduce the acids, waste chemicals, waste paint, mists and scrap.

Therefore, the problem is how to choose Z and how to modify Z over a series of stages in time. Each of the stages is recurrent; thus the problem is amenable to a Markovian decision process. For each reduction of a weight, there is both a probability that we can realize the weight reduction as well as a cost for reducing the subject material waste. In this example we assume that the basic IOA state space structure does not change during the analysis. (In fact, such changes may well change the structure: this is part of the knowledge that must be gained from research in this field.) At each stage we must make decisions about what value of Z elements to apply in the IOA. To illustrate the types of decisions leading to Z vector values, we give two situations.

Situation 1: We may reduce misting by 300 lbs at the CNC punching operation by advances in dry machining. The cost of a dry machining operation increases because of the need for both more power and higher performance tooling. At the same time, there may be a 50-50 chance that dry machining will meet the needs of frame manufacturing. The cost of performing dry machining research will be approximately $500,000. The results of a successful project will be equal production rates and the ability to meet the 0.5 mg/m² mist standard requested by the union. Project failure will result in no appreciable gain in mist reduction.

Situation 2: We may reduce acid usage 25% by an improved coil unrolling process which mechanically de-scales and removes surface soilage from the steel sheet. The process adds cost to the unrolling process. Overall costs are estimated at $750,000. While it is 75% likely that the process will succeed, the plant will encounter a retooling down time of two weeks. Project failure will result in no benefits.

Either of these situations may be applied at any given stage in any order. In addition, there are other alternatives not listed here. Assuming that the decision maker will not (and may not have the resources to) allow all of the projects to proceed, which will gain the greatest environmental benefit at the lowest cost? To measure the environmental benefit, the IOA is used once a Z vector has been created. The Z vector choice is a Markovian state policy. The choice of the values depend only upon the current system, the costs and the probabilities of project success.

The Markovian transition matrix, P, is defined by listing the probabilities of transfer from a given system state to a new state. If we were to number the system states 1 to n, p_{ij} is interpreted as the probability of reaching state j from state i for one time step or stage. The sum of all values on a given row must equal 1. These probabilities can be projected through any number of stages, say m, by multiplying P by itself m times, P^m. If the system is irreducible, the probabilities, p_{ij}, will eventually reach steady values. The steady state probabilities are denoted

\[ \pi_j = \lim_{n \to \infty} \left( \frac{1}{n} \sum_{k=1}^{n} P^{(k)}_{ij} \right) \]

where \((k)\) in the superscript is used to indicate stage[Heyer & Lieberman, 1986]. The expected system state costs can then be computed by

\[ \text{Cost} = \sum_{k=1}^{n} \pi_k C_k \]

for alternative costs. From this point, the problem solution proceeds using traditional dynamic programming methods. We begin from the goal state and work towards the current state solving the optimality problem a piece at a time. When we have arrived at the current state, we will have optimal order of decisions for the Z vectors at each stage of the process.

In practice, several choices of every value of the Z vector could be used for the basis of state construction. For this demonstration, we will work with only two reductions: mist and acids. The goal state is a reduction of acid by 25% (425 lbs) and a reduction of mist by 300 lbs. There are 8 possible ways that technical choices which will improve the facility under consideration. The outcome of these technical choices are defined as states. Each state can be represented by a Z vector. For example, referring to the state table below, to reach state 4 (reduction of 100 lbs mist and
50 lbs acid) the \( Z \) vector would have a value of 1650 in row 4 (corresponding to acid) and 250 in row 13 (corresponding to mist). If a transition were required from state 4 to state 5 (reduction 100 lbs mist and 200 lbs acid), the \( Z \) vector would then have -200 in row 4 and 250 in row 13. The benefits (considered to be negative costs) of each state are also given in the state table. The states are defined in the table 2 below. The cost of moving from a state on the row to a state on the column is given by the decision table 3.:

**Table 2: State Definition**

<table>
<thead>
<tr>
<th>State</th>
<th>Reduction of mist (lbs)</th>
<th>Reduction of acid (lbs)</th>
<th>State Benefit per stage ($millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-10</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>0</td>
<td>-8</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>100</td>
<td>-4</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>100</td>
<td>-1</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>200</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>425</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>300</td>
<td>425</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table 3: Decision Cost Definition ($Million)**

<table>
<thead>
<tr>
<th>States</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>13.8</td>
<td>9.59</td>
<td>21.4</td>
<td>22.7</td>
<td>14.5</td>
<td>19.9</td>
<td>93.6</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>7.16</td>
<td>0.258</td>
<td>1.7</td>
<td>4.65</td>
<td>34.9</td>
<td>71.4</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.44</td>
<td>9.12</td>
<td>4.22</td>
<td>37.3</td>
<td>37.8</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13.2</td>
<td>0.582</td>
<td>17.4</td>
<td>32.5</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6.73</td>
<td>3.17</td>
<td>17.2</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.438</td>
<td>0.667</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.15</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Finally, the Markov transition matrix, $M_T$ has been estimated to be

\[
M_T = \begin{bmatrix}
0.0669 & 0.0309 & 0.265 & 0.000921 & 0.329 & 0.223 & 0.0692 & 0.105 \\
0 & 0.00105 & 0.0218 & 0.201 & 0.199 & 0.173 & 0.266 & 0.137 \\
0 & 0 & 0.0355 & 0.305 & 0.314 & 0.149 & 0.0751 & 0.122 \\
0 & 0 & 0 & 0.33 & 0.000965 & 0.143 & 0.111 & 0.417 \\
0 & 0 & 0 & 0 & 0.436 & 0.053 & 0.00288 & 0.508 \\
0 & 0 & 0 & 0 & 0 & 0.417 & 0.581 & 0.00229 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.443 & 0.557 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

We have assumed that once an improvement has been made, the improvement will not be undone by any future technical choice therefore the transition matrix is upper triangular. In addition, the values on the main diagonal reflect the probabilities that it is possible for the process to halt before reaching the goal state, state 8.

Based on a solution obtained by using dynamic programming and after exploring a number of policies, the best strategy is to attempt state 4 followed by state 6 followed by state 7 which then allows the goal state to be achieved. The benefit of this solution is $6,791,400. The IOA matrix can provide the necessary input output expectations for the interim states.

This analysis is based upon a static IOA with static data. The future research would focus the data collected over time. Dynamics models obtained from such data can be used to predict the variables in the future and then incorporated into the decision process. Moreover, the analysis of the dynamics of such models can also be utilized to study the impact of design changes in the future.

SUMMARY AND CONCLUSIONS

A new life cycle analysis methodology has been presented in this paper which includes Markovian decision making and acts as a vehicle for more prudent process and product design decisions. The motivation of this paper is the realization that current resource consumption trends cannot continue unchecked through the next century. The viability of this methodology has been shown via a frame stamping process example which utilizes viable manufacturer's data. Future work needed to develop this tool includes gathering/cataloging input/output data, formalizing data integration techniques, and validation/refinement through actual implementation of this tool in the marketplace. Also no analysis has been done to find out the energy inputs and outputs. This will constitute a new area having strong potential for application of these tools.

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