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ENTERPRISE MODELS FOR THE DESIGN AND MANAGEMENT
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ENTERPRISE MODELS FOR THE DESIGN AND MANAGEMENT OF MANUFACTURING SYSTEMS

By

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ABSTRACT

ENTERPRISE MODELS FOR THE DESIGN AND MANAGEMENT OF MANUFACTURING SYSTEMS

By

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All engineered systems and their products (hereafter collectively referred to as manufacturing systems) are called upon to perform particular technical functions in an economic system. Economic systems are in reality networks of enterprises (corporate and/or individual) each of which is engaged in two generic classes of processes: a) the *"real"* physical/biological processes that use energy to transform matter from one technically specific form to another through the application of human knowledge and the dissipation of physical energy and skill-specific human time, and b) human-based *cybernetic* (information and decision) control processes for which the "real" physical and biological processes are objects of development and control. This dissertation reports a theoretical framework and a set of logically consistent models for quantitatively evaluating the underlying material and energy requirements of manufacturing enterprises and the products which they produce as a physical system. This framework can be used to compare trade-offs between monetary performance measures and loads placed on the natural environment. These methods integrate engineering and economic information necessary for design and management decisions at various levels of organization of the enterprise. Because they can provide analysis at multiple levels of enterprise and

economic organization, the models are also ideally suited to environmental "Life-Cycle Assessment" of the material and energetic loads imposed on the natural environment by networks of enterprises producing products. Quantitative analysis using these methods may be readily implemented using computer software. A life-cycle assessment of two alternative packaging materials is presented, paper and polystyrene. Four alternatives for disposal are examined; landfill, incineration, electrical power generation and recycling. For the technologies modeled, a number of surprising results are obtained. Recycling paper requires similar amounts of petroleum energy as the manufacture of virgin paper. The lowest petroleum requirements are obtained when waste paper is burned to generate electrical power, with a higher requirement of forest resources. Recycling of polystyrene plastics results in substantially lower petroleum requirements than the other polystyrene disposal alternatives, and lower than that of recycling paper. Water effluents and air missions, including CO_2, are lower for recycling polystyrene than any of the alternatives for products or disposal.

Dedicated To My Beloved Father And Mother

Herman and Janet Koenig

ACKNOWLEDGEMENTS

This work begins with equations describing material transformations and energetic costs in physical and biological systems which were developed by my father, Herman Koenig, and his colleague, R. Lal Tummala, in 1972. Their profound development forms the basis for this work and provides the opportunity for exciting and vital future work by many in engineering, economics, agriculture and ecology. I am deeply indebted to my father for his insight, wisdom and support, and to Lal Tummala for his direction, interest and assistance in beginning my research career.

I am also grateful for the advice and guidance of my committee members, Hassan Khalil, Erik Goodman and Lindon Robison. Their interest, criticism and approval provided valued contributions to the work presented here.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The relationships between engineered systems and their performance in the economies and natural environments within which they function is incompletely or poorly understood both in theory and practice. Contemporary business and economic sciences focus primarily on the information and decision processes of the economy (the human behavioral aspects) with very limited reference to the underlying physical and biological processes and the material and energy loads they impose on the natural environment. Engineering sciences, in general, have not as yet been quantitatively linked to the economic and ecological levels of organization. The theoretical structure and analytical tools presented in the following development provide the basis for integrated design, management and analysis of tradeoffs between economic factors, technical performance and environmental loads.

In general engineered systems of production can be dichotomized into *physical and biological processes* and human *cybernetic control processes* as shown in Figure 1. *Physical and Biological Processes Models* of the engineered system are represented by networks of physical and biological transformations on the technical state of materials which take place through specific means of transformation, called the processing environment, and are driven by physical energy and skill-specific human time. Technologies appear as parameters in the functional form of the model and the flow rates of materials, energy, and human time appear as variables.

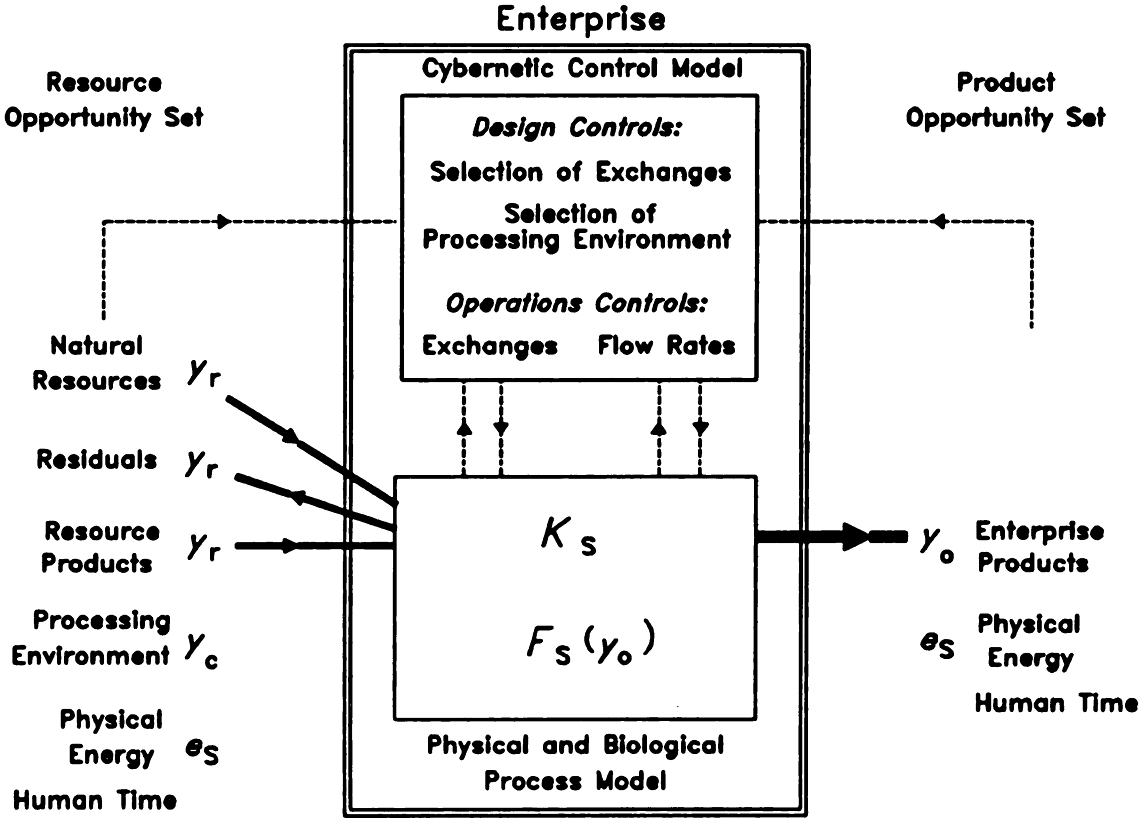

Figure 1 Manufacturing Enterprise Processes

The processing environment may include specific combinations of automated equipment, tools, physical structures, chemical catalysts, biological organisms, humans with specific skills, etc. Models of these types were initially reported by Koenig and Tummala [1], and Tummala and Connor [2].

The *Cybernetic Control Model* of the manufacturing system, which represent the human decision and management aspects, can be divided into two parts; *Design Control* and *Operational Control* as discussed by Koenig [3], Koenig and Tummala [4], and Tummala and Koenig [5].

Design Control (the design phase of the control process) involves two generic control activities. They are 1) the *selection of exchanges; i.e.* the identification and selection between alternative opportunities for the physical exchange of materials, energy and human time with other enterprises and with the natural environment, and 2) the *selection of the processing environment*; *i.e.* the identification, selection and engineering or implementation of the requisite transformation process and the processing environment. Design Control utilizes information including but not limited to, market research, basic research and product development, process engineering, and technological innovation.

Operational Control (the operation phase of the control process) involves the fulfillment of the objectives of the design control through temporal and/or spatial distributions of the physical and biological processes. It consists of two generic control activities; 1) the *control of flow rates* of material and energy through the selected transformation processes, and 2) the *control of exchanges* and the associated relative rates of exchange (prices) with other enterprises and with the natural environment. Operations Control utilizes information including but not limited to, purchasing, materials and logistic management, marketing, production level and pricing decisions, and finance, taxation, employee contracts, personnel relations, environmental regulation and public relations.

Together the cybernetic control model and the physical and biological process models provide the framework for an integrated managerial/engineering information, analysis, and accounting system which is truly *isomorphic* with the physical material, energy, equipment and human time factors involved in the production processes, and the design and operational control decisions of manufacturing enterprises. Furthermore this linkage provides a basis for evaluating alternative designs and management decisions such as;

- choices between alternative technologies for production processes,
- selection of the type and the level of automation, diversity and configurations of automated equipment and physical facilities,
- evaluation of the physical material and net energy costs of alternative products and production processes,
- evaluation of the skill-specific human time costs of alternative products and processes,
- analysis of costs as a function of production rates and scale,
- analysis of the by-products and environmental residuals produced by alternative processes,
- alternative policies for the allocation or amortization of the "fixed" costs of the processing environment to products and alternative processes--including selection of appropriate time scales and time horizons.

Chapter 1 discusses the general mathematical description of elemental physical and biological processes upon which the process network is based. Chapter 2 provides the methods and theory for organizing these elemental process into networks and hierarchical levels of network organization. Models of the processing environment, that is the infrastructure or plant where processing takes place, are developed. A number of measures of energy efficiency of the network are presented, and key features of process network models and comparisons with other representations are discussed. Chapter 3 extends the physical and biological models of Chapter 2 into monetary and economic contexts by *mapping* the process network models into economic variables. These mappings are *isomorphic* to the physics and biology of the processes, and thus provide a unique solution to contemporary issues in business management and engineering design. The basic classes of decisions which enterprises perform in the context of the models are discussed.

Chapter 4 introduces an application of the theory to life-cycle assessment and discusses computation and data for such models. Chapter 5 presents first a process network model of a paper manufacturing enterprise producing paper from both virgin materials and recycled materials. Next, analysis at the higher level of organization, the use and disposal / recycling of used paper, completes the life-cycle assessments for paper packaging. Chapter 6 repeats the same stages of analysis for polystyrene packaging materials and their life-cycle. Chapter 7 provides an extensive discussion of the results of these life-cycle assessments, comparing the two products and four disposal alternatives for each product; landfill burial, incineration, electric power generation and recycling. Conclusions and policy implications are presented in Chapter 8.

1 ELEMENTAL PHYSICAL AND BIOLOGICAL PROCESSES

We begin with mathematical representations of the material transformation processes of the enterprise, beginning initially with a material transformation at the lowest or most basic level of the processing system, called an *elemental process*.

1.1 Material Processing and the Technical Coefficients of Transformation

By definition, an elemental process s involves a column vector of technically-specific material *resources* $y_{rs} = \{y_1, y_2, \dots\}_{rs}$ and exactly one technically-specific material y_{os} which represents the *object* of the material transformation. As illustrated in the graphical representation of Figure 2, a closed line is used to represent the boundary of process s.

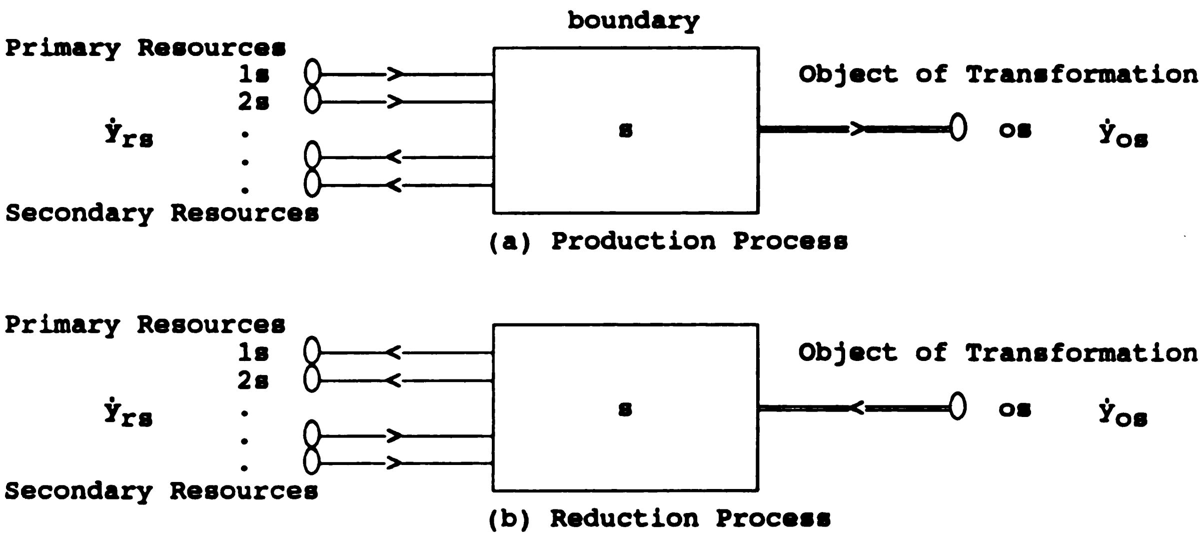

Figure 2 Elemental Processes

A set of directed line segments, called edges {os, 1s, 2s, ... } are used to establish a directional reference frame relative to the boundary of the process for the *flow rates* (in units of material per unit time) of the technically-specific object of transformation $\dot{y}_{os}$ and the set of technically-specific material resources $\dot{y}_{rs} = \{\dot{y}_1, \dot{y}_2, \dots\}_{rs}$.

The flow rates $\dot{y}_{rs}$ of the technical-specific resources are linearly related to the flow rate of the object of transformation $\dot{y}_{os}$

$$\dot{y}_{rs} = k_{rs}\, \dot{y}_{os} \tag{1.1}$$

where k_{rs} is a column vector with positive constants $k_{rs} = \{k_1, k_2, \dots\}_{rs}$ called the *technical coefficients of transformation.*

The bold-face edge in Figure 2 is used to identify the variable which represents the object of the transformation and which appears as the stimulus (independent) variable in Eq. (1.1). Thus, the bold-faced edge is said to define *stimulus-response orientation* for the mathematical representation of the material transformation process. The orientation of the line segments in the reference frame of the mapping in Figure 2 are selected to correspond to the direction of the respective physical material flows relative to the boundary of the process. This confines all material flow rates $\dot{y}_{os}$ and $\dot{y}_{rs}$, to the positive range of the real number system and the stimulus variable (object of the transformation) $\dot{y}_{os}$ may be either an output or an input flow rate to the process as shown in Figure 2(a) and 2(b), respectively.

Reference frame Figure 2(a) is said to correspond to a *production process* in which the input resources are called the *primary resources* since they represent the materials from which the product is actually structured. The resource outputs, on the other hand, are called *secondary resources* or by-products since they represent technically specific residuals of the process.

Reference frame Figure 2(b) is said to correspond to a *reduction process* in which the output resources are called the primary resources because they are the consequences of the reduction of the object material y_{os} in some technically-specific sense. The input resources on the other hand are called secondary resources or co-resources since they are essential to decomposition of the object material $\dot{y}_{os}$.

1.2 The Energetic Costs of Material Processing

Any and all material transformations involve *energetic resources* in the form of *skill-specific human time* and/or *thermodynamically-specific physical energy* to effect the transformation. They are *endoenergetic* if they are be driven by physical energy and/or skill-specific human time. They are *exoenergetic* if they generate physical energy and/or human time in the sense of sustaining human populations biologically and intellectually.

The first step in establishing a minimal mathematical representation of the energetic properties of the material transformation process s of Figure 2 is to impute an *energetic cost* x_{os} to the object of transformation $\dot{y}_{os}$ according to the following relation

$$x_{os} = - k_{rs}^{T} X_{rs} - f_s(\dot{y}_{os}) \tag{1.2}$$

where

$f_s(\dot{y}_{os}) = \{f_1(.), f_2(.), \dots\}_{os}$ is a row vector representing the *energetic cost* of transformation,

$x_{rs} = \{x_1, x_2, \dots\}_{rs}$ is a row vector representing the *accumulated* energetic costs of making each technically-specific resource $\dot{y}_{rs}$ available to the boundary of the process,

X_{rs} is a matrix composed of row vectors x_{rs} ,

$x_{os} = \{x_1, x_2, \dots\}_{os}$ is a row vector representing the accumulated energetic costs of the object of transformation y_{os},

k^T_{rs} is the transpose of the vector k_{rs} given in Eq. (1.1), and represents the weightings applied to the energetic costs of the resources $\dot{y}_{rs}$ in imputing an accumulated energetic cost to the object of transformation.

The components of the energetic cost variables $f_s(\dot{y}_{os})$ and x_{os} have the dimensions of skill-specific time (person hours) and physical energy (measured in kW hours, units of fuel, etc.) *per unit of technically specific material* y_{rs}. A mathematical representation of the energetic properties of the material transformation process s of Figure 2 is completed by defining a generalized *energy rate* variable for each technically-specific material rate according to the relation

$$\begin{aligned} \dot{e}_{os} &= \dot{y}_{os}\, x_{os} \\ \dot{e}_{rs} &= \dot{y}_{rs}\, x_{rs} \qquad rs = rs_1,\ rs_2,\ \ldots \end{aligned} \tag{1.3}$$

which has the dimensions *person hours, and physical energy per unit time* (hour, day, month, etc.)

The rate at which generalized energy is produced (or consumed) by process s is obtained by summing the energy rate $\dot{e}_{rs}$ and $\dot{e}_{os}$ in Eq. (1.3) over the boundary of the process, thus

$$\dot{e}_s = \dot{e}_{os} + \sum_{rs} \dot{e}_{rs} = \dot{y}_{os}\, x_{os} + y^T_{rs}\, X_{rs} \tag{1.4}$$

where x_{os} and y_{rs} are given by Eqs. (1.2) and (1.1), respectively. When these expressions are substituted into Eq. (1.4), all terms vanish except for the term representing the energy produced or consumed within the boundary of the process. Thus, the generalized energy produced or consumed by the transformation itself is

$$\dot{e}_s = -\dot{y}_{os}\, f_s(\dot{y}_{os}) \tag{1.5}$$

The components of the row vector $\dot{e}_s$ in Eq. (1.5) represent the weekly or monthly work force and energy requirements for the process s measured in *real terms* and broken down by skill categories (engineers, technicians, etc.) and the thermodynamic properties (heating gas, motor fuel, electrical, etc.), respectively.

Negative values in the energy rate vector represent energy consumption (endoenergetic process) while positive values represent energy generation (exoenergetic processes). For example, an electrical power generating plant as a material (fuel) decomposition process will be exoenergetic in electrical energy, but endoenergetic in all other thermodynamically-specific forms of energy, and in skill-specific human time. On the other hand, a household or urban population center as a materials (food and household items) decomposition process will be exoenergetic in some skill-specific human time (labor) but endoenergetic in other skill-specific human time such as medical and education services and in thermodynamically-specific forms of energy.

It must be emphasized that the energetic cost function $f_s(y_{0s})$ in Eqs. (1.2) and (1.5) is actually a set of functions all of which, in general, may be nonlinear and often discontinuous with respect to the processing rate y_{0s} and are applicable *only* for a given technically specific environment. If the technical features or organizational structures of the processing environment change significantly, the component of $f_s(y_{0s})$ will change accordingly. And this is exactly the purpose of many analyses; to explore the generalized energy requirements of alternate processing environments, all evaluated in relationship to variable processing rates, y_{0s}.

1.3 The Processing Environment

Any and all material transformations take place within the context of a technically specific *processing environment*, which may also be thought of in industry and agriculture as the technical means of production or transformation.

Numerical values of the technical coefficients of material transformation in the column vector k_{rs} of Eq. (1.1), and the rate dependent energetic costs of transformation in the row vector $f_s(\dot{y}_{os})$ of Eq. (1.2), are referred to collectively as the *technical parameters* of process s. Their specific values depend ultimately upon technical features of the object of transformation (product) *and* upon the structural and organizational features of the processing environment (means of production). For this reason the vectors k_{rs} and $f_s(\dot{y}_{os})$ are said to define the *technology* of the process s.

Let y_{cs} represent the technically-specific environment of a technically-specific transformation process $\dot{y}_{os}$ as represented in Eqs. (1.1) and (1.2). The environment y_{cs} of this process is in itself the object of yet another material transformation process on another set of technically-specific resources over another time frame. Since the processing environment y_{cs} must be completed as an object of transformation *before* it can serve as a processing environment, it is convenient to refer to the materials, energetic costs, and energy required to produce the completed processing environment.

Specifically, let y_{cs} represent the technically-specific processing environments required to produce a given flow rate of a technically-specific objects of transformation $\dot{y}_{os}$ per unit time. The material resources required to construct the technically-specific environment y_{cs} is

$$y_{rs} = k_{cs}\, y_{cs} \tag{1.6}$$

where k_{cs} is a column vector representing the technical material composition of the processing environment. It follows that energetic resources required to engineer and construct the processing environment are given by

$$x_{cs} = -k_{cs}^{T}\, x_{rs} - f_{cs}(y_{cs}) \tag{1.7}$$

where $f_{cs}(y_{cs})$ is a row vector representing the skill-specific labor time and thermodynamically-specific energy required to engineer and construct the processing environment, and x_{cs} represents their accumulated energetic costs, all measured in real terms.

The generalized energy dissipated in the engineering and construction of the processing environment, measured in real terms is

$$e_{cs} = -\, y_{cs}\, f_{cs}(y_{cs}) \tag{1.8}$$

where the components of the row vector e_{cs} represent the skill-specific human time (person hours) and technically specific physical energy (kWh), measured in real terms, required to construct (reconstruct) the processing environment y_{cs}.

Note that:

a) the accounting time frames for the material resources $\dot{y}_{rs}$ and the technical cost x_{os} of the object of transformation $\dot{y}_{os}$ are based on *rates* of materials and energy per unit time,

b) the accounting time frame for the materials y_{rs} and technical cost x_{cs} of the processing environment, y_{cs}, is based on the engineering and construction time,

c) construction must be completed before the time frame for transformation of $\dot{y}_{os}$ can begin.

Thus, there is *no physical basis or principle* for reconciling these differences in time frames. The choice of how to allocate or amortize the accumulated technical cost e_{cs} of constructing the processing environment y_{cs} to the transformation $\dot{y}_{os}$ is strictly a human cybernetic control decision of the enterprise, and the rules of the social/political system that the enterprise functions in.

If the technical features of the object of transformation (product) and/or the primary resources are changed significantly, the components of k_{rs} will change accordingly. The components of $f_s(\dot{y}_{os})$ may or may not change, depending upon the degree of flexibility designed into the processing environment (the means of production). However, in general there may be many specific processing environments that might be engineered to support a given transformation process. The technical features and organizational structure of the process environment determine the specific components of $f_s(\dot{y}_{os})$.

2 NETWORKS OF ELEMENTAL PHYSICAL AND BIOLOGICAL PROCESSES

We turn now to mathematical representations of networks of transformation processes, focusing on a mathematical representation of the physical interconnections between the elemental processes as discussed above. This discussion follows that in Koenig and Tummala [4]. For additional discussion the reader is referred to [1], [2] and [3].

2.1 Continuity and Compatibility Equations

By definition, a process network S consists of two or more processes that are interconnected such that the objective y_{os} of one material transformation process serves as a resource to one or more other processes or vice-versa. A directional reference frame for the flow of technically-specific materials between processes is obtained operationally by interconnecting the edges in the reference frames of the elemental processes in Figure 2 above. The set of interconnected edges is called a *graph* of the network S.

The bold-faced edges of a graph are called *branches* because each edge is associated with a unique elemental subprocess or branch process os in the overall network S. The remaining edges of are called *links* because they show how the process identified by branch os is connected (linked) to the resources of other processes in the network. An edge in the graph that does *not* share its end-point with at least one other edge is called a *boundary* edge. The set of all boundary edges is called the boundary of the network S.

In general, the continuity equation at vertex s refers to a technically-specific material rate $\dot{y}_{os}$ and can be written in the general form

$$\dot{y}_{os} = \alpha_s \, \dot{y}_l \tag{2.1}$$

where $\dot{y}_{os}$ is a scalar representing the technically specific material flow rate of branch os, $\dot{y}_l$ is a column vector representing the material flow rates of the *links* in the network, and where $\alpha_s = \{\alpha_{s,l}\}$ is a row vector with entries

$$\alpha_{s,l} = \begin{cases} 1 & \text{if link } l \text{ is incident to vertex s with orientation opposite to branch os} \\ -1 & \text{if link } l \text{ is incident to vertex s with orientation the same as that of branch os} \\ 0 & \text{if link } l \text{ is not incident to vertex s.} \end{cases}$$

The row vector α_s is referred to as the *material continuity vector* for vertex s. The matrix $A = \{\alpha_s\}$ contains a row for each vertex s and is called the *material continuity matrix* for the network S of elemental processes. In contrast to the mathematical representation of the material transformation process given in Eq. (1.1), $\dot{y}_{os}$ appears as the dependent variable in the continuity equation Eq. (2.1).

The continuity equation for the entire network is

$$\dot{y}_b = A \, \dot{y}_l \tag{2.2}$$

where $\dot{y}_b$ is a column vector representing the branches in the network S and $\dot{y}_l$ is a column vector representing the links in S.

By definition, a *path* in network S of elemental process is a subset of edges that: a) connect the boundaries of two processes, and b) contains *exactly* one branch and one link. Each of the links incident to the vertex s of branch y_{os} defines a path in the network. The *orientation* of a path is defined by the orientation of the branch os included in it. The energetic costs associated with a path of edges in a network S of elemental processes are said to be compatible, if and only if, their oriented sum vanishes. The compatibility equations can be written in the general form

$$x_l = \beta_l X_o \qquad (2.3)$$

where x_l is a row vector representing the energetic costs of link l of the network, X_0 is a matrix whose rows represent the energetic costs of the branches in the network, and $\beta_l = \{\beta_{l,s}\}$ is a row vector with entries

$$\beta_{l,s} = \begin{cases} 1 & \text{if branch os is in the path defined by link } l \text{ with orientation opposite to } l \\ -1 & \text{if branch os is in the path defined by link } l \text{ with the same orientation as } l \\ 0 & \text{if branch os is not in the path defined by link } l \end{cases}$$

The row vector β_l is referred to as the energetic cost *compatibility vector*, for link l. The matrix $B = \{\beta_l\}$ contains a row for each link l and is called the *compatibility matrix* for a network S of elemental processes. In contrast to the mathematical representation of the energetic costs given in Eq. (1.2), x_{os} appears as the independent variable in the energetic cost compatibility equation Eq. (2.3).

The compatibility equation for the entire network is

$$X_l = B\, X_b \qquad (2.4)$$

where the X_b represent the energetic costs of the branches in the network S, and where rows of X_l represent the energetic costs of the resource links.

One of the fundamental properties of linear graphs of central interest in processing networks is that material continuity matrix A and the energetic costs compatibility matrix B are orthogonal, *i.e.*

$$A + B^T = 0 \quad or \quad A = -B^T \quad or \quad B = -A^T \qquad (2.5)$$

The implication of Eq. (2.5) is that the inner product γ_s of the material rates and energetic costs vanish identically at each vertex s in the network. Indeed, consider

$$\gamma_s = \dot{y}_b^T X_b + \dot{y}_l^T X_l \tag{2.6}$$

Substituting Eqs. (2.1) and (2.3) into Eq. (2.6) gives

$$\gamma_s = \dot{y}_l^T A^T X_b + \dot{y}_l^T B X_b = 0 \qquad \textit{for } B = -A^T \tag{2.7}$$

Since Eq. (2.2) is isomorphic to the graph of the network it is appropriately referred to as a mathematical representation of the *technical structure* of the processing network and the matrix A as the *interconnection* matrix of the network. The graphs then are expedients or tools for establishing the interconnection matrix A and identifying and coordinating the choice of dependent and independent variables in the mathematical representation of the network S.

2.2 Representation of Open Networks and Multiple Levels of Organization

A network S of elemental processes is said to be materially open (to its material environment), if and only if, the boundary of S includes a non-empty set of technically specific resources $\dot{y}_r$ *and* a non-empty set of technically-specific objects of transformation $\dot{y}_0$. The objective here is to determine the boundary and the processes included in the system.

In the case of an individual enterprise the boundary can be viewed as circumscribing all branch processes over which management has direct control both with regard to their technical design and their technical operation. In this context, the boundary flow rates represent material exchanges with other enterprises and/or the physical and biological processes of the material environment. Alternatively, the boundary can be viewed as circumscribing only a sub-network of processes over which management has direct control; in which case some of the boundary flow rates might represent material exchanges between operating divisions of the enterprise. In the case of *Product Life-Cycle Assessment* [5] the boundary of the system might represent exchanges with the natural environment of both raw materials and the disposal of residuals or wastes.

The objective of the following development is to derive the representation of a network of transformation processes from the representation of the component elemental processes of the network and the specific manner in which they are technically interconnected, so that the technical parameters of the former can be evaluated from the technical parameters of the latter. This procedure may be continued throughout levels of organization, thereby aggregating lower level networks into higher level networks for the purposes of analysis and design.

The continuity and compatibility equations for the network of processes internal to the boundary of S were given as Eqs. (2.2) and (2.4), where the components of vector $\dot{y}_b$ and the matrix X_b are isomorphic to the *branches internal to the boundary* of S, and the components vector $\dot{y}_l$ and matrix X_l are isomorphic to the *links internal to the boundary of S*.

Let the elemental transformation processes in the network S as given in Eqs. (1.1) and (1.2) be compiled into partitioned matrix forms

$$\begin{bmatrix} \dot{y}_l \\ \dot{y}_r \end{bmatrix} = \begin{bmatrix} K_{lb} & K_{lo} \\ K_{rb} & K_{ro} \end{bmatrix} \begin{bmatrix} \dot{y}_b \\ \dot{y}_o \end{bmatrix} \tag{2.8}$$

and

$$\begin{bmatrix} X_b \\ X_o \end{bmatrix} = - \begin{bmatrix} K_{lb}^T & K_{rb}^T \\ K_{lo}^T & K_{ro}^T \end{bmatrix} \begin{bmatrix} X_l \\ X_r \end{bmatrix} - \begin{bmatrix} F_b(\dot{y}_b) \\ F_o(\dot{y}_o) \end{bmatrix} \tag{2.9}$$

where the components of vector $\dot{y}_0$ and the matrix X_0 are isomorphic to *branches on the boundary* of the network S, and the components of vector $\dot{y}_r$ and the matrix X_r are isomorphic to *links on the boundary* of S. Coefficient matrices $[K_{lb}\ K_{lo}]$ represent the technical coefficients of transformation between the objects of transformation $\dot{y}_b$ and $\dot{y}_o$ and the resources $\dot{y}_l$ within the boundary. Matrix $F_b(\dot{y}_b)$ and $F_o(\dot{y}_o)$ represent, respectively, the energetic costs $f_s(\dot{y}_{os})$ for elementary branch processes within and, on the boundary of S, as compiled from Eq. (1.2).

The minimal representation of a network S at its boundary is obtained from the simultaneous solution of Eqs. (2.2) and (2.8), and Eqs. (2.4) and (2.9). Specifically, substituting the expression for $\dot{y}_l$ in Eq. (2.8) into Eq. (2.2) and solving for the internal processing rates gives

$$\dot{y}_b = K_b\, \dot{y}_o \tag{2.10}$$

where

$$K_b = (I - A\ K_{lb})^{-1}\ A\ K_{lo} \tag{2.11}$$

is called the *process schedule matrix* because it gives the transformation (production) schedules $\dot{y}_b$ of the internal branch processes, as an explicit function of the transformation schedule $\dot{y}_o$ on the boundary of the network, i.e. the branch rate schedules as a function of the "master" schedule. The external resources required to support the processing network is obtained by substituting Eq. (2.10) into Eq. (2.8). The result is

$$\dot{y}_r = K_S \, \dot{y}_o \tag{2.12}$$

where

$$K_S = K_{rb} \, K_b + K_{ro} \tag{2.13}$$

represents the technical coefficients of transformation *for the network*, (from resources to object of transformation) as computed from the technical coefficients of transformation of the branch processes of the network S and the interconnection matrix A.

Substituting X_l in Eq. (2.4) into Eq. (2.9) and solving for X_b gives

$$X_b = -(I - K_{lb}^T A^T)^{-1} K_{rb}^T X_r - (I - K_{lb}^T A^T)^{-1} F_b(\dot{y}_b) \tag{2.14}$$

Substituting Eq. (2.14) into Eq. (2.9) gives the energetic cost X_o of delivering the final objects of transformation (products) $\dot{y}_o$ to the boundary of the network. The result is

$$X_o = -K_S^T X_r - F_S(\dot{y}_o) \tag{2.15}$$

where

$$F_S(\dot{y}_o) = K_b^T F_b(\dot{y}_b) + F_o(\dot{y}_o) \tag{2.16}$$

is a matrix whose rows represent the unit energetic costs of transformation for the boundary objects of transformation $\dot{y}_o$ as computed from the technical parameters of the branch processes of the network S and the interconnection matrix A. Since the argument $\dot{y}_b$ of $F_b(\dot{y}_b)$ is a parametric function of $\dot{y}_o$ as given by Eq. (2.10), the unit energetic costs of transformation are computable as an explicit function of the boundary flow rates $\dot{y}_o$. Further, the unit energetic costs of transformation $F_S(\dot{y}_o)$ for the network S is a weighted combination of the energetic costs of the elemental branch processes $F_b(\dot{y}_b)$; the weighting matrix being the *transpose* of the process schedule matrix in Eq. (2.10).

The generalized energy $\dot{e}_S$ produced or consumed per unit of time by the network itself is easily shown to be

$$\dot{e}_s = -\dot{y}_o^T F_S(\dot{y}_o) \tag{2.17}$$

The vectors K_S and $F_S(\dot{y}_O)$ define the technology of the network S.

It has been established that;

(a) the minimal mathematical representation of a network S of elemental processes at its boundary is invariant in analytical form from the component elemental processes s,

(b) the technology of the network S as represented by the transformation matrix K_S in Eq. (2.11) and $F_S(\dot{y}_O)$ in Eq. (3.16) are computable as linear combinations of the technologies of the component elemental processes s, as represented by k_{rs} in Eq. (1.1) and $f_s(\dot{y}_{Os})$ in Eq. (1.5), and their technical mode of interaction as represented by the connection matrix A.

2.3 The Network Processing Environment

We now consider the *processing environment* for the network S of elemental processes s. In section 1.3 above, Eqs. (1.6) and (1.7) describe the material resources and energetic costs required to construct the processing environment y_{cs} for an elemental transformation process $\dot{y}_{Os}$. The processing environment for the network as a whole is composed of the collection of these processing environments y_{cs}, such as machines, materials handling equipment, reaction vessels, etc. for all processes within the boundary of the network. In addition there will normally be some components of the network processing environment which cannot be identified with an individual elemental processes, but are essential for the operation of the processing network as a whole. Examples might include buildings, lighting, heating, etc. By definition all components of the network processing environment are constructed external to the boundary of the network, and construction must be completed before processing can begin. Compiling Eqs. (1.6) and (1.8) for each and all of the components of the network processing environment into matrices gives the representation of the material resources y_r and energetic costs X_c required to provide the processing environment y_c

$$y_r = K_c\, y_c \tag{2.18}$$

$$X_c = -K_c^T X_r - F_c(y_c) \tag{2.19}$$

The inclusion of the material requirements for the processing environment and energetic costs in the model of the processing network is fundamental to the analysis of alternative product and process designs. For many types of technologically advanced products and/or automated production environments, the material requirements and energetic costs of the processing environment may greatly exceed the materials and energetic costs of the processing itself. And in cases such as electrical power generation, the physical endoenergetic costs of the processing environment may total 25% or more of the exoenergetic energy generated over the life of the facility.

2.4 Energy Efficiency of the Network

The process network model provides variables and a number of useful definitions and mechanisms for comparing the energy efficiency of alternative networks of processes and the production of products.

The elements of the matrix $F_S(\dot{y}_O)$ have dimensions of units of physical energy / unit of material, *e.g.* kWh/kg material, labor hours/kg material, etc. Thus, efficiency as energetic costs of transformation per unit material are given by $F_S(\dot{y}_O)$ for each object of transformation y_O.

The elements of the matrix X_0 also have dimensions of units of physical energy / unit of material. X_0 includes both the energetic costs of transformation within the boundary of the network and the energetic costs of bringing materials y_r to the boundary of the system. So X_0 represents efficiency as total energetic costs per unit material, such as may be used in a life-cycle assessment.

Another measure of energy efficiency may be defined as the energetic costs per unit time. The transformation energy per unit time is given by Eq. (2.17)

$$\dot{e}_S = -\dot{y}_o^T F_S(\dot{y}_o) \tag{2.17}$$

where $\dot{e}_S$ is a row vector with elements representing each energetic form. The total energy per unit time for each of the energetic forms is similarly given by

$$\dot{e}_o = \dot{y}_o^T X_o \tag{2.20}$$

The energy required for production of a given vector of materials y_0 is given for the network of processes by

$$e_S = -y_o^T F_S(\dot{y}_o) \tag{2.21}$$

and the total energy including the energy costs brought to the boundary of the network is given by

$$e_o = y_o^T X_o \tag{2.22}$$

The energy required for operation of the network over a given time period $t_0 \leq t \leq t_f$ is

$$e_S = \int_{t_o}^{t_f} -\dot{y}_o^T F_S(\dot{y}_o)\, d\tau \tag{2.23}$$

and the total energy for operation over a time period is

$$e_o = \int_{t_o}^{t_f} \dot{y}_o^T X_o \, d\tau \tag{2.24}$$

The life span of the processing environment, y_c may be defined by the number of units of product(s) produced y_o or by a given time interval $t_o \leq t \leq t_f$. The energy required to produce the processing environment is given as X_c in Eq. (2.19). So the total energy e_{oc} required to produce a given number of products during the life of the processing environment may be defined as

$$e_{oc} = y_o^T X_o + y_c^T X_c \tag{2.25}$$

And the energy required to operate the processing environment over a temporal life span of the processing environment may be defined as

$$e_{oc} = \int_{t_o}^{t_f} \dot{y}_o^T X_o \, d\tau + y_c^T X_c \tag{2.26}$$

2.5 Key Features of the Process Network Model

The key features of the process network model of physical and biological processes are:

- All variables can be measured in physical and biological units and the process network model is *dimensionally consistent* in these real units as well as in monetary units if and when prices are associated with the real units.
- The observables of the system are of two distinct classes; a) the technically-specific

materials y_r and y_o which are physically *conserved* through transformations and b) the thermodynamically-specific physical energy and skill-specific human time eS which are physically *dissipated* in the transformation processes. This is an essential distinction first noted by Koenig and Tummala [1].

- The technically-specific materials are of three distinct subclasses; y_r which are *components* of the objects of transformation (products) y_o, and y_c which constitute the technically-specific *processing environment* utilized to produce or reduce objects of transformation, Koenig [3] and Koenig and Tummala [4]. The processing environment may include specific combinations of automated equipment, tools, physical structures, chemical catalysts, animals and other biological organisms, humans with specific skills, etc.
- The technologies employed in the transformation processes (the production technologies) appear as the parameters K_S, K_b and F_S in the equations of transformation.
- The system variables and the mathematical structure of the model are invariant and are conceptually and analytically consistent across boundaries of exchange, and across boundaries of partitionings and levels of aggregation within the enterprise and the economy. The technological parameters K_S, K_b and F_S at any given level of organization are computable from lower level parameters. These properties are necessary and sufficient for projecting the technical and economic analysis of alternative product designs and alternative product production processes into higher levels of organization both within the enterprise and within an economy, and they provide an analytical basis for product Life-Cycle Assessments.

- All exchanges of materials, physical energy, and human time are accounted for in the model, whether or not they have monetary values associated with them. This feature provides the capability to analyze the flows of environmental residuals and the effects of regulatory restrictions on the material flows of enterprises and networks of enterprises in an economy.

2.6 Comparison with Leontief Representations

It is essential to note that the process network models presented here are distinctly different from the mathematical representations of production processes employed in economic analysis. Input-Output models of the Leontief type [6] and [7] are in some respects mathematically similar to Eq. (2.12). However they make no distinction in the definition of observable variables between the fundamental physical properties of material flows (which are inherently conserved in the network of physical and biological transformations) and physical energy and human time (which are inherently dissipated or generated) in the transformation processes. This distinction is essential for both the integrity of the physical representation of the processes and the *isomorphism* of management information and accounting systems to the underlying technology and physical and biological processes.

2.7 Comparison with Economic Production Functions

Contemporary economic theory and econometric modeling rely heavily on the Generalized Cobb-Douglas production function, $y_j = \Pi\, y_{ij} \exp(k_{ij})$, $i=1,2,\ldots$, as a representation of the material and labor requirements of transformation processes, Varian

[8]. In fact, these families of production functions are equivalent to optimized Leontief coefficients, El-Hodiri and F. Nourzad [9].

A wide variety of production functions have been developed around the general representation given by Wicksteed in 1894, $y_0 = f(y_{r1}, y_{r2}, \ldots)$. Like the Cobb-Douglas production function, these representations choose the resources as independent variables, with the product as the dependent variable, Henderson [10]. This is exactly opposite to the choice of variables in process network theory. Conceptually it seems far more logical from both an engineering and an economic perspective to choose the product y_0 as the independent variable -- the decisions and objectives of the manufacturing enterprise are oriented towards choosing and producing products, rather than arbitrarily combining resources.

Most variants of these production functions are taken by construction to be twice differentiable so that optimization can be performed with straightforward calculus. In fact, the physical based energy functions $f_s(y_{0s})$ in process network theory will in general be discontinuous and only locally differentiable at best. This is not a matter of construction, but rather the *nature* of the physical and biological processes they represent. Most importantly, in contemporary economic production functions, the essential distinction between the conservative nature of material flows and the dissipative nature of physical energy and human time is lost and *the representation is not isomorphic to the underlying physical and biological processes*.

3 ISOMORPHIC MANAGEMENT INFORMATION AND MANAGEMENT ACCOUNTING SYSTEMS

The description variables, technologies, network structure and multiple levels of organization presented in Chapter 2 provide physical and biological models of the material flows and energetic costs of the manufacturing system. These models can in turn be *mapped* into monetary variables which may be used in design, management and evaluation of the enterprise's performance. This combination of process models and mapping into monetary variables provides an *isomorphic* management information and accounting system.

3.1 Material and Energetic Exchanges of the Enterprise Processing Network

In this physical and biological model of the process network, any and all enterprises engage in four classes of *exchanges* of technically-specific materials, physical energy and human time with the process networks of other enterprises in the economy and with natural systems of the environment.

1) Exchanges of resources y_r with other enterprises and the environment.
2) Exchanges of objects of transformation (products) y_o with other enterprises and the environment.
3) Exchanges of physical energy and skill-specific human time f_o with other enterprises and/or utilization of the natural environment.
4) Acquisition of the processing environment y_c from other enterprises.

These exchanges take place for all material flows and energetic costs across the boundary of the network, whether or not there are monetary prices associated with the exchanges.

Some enterprise exchanges may take place as bartered transactions, some may be constrained by regulation, such as air emissions or water effluents, some may have prices in the form of taxation, and of course some may be market exchanges with monetary prices.

3.2 Monetary Prices and Cash Flow

Consider now a set of price vectors associated with the materials and energetic costs at the boundary of the process network. These prices may be defined in monetary units, or they may be defined as ratios of exchange between physical quantities of materials, energy, and/or human time as the purposes of analysis dictate. The process network model is mapped into economic performance by assigning price vectors to the material resources, products, byproducts, and the various forms of energy at the boundary of the network as follows:

$\boldsymbol{p}_r$ - a price vector for the resource materials and byproducts $\boldsymbol{y}_r$ crossing the boundary

$\boldsymbol{p}_o$ - a price vector for the object(s) of transformation (products) $\boldsymbol{y}_o$ crossing the boundary

$\boldsymbol{p}_e$ - a price vector for the energetic costs of transformation $\boldsymbol{F}_S$ and $\boldsymbol{X}_o$ -- the technically-specific physical energy and skill-specific human time utilized by the network

$\boldsymbol{p}_c$ - a price vector for the processing environment $\boldsymbol{y}_c$

With reference to monetary prices, if in Eq. (2.15) the energetic costs $\boldsymbol{X}_r$ of the materials $\boldsymbol{y}_r$ brought to the boundary of the system are known, *cash flow* (exclusive of processing environment costs) for the enterprise can be defined as a scalar $\dot{v}_S$

$$\dot{v}_S = \dot{y}_o^T p_o + \dot{y}_o^T X_o p_e \tag{3.1}$$

If the energetic costs X_r are not known in real terms at the boundary of the system, *i.e.* if only the energetic costs of transformation F_S are known, the cash flow (exclusive of the processing environment costs) for the enterprise can be defined as

$$\dot{v}_S = \dot{y}_o^T p_o - \dot{y}_r^T p_r - \dot{y}_o^T F_S(\dot{y}_o) p_e \tag{3.2}$$

which is equivalent to

$$\dot{v}_S = \dot{y}_o^T p_o - \dot{y}_o^T K_S^T p_r - \dot{y}_o^T F_S(\dot{y}_o) p_e \tag{3.3}$$

3.3 Value Added and Amortization

As discussed in section 1.3 above, there is no physical basis for assigning the material requirements and energetic costs of engineering and constructing the processing environment to the objects of transformation y_o. This allocation or amortization is a control decision of the enterprise and the social/political rules of the economy in which the enterprise functions. Let g_S be a scalar valued function in monetary units, which incorporates these enterprise management control decisions and the economy's rules for the amortization of the costs of the processing environment

$$g_S \equiv g_S(y_c, p_c, X_c, p_e, \dot{y}_o, F_S(\dot{y}_o), t_o, t_f) \tag{3.4}$$

where the arguments of g_S represent the processing environment y_c, the price of the processing environment p_c, the energetic costs of engineering and constructing the processing environment X_c, the price of energetic resources p_e, the rate of production $\dot{y}_o$, the energetic costs of the transformation $F_S(\cdot)$, and the beginning and ending time of the amortization t_o, t_f.

There are three special cases of the general amortization function g_S:

1) $g_S(X_c, p_e, \dot{y}_o)$ and $g_S(y_c, p_c, \dot{y}_o)$ corresponding to the case where the cost of the processing environment is allocated as a linear or nonlinear function of the processing rate $\dot{y}_o$, as may sometimes be the case for manufacturing equipment.

2) $g_S(X_c, p_e, F_S(\dot{y}_o))$ and $g_S(y_c, p_c, F_S(\dot{y}_o))$ corresponding to the case where the cost of the processing environment is allocated as a linear or nonlinear function of the energetic costs of processing $F_S(\dot{y}_o)$, as may be the case in electrical power plant operations where the costs of the processing environment are amortized over the production of exoenergetic energy.

3) $g_S(X_c, p_e, t_o, t_f)$ and $g_S(y_c, p_c, t_o, t_f)$ correspond to the case where the cost of the processing environment is allocated as a linear or nonlinear function of the time interval t_o to t_f. An example might be the amortization of the costs of a building over time, or amortization according to discount rate.

With the amortization function g_S, a *value added* (profit) function for the enterprise may now be defined as

$$v_S = y_o^T p_o - y_r^T p_r - y_o^T F_S(\dot{y}_o) p_e - g_S \tag{3.5}$$

The price vectors in the value added function may be taken as functions of time $p_r(t_o,t_f)$, $p_o(t_o,t_f)$, $p_e(t_o,t_f)$, $p_c(t_o,t_f)$. They may also be taken as *expectational* or *stochastic* variables with stationary or non-stationary probability distribution functions.

The choice of the function g_S is a complex matter, but crucial to the economic performance and technical design of the enterprise. The process network model with the general amortization function g_S can in principle incorporate any and all economic, accounting and management rules for the allocation of fixed or indirect costs.

3.4 Allocation of Processing Environment Costs Between Multiple Products

An important contemporary controversy surrounding amortization of capital (processing environment) costs is discussed by Kaplan in a 1989 article in *Science*, "Management Accounting for Advanced Technological Environments" [11]. "Flexible manufacturing" refers to a production plant producing a variety of products with a variety of equipment, which may be arranged in a network of "work cells", Sethi [12]. In [11] Kaplan discusses a representative example of a manufacturing plant engineered and operated by the Siemens company, which produces a variety of electrical motors, some of which are quite specialized and many of which are high volume standard items. The problem becomes how to allocate the fixed and indirect costs of capital (the processing environment) to individual products in pricing and management decisions. Previously there has not been a systematic or scientific way to perform these allocations, often resulting in unprofitable cross subsidies between products.

Process network theory provides a straightforward and scientific way to allocate the amortized costs of individual processes to end products. Suppose that an amortization function, scalar valued in monetary units, g_s has been chosen for each individual elemental process in the network where the general arguments of g_s are as above

$$g_s = g_s(y_c, p_c, X_c, p_e, \dot{y}_o, f_s(\dot{y}_o), t_o, t_f) \tag{3.6}$$

As in the case of the energetic cost functions, $f_s(\dot{y}_{os})$, the functions $g_s(\cdot)$ may be compiled into column vectors, g_b of the amortization functions, with one element for each branch processes within the boundary of the network. And let g_o be a column vector of the amortization functions for the processes on the boundary of the network.

Recall that the material flow rates within the boundary of the network $\dot{y}_b$ are related to the flow rates crossing the boundary $\dot{y}_o$ by the schedule matrix K_b.

$$\dot{y}_b = K_b \, \dot{y}_o \tag{2.10}$$

Also recall that the energetic costs for the network are related to the energetic costs of the internal and boundary processes by the relation

$$F_S(\dot{y}_o) = K_b^T \, F_b(\dot{y}_b) + F_o(\dot{y}_o) \tag{2.16}$$

In a like manner, the amortization functions g_b and g_o can be logically related to allocate the individual process to the final products y_o,

$$g_S = K_b^T \, g_b + g_o \tag{3.7}$$

where g_S now has dimensions of units money/unit product for each of the products of y_o. Now the value added function in Eq. (3.5), (which is again scalar valued) takes the form

$$v_S = y_o^T \, p_o - y_r^T \, p_r - y_o^T \, F_S(\dot{y}_o) \, p_e - y_o^t \, g_S \tag{3.8}$$

To complete the analysis and to solve the dilemma posed by Kaplan, consider the cash flow and value added for each individual product in the (column) vector of products y_o. Let $\dot{v}_S$ be a row vector, in monetary units, whose components represent the cash flow for each of the products. Also, let * designate the outer product of vector multiplication. The cash flow vector for the vector of individual products is then

$$\dot{v}_S = \dot{y}_o^T * p_o - \dot{y}_r^T * p_r - \dot{y}_o^T \, F_S(\dot{y}_o) * p_e \tag{3.9}$$

The value added for the individual products is represented by the vector v_S where

$$v_S = y_o^T * p_o - y_r^T * p_r - y_o^T \, F_S(\dot{y}_o) * p_e - y_o^t * g_S \tag{3.10}$$

The ability to scientifically allocate both the *variable* material and energy costs, and the *fixed* processing environment costs between multiple products is an extremely important development. Such a theory for allocation of fixed costs between multiple products does not seem to be available in the literature, Kaplan [11] and [13], Fogarty [14], Orlicky [15], Browne [16].

3.5 Enterprise Performance Measures

From the derivation of cash flow and value added performance measures in the sections above, other enterprise performance measures follow directly. If return on assets (ROA) is defined as cash flow / net asset value then

$$ROA = \frac{\dot{v}_S}{y_c^T p_c - g_S} \tag{3.11}$$

If return on investment (ROI) is defined as net value added (profit) / initial investment then

$$ROI = \frac{v_S}{y_c^T p_c} \tag{3.12}$$

These cash flow, value added, amortization, ROA and ROI functions provide consistent and scientifically based mappings of the technical performance of the manufacturing enterprise into economic performance. Unlike the problems arising from contemporary management and financial accounting systems described by Johnson and Kaplan [17], these mappings are *isomorphic* to the underlying resource and product flows and energetic costs of physical energy and human time. In addition they provide a systematic and logical method for allocating fixed and indirect costs between multiple products.

3.6 Opportunity Sets for Exchange Within an Economy

Within an economy let the collection of technically-specific materials and energy be the identified as the *naturally feasible opportunity set*, N $\{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\}$, for exchanges between enterprises and between enterprises and the environment. Six subsets of the feasible opportunity set N may be defined:

1) Information (knowledge) of the exchange opportunities in the feasible set may be limited or bounded. The opportunity set of which a given enterprise j has information is the *information opportunity set*, I_j $\{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\}$, $I_j \subseteq N$, and may in general be unique to the enterprise or may be common to a group or collection of enterprises. The information opportunity set for the social/political processes is $I \subseteq N$.

2) Social/political processes may bound or constrain the exchange opportunities available to enterprises. The *permissible* (legal) *opportunity set* for the economy is defined as L $\{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\}$, $L \subseteq I$. The permissible opportunity set for a enterprise j, L_j $\{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\}$, $L_j \subseteq L$, may in general be unique to the enterprise or may be common to a group or collection of enterprises.

3) Enterprises may bound or constrain the opportunities for exchange they offer to other enterprises. The *tendered opportunity set* of exchanges offered by enterprise j to enterprise k, T_{jk} $\{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\}$, $T_{jk} \subseteq I_j$, $k = 1,2,\ldots,n$, $k \neq j$, specifies the enterprise to which the exchanges are offered and may in general be unique to the enterprise or may be common to a group or collection of enterprises.

4) The *available opportunity set* offered to enterprise j by a enterprise k is A_{jk} $\{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\}$ $= T_{kj}$. The available opportunity set offered to enterprise j by all

enterprises k is $A_j \{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\} = T_{1j} \cup T_{2j} \cup \ldots \cup T_{kj}$, $k \neq j$.

5) The *exchange opportunity set* for an enterprise j with a enterprise k is $O_{jk} \{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\} = L_j \cap A_{jk}$. Similarly, the exchange opportunity set for enterprise j with all enterprises k is $O_j \{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\} = L_j \cap A_j$.

Permissible and tendered opportunity sets for exchange either explicitly or implicitly include *utilization rights* that may take on a wide variety of forms. Some natural materials and products may be inherently indivisible by the nature of the specific technical characteristics. The atmosphere is an example. In principle both the divisible and indivisible utilization rights associated with a particular resource, product, or technical form of energy become part of the bounds or constraints imposed by social/political processes in the case of permissible opportunity sets and by enterprises in the case of tendered opportunity sets.

6) Exchanges between enterprises k in an economy are represented at a strictly physical level by the *selected exchanges* between an enterprise j and an enterprise k, $E_{jk} \{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\} \subseteq O_{jk} \cap O_{kj}$, and the selected exchanges between an enterprise j and all enterprises, $E_j \{\dot{y}_r, \dot{y}_o, y_c, \dot{e}_S\} = E_{j1} \cup E_{j2} \cup \ldots \cup E_{jk}$, $k \neq j$.

Key features of this definition of opportunity sets and exchanges are:

- All exchanges of materials and energy are accounted for in the representation, whether or not monetary prices are associated with them.
- The exchanges in the economy are *dimensionally consistent*, units and rates of materials, energy, time, and prices are compatible throughout the representation.
- The selection of the opportunity sets for permissible exchanges L, tendered exchanges T_{jk}, and exchanges E_j are *independent*, reflecting group and individual preferences

and control behavior.

- Exchange opportunity set O_{jk} gives an explicit representation of how the opportunities for an enterprise j are *dependent* on the information and behavior of social/political processes I and L, other enterprises I_k and T_{jk}, and its own information I_j.
- All preferences and control behaviors of enterprises and social/political processes ultimately effect the system through selected *real* exchanges E_j of technically-specific materials and energy between enterprises.
- It explicitly shows how the structure of the economy is determined by the exchanges E_j selected by enterprises, including the selection of the means of transformation (technology) y_c.

3.7 Design Control

The application of the enterprise's cybernetic control activities to the enterprise's physical and biological process network model forms the basis for the design and management of the overall enterprise. The enterprise's cybernetic control process is divided into two subclasses as illustrated in Figure 1 above. They are; *Design Control* (the design phase of the control process) and *Operational Control* (the operation phase of the control process). The objective of this paradigm is to illustrate how physical and biological process network models can be used to meet the overall objectives of the enterprise -- be they economic competition, energy efficiency, environmental compatibility, etc.

Design Control at the enterprise level involves two generic control activities:

1) *Selection of Exchanges*; the identification and selection between alternative opportunities for the physical exchange of materials, energy and human time with other enterprises and with the natural environment. As shown in Figure 1, the enterprise's initial and fundamental design activity is to identify the resources y_r, physical energy and skill-specific human time e_S that are available to it, and the opportunities to transform those into products y_0 (or physical energy e_S in the case of exoenergetic energy generation, and skill-specific human time e_S in the case of an enterprise producing "services").

This phase includes analysis of; what products are technologically feasible, the material and energy requirements of those products, the prices and quantities (exchange rates) associated with resources, energy and products during a selected time horizon, and any regulatory constraints that may be placed on the utilization of materials and energy.

Using the multi-level analysis of the process network described above, the enterprise may evaluate the exchange opportunities for divisions of the enterprise, for the enterprise as a whole, or for the enterprise's activities as part of an industry. By applying process network models to Life-cycle Analysis as illustrated in the following section, the enterprise may analyze its role and opportunities in the context of the network model of the entire cycle of products from raw materials and energy, through disposal or discharge of materials to the natural environment.

2) *Selection of Processing Environment*; the identification, selection and engineering or implementation of the requisite transformation process and the processing environment. The selection of the processing environment $\boldsymbol{y}_{\mathrm{C}}$ typically may involve the evaluation of known technologies, basic and applied research into new technologies, engineering of elemental processes, the engineering of the processing network, analysis of prices of alternative processing environments, decisions about amortization of the processing environment costs, and evaluation of the material and energy efficiency of producing products with the alternative processing environments. In process network models the production environment technologies are described by the parameters of $\boldsymbol{K}_{\mathrm{S}}$ and $\boldsymbol{F}_{\mathrm{S}}$. Thus alternative processing technologies may be evaluated through the modeling and comparison of their process networks.

Normally the selection of the exchanges and selection of the processing environment may be simultaneous activities. As discussed by Kaplan [11], financial accounting and management accounting systems currently in use do not incorporate a representation of production processes for purposes of design and engineering decisions. Utilizing models of the process network during the design control activities provide a *management* *information* and *management accounting system* which is *isomorphic* to the underlying physical and biological transformation processes and exchange opportunities of the enterprise and incorporates complete information about the parameters of the technology K_S and F_S and the variables y_r, y_o, e_S and y_c. Bacon and Butler [18] discuss several aspects of the design control activities.

3.8 Operations Control

Operations Control activities of the enterprise involve the fulfillment of the objectives of the design control through temporal and/or spatial distributions of the physical and biological processes and consist of two generic control activities:

1) *Control of Flow Rates*, the control of material and energy flow rates through the selected transformation processes. There are four general classes of control of flow rates that can arise in the context of the process network model.

Control of production rates $\dot{y}_o$ with;

a) prices p_o, p_r, and/or p_e serving as control signals,

b) stocks (inventories) of y_o and/or y_r serving as control signals,

c) exchange opportunities serving as control signals,

d) the flow rate $\dot{y}_o$ itself serving as a control signal.

2) *Control of Exchanges*, the control of exchanges and the associated relative rates of exchange (prices) with other enterprises and with the natural environment. There are four general classes of control of prices that can arise in the context of the process network model.

Control of prices p_o, p_r, and/or p_e with;

a) flow rates $\dot{y}_o$, $\dot{y}_r$, and/or $\dot{e}_s$ serving as control signals,

b) stocks (inventories) of y_o and/or y_r serving as control signals,

c) exchange opportunities serving as control signals,

d) prices p_o, p_r, and/or p_e themselves serving as control signals.

Numerous other controls may be described as combinations of the above cases.

Operations Control utilizes information including but not limited to, purchasing, materials and logistic management, marketing, production level and pricing decisions, and finance, taxation, employee contracts, personnel relations and public relations. Neoclassical economic theories of firm behavior are cases of controls 1 a) and 2 a). Kornai and Martos [20] have developed twenty one models of 1 a) and 1 b) as "non-price" controls for Leontief type economies. Control 1 b) has been used historically by the U.S. automobile industry and by enterprises in planned economies. Controls 1 c) and 1 d) are analogous to "management by objectives" and "market share" acquisition. Control 2 d) is analogous to "technical trading" and "cost plus" pricing of y_o.

Accounting systems and economic theory in general do not make a distinction between the technically-specific *materials* y_r and y_o which are *conserved* and the *dissipated variables* $\dot{e}_p$, (thermodynamically-specific physical energy and skill-specific human time) which are actually dissipated in the transformation (production) processes. Utilizing models of the process network for operational control activities provides a *management information* and *management accounting system* which is *isomorphic* to the underlying physical and biological transformation processes and exchange opportunities of the enterprise in its control of flow rates and prices.

4 A LIFE-CYCLE ASSESSMENT IN MANUFACTURING - PAPER VS. POLYSTYRENE PACKAGING MATERIALS

There are many potential applications of the paradigm of process network theory and the economic mapping outlined above. Some applications of process network theory in agriculture are given in references [20] through [25]. Koenig and Tummala [1] presented the initial representation of the theory in the context of ecological systems. At the time these analysis were done, the particulars of the economic mappings developed in Section 4 of this dissertation were not available. Obviously there are many other applications that may be imagined, in manufacturing, micro and macroeconomic analysis, and ecology. Some of these potential applications are described briefly as follows:

At the level of the global human economy, the system boundary may be defined as exchanges with the natural environment, the resource vector $\dot{y}_r$ representing the exchange rates of natural resources and byproducts between the natural environment and the global economy, and the technical state vector $\dot{y}_0$ representing the accumulation of net products from the global economy in the natural environment. At the level of a national or regional economy $\dot{y}_r$ may defined as imports from other economies, and $\dot{y}_0$ as exports to other economies. At a corporate level of organization $\dot{y}_r$ and $\dot{y}_0$ may represent the exchange of inputs and outputs. At an intra-firm level, the boundaries $\dot{y}_r$ and $\dot{y}_0$ may represent exchanges between subprocesses or divisions of the firm itself. And $\dot{y}_r$ and $\dot{y}_0$ may be defined as exchanges at the household or individual level.

Useful definitions of the system boundaries $\dot{y}_r$ and $\dot{y}_0$ may be defined on a purely physical basis for particular analysis or purposes, including:

- Technically-specific types of materials and energy, net products and byproducts exchanged with the natural environment.
- Exchanges of materials and energy between ecological zones.
- The material and energy requirements, products and byproducts of alternative transformation processes (technologies).
- The thermodynamic "net energy" returns of alternative (physical) exoenergetic technologies.
- The *reachability* and *stability* of alternative technical states as bounded by net energy and material requirements.

System boundaries may be defined on the basis of cybernetic control processes at the enterprise level for analysis of:

- Management "control" strategies and managerial accounting.
- Engineering design and cost analysis.
- Opportunities for technological and marketing innovation by enterprises in the context of a technically-specific economic environment.
- Competition between firms in industries or nations.
- Vertical relationships between enterprises within industries.
- The material (real) income and living standards of individuals.

System boundaries may be defined on the basis of cybernetic control processes at the economy level for analysis of:

- The "distributed control" structures of alternate political/economic systems and their functioning and performance.
- Competition/cooperation between geographic regions or national economies.

- The role of structural and technological innovation in economic evolution.
- Definitions of "economic sectors" as employed in macroeconomic modeling.
- The role of non-priced exchanges in economies.
- Relative "real" price comparisons and monetary price level inflation.
- Material vs. monetary exchange rates between "currency zones".

4.1 Life-Cycle Assessment

A life-cycle assessment was chosen as an example of the theory and practice for this dissertation for a variety of reasons:

- It provides an example for the analysis and comparison of manufacturing systems, including systems with feedback or recycling loops.
- It provides an opportunity to illustrate economic mapping and how the paradigm may be used to provide an isomorphic management information and accounting system for both enterprise level and for policy decision making.
- It provides an example where ecological-environmental loadings are an integral part of the analysis.
- It illustrates the application of the paradigm within the broader context of an economic system or subsystem composed of a number of enterprises.
- It provides an opportunity to examine the material and energy requirements of alternative manufactured products, their distribution systems, utilization, and disposal or recycling alternatives.
- Life-cycle assessment has become an important and controversial contemporary issue, of great interest to policy makers, manufacturers, and the public in general.

What is referred to here as life-cycle assessment has roots extending back to the late 1960's when the need for calculation of the energy requirements of extended production systems was recognized. During the 1970's "fuel cycle" studies were performed to estimate the monetary costs and environmental implications associated with alternative energy sources, including estimates of gaseous, solid, and liquid emissions. Such work included the construction of "mass balances" accompanying the energy calculations, and thus provided data on raw material requirements and on the mass of solid waste emissions. During the 1980's the focus of attention in the U.S. and Europe shifted to the solid waste disposal aspects of product life cycles as well as air and waterborne emissions [26].

A contemporary survey of the state of the art of life-cycle assessment and methodologies was published in January 1991 under the title *A Technical Framework For Life-Cycle Assessments* by the Society of Environmental Toxicology and Chemistry and the SETAC Foundation for Environmental Education, Inc. [26]. This publication was the result of a workshop sponsored by 15 industry and public interest groups and organizations, research institutions and major industrial manufacturers, and the U.S. Environmental Protection Agency.

A succinct definition of life-cycle assessment is provided in [26] and quoted here.

> "The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, processes, or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements.

The assessment includes the entire life cycle of the product, processes, or activity, encompassing extraction and processing of raw materials, manufacturing, transportation and distribution, use/re-use/maintenance, recycling and final disposal."

SETAC defines three components of life-cycle assessments;

- *Life-Cycle Inventory* - An objective data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste, and other environmental releases throughout the life cycle of a product, process, or activity.
- *Life-Cycle Impact Analysis* - A technical, quantitative, and/or qualitative process to characterize and assess the effects of environmental loadings identified in the inventory component.
- *Life-Cycle Improvement Analysis* - A systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw materials use and environmental releases throughout the whole life cycle of the product, process, or activity.

Life-cycle inventory forms the basic information, or model, for subsequent impact analysis at ecological and human health levels. Similarly, the inventory provides for identification of opportunities for improvement and the analysis of improvements. A diagrammatic representation of life-cycle inventory is presented in Figure 3, reproduced from [26].

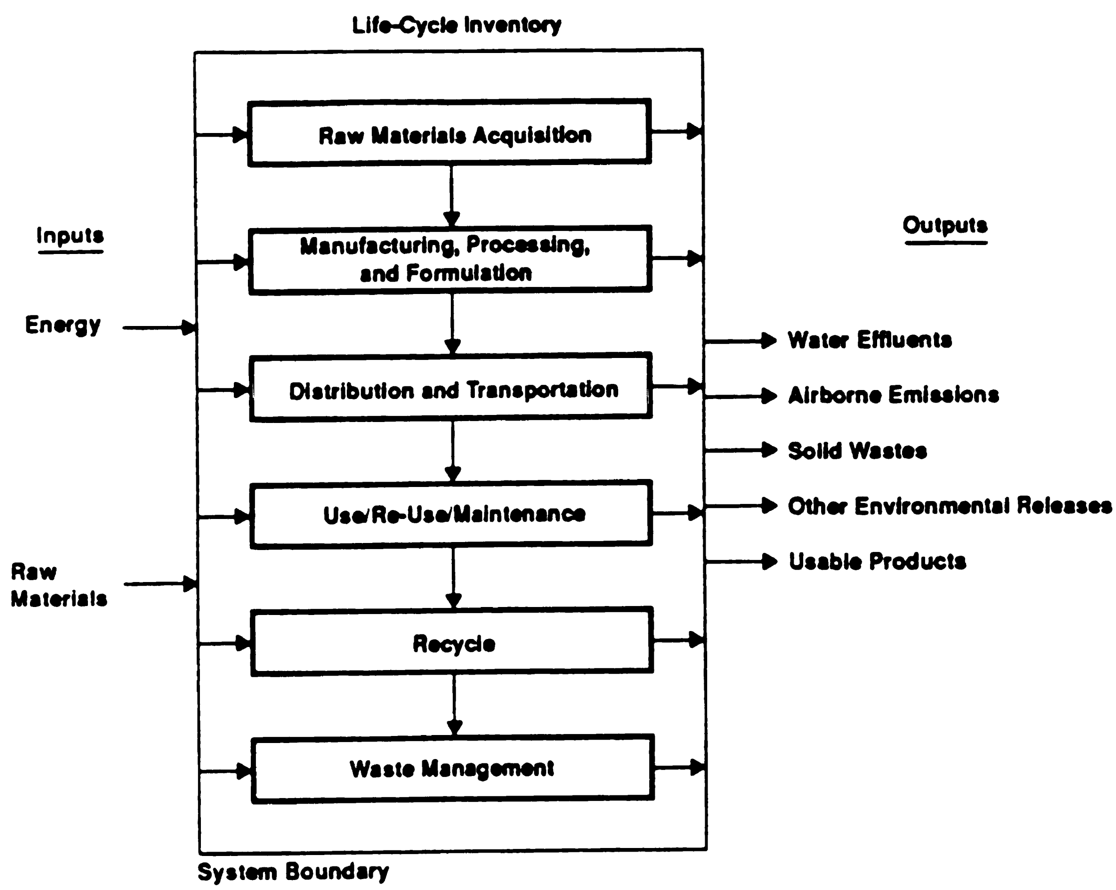

Figure 3 Life Cycle Inventory From SETAC Report, pp. 10

In this context, SETAC [26] lists four major research needs for the life-cycle inventory component which are fulfilled by the process network models described in the proceeding sections of this dissertation and are illustrated in the following life-cycle assessment examples;

- Development of generic models
- Development of approaches to allocate inputs and outputs among coproducts
- Development of approaches to allocate energy and environmental releases among incoming waste streams and to all environmental media
- Development of approaches to take into account sensitivity analysis in life-cycle inventory methodology

That process network theory is a generic model has already been established. The allocation of inputs and outputs (including environmental releases) among coproducts is performed explicitly by the parameters of the matrices $\boldsymbol{K}$ relating variables $\boldsymbol{y}$. Likewise, the allocation of energy is described in the matrices $\boldsymbol{X}$ and $\boldsymbol{F}$ of the model. Obviously, since the model is a complete representation of the system, changes in parameters and variables can be utilized for sensitivity analysis.

Chemical engineering literature from the 1960s [27] through the 1980s [28] and the SETAC framework [26] discuss straightforward algebraic methods for calculating "steady state" material flows and energy requirements for "cascaded sequences" or "linear sequences" of processes in material-energy balance computations. However networks or processes and processes involving recycling *do not* have closed form solutions using these methods. Again quoting SETAC [26]:

"The only satisfactory way of dealing with such networks is iteration; that is, initial values are assigned to the operators and the system is calculated. The calculated values are now substituted for the initial values and the system is recalculated. The new values are now substituted and the recalculation performed again. This procedure is repeated until the changes in the recalculated values are equal in accuracy to the input data".

And in a discussion of "Evaluation of Recycling Systems" [26]:

"There is no scientifically valid way of separating this system into individual product components; any method is purely arbitrary. Two methods commonly used follow.

1. *Equally divide impacts added to the system because of recycling. . .*

2. *Allocate the disposal credits to the product that gets recycled. . .*"

Processes network theory provides an analytical framework for closed form solutions of networks of processes in steady state, including solutions for networks with recycling loops not otherwise available in the literature. As discussed previously, Leontief representations provide this description for the linear material relationships, but do not permit nonlinear energy costs. The innovation of processes network theory that makes this possible is simply the recognition that the energy costs x_{rs} of the materials brought to the boundary of a process are linearly related to the material flow rates, and that the normally nonlinear costs of transformation $f_s(y_{0s})$ are additive. Additionally, these features, along with the continuity and compatibility relations, make multiple levels of analysis of networks, including recycling loops, possible. This enables the problem to be decomposed and aggregated through levels of organization, with lower level detail incorporated in the reduced-order, higher-level representation. Thus, processes network theory provides a unique and heretofore unavailable analytical tool for life-cycle assessment.

4.2 Computation of Process Network Models

With reference to Chapter 2, the computation of closed form solutions for process network models requires a schematic diagram, called a network diagram, which characterizes the system as a network of materially interconnected processes, and the following information about parameters and variables:

1) Coefficients of material transformation, K_{lb}, K_{rb}, K_{lo}, K_{ro}. These coefficients specify a unique product(s) y_o produced from a unique set of resources y_r, with a unique set of material flows within the network, y_b, y_l and a unique set of technologies.

2) Stimulus variable(s) y_o.

3) Matrix X_r specifying the energy costs of bringing materials y_r to the boundary of the network.

4) Functions specifying energetic costs of transformation $F_b(\dot{y}_b)$ and $F_o(\dot{y}_o)$. These functions normally are nonlinear, and may be discontinuous over a range of values of variables $\dot{y}_b$ and $\dot{y}_o$. In some cases they may be taken as linear functions over a relevant range of $\dot{y}_b$ and $\dot{y}_o$.

5) The continuity matrix A describing the material flow interconnections between the

processes of the network.

If the process network computations are to include an economic mapping and amortization of processing environment costs as discussed in Chapter 3, the following variables are required.

6) Economic prices p_r, p_o, and p_e for materials and energy.

7) Amortization functions g_b and g_o for the economic costs of the processing environment for the processes within and on the boundary of the network respectively.

Given the specification of these parameters and variables, the mathematical sequence of computation proceeds as follows.

$$K_b = (I - A\, K_{lb})^{-1} A\, K_{lo} \qquad (2.11)$$

$$K_S = K_{rb}\, K_b + K_{ro} \qquad (2.13)$$

$$\dot{y}_b = K_b\, \dot{y}_o \qquad (2.10)$$

$$\dot{y}_l = \begin{bmatrix} K_{lb} & K_{lo} \end{bmatrix} \begin{bmatrix} \dot{y}_b \\ \dot{y}_o \end{bmatrix} \qquad (2.8)$$

$$\dot{y}_r = K_S\, \dot{y}_o \qquad (2.12)$$

$$X_b = -\,(I - K_{lb}^T A^T)^{-1} K_{rb}^T X_r - (I - K_{lb}^T A^T)^{-1} F_b(\dot{y}_b) \qquad (2.14)$$

$$X_l = -\,A^T X_b \qquad (2.4) \text{ and } (2.5)$$

$$F_S(\dot{y}_o) = K_b^T F_b(\dot{y}_b) + F_o(\dot{y}_o) \qquad (2.16)$$

$$X_o = -K_S^T X_r - F_S(\dot{y}_o) \qquad (2.15)$$

$$\dot{e}_s = -\dot{y}_o^T F_S(\dot{y}_o) \qquad (2.17)$$

Cash flow and value added may then be calculated as

$$\dot{v}_S = \dot{y}_o^T p_o - \dot{y}_r^T p_r - \dot{y}_o^T F_S(\dot{y}_o)\, p_e \tag{3.2}$$

$$g_S = K_b^T g_b + g_o \tag{3.7}$$

$$v_S = y_o^T p_o - y_r^T p_r - y_o^T F_S(\dot{y}_o)\, p_e - y_o^T g_S \tag{3.8}$$

An ideal working environment for the modeling and computation of process networks would be a graphically based engineering work station or personal computer software environment that would simultaneously;

1) enable construction or "drawing" of the process network diagram,

2) provide for the entry of coefficients k_{rs} and the function $f_s(\dot{y}_{os})$ and g_s for each component processes in the network diagram location corresponding to that processes,

3) provide for the entry of boundary energy information x_{rs} for materials y_{rs},

4) compile matrices and/or iteratively perform the calculations outlined above directly from the information entered into the network diagram.

Earlier in this dissertation research, a commercial software package "Simulab" by the Mathworks was purchased in an attempt to create such an ideal working environment. Simulab provides the general working environment described above for modeling linear and nonlinear systems, including extensive control libraries and the ability to write extended functions in either the Matlab programming language or in such languages as C and Fortran. Unfortunately the "signal flow" orientation that makes Simulab (and programs like it) suited to graphical representations also prohibits its use in this application. Referring to Eq. (2.12) the "signal flow" where y_r is the dependent variable is opposite the direction of signal flow in Eq. (2.15) where the associated energetic costs X_r are the independent variable. An object of future work is to identify or develop a software environment with the four characteristics listed above and the ability to manage the paired independent-dependent variable problem associated with the modeling of process networks with a graphical block diagram user interface.

For the modeling and computation of the life-cycle assessment example presented here a combination of three personal computer software packages were utilized sequentially. Block diagrams giving a graphical representation of the network(s) and the specification and labeling of variables were constructed using a word processing program, Wordperfect 5.1, although any "draw" program for constructing and labeling block diagrams could have been used. Tables for data entry and the representation of results were constructed using a spreadsheet program, Framework III, which permits individual spreadsheets to be linked--that is, to exchange data. This is important in this application since as many as twenty linked spreadsheet "frames" were required for data entry and for exporting data in each model. Data was exported and imported from Framework as ASCII text files. By importing and exporting these text files, the matrix oriented program "PC Matlab" was used to perform all mathematical calculations except for the energy functions $F_b(\dot{y}_b)$ and $F_o(\dot{y}_o)$ which were calculated within the spreadsheet environment. If necessary or desired, more complex energy functions could readily be implemented in the Matlab programming language.

The hardware operating environment was an 80286 PC with 640 kB of RAM and math coprocessor. This was sufficient for the required Matlab matrix operations, which included 34 x 13 matrices, inversions, etc. as indicated. For development of the models and twelve cases described below, approximately 8 megabytes of hard disk space was required for data files of various types.

This implementation illustrates that process networks can be modeled in a very basic and readily available software and hardware environment. However the use of three different programs and the laborious data transfer procedure between the linked spreadsheets and Matlab make the process of adding or deleting variables, changing parameters, the examination of alternative cases and sensitivity studies very tedious at best. Development of a truly interactive environment will greatly enhance the modeling and analysis processes. The Matlab program code utilized for these models is given in an Appendix.

4.3 Paper Packaging vs. Polystyrene Packaging As An Example

The two examples chosen for the application of processes network theory to life-cycle assessment are the cases of paper packaging materials and plastic packaging materials. This choice was motivated by the contemporary international debate and controversy surrounding the comparative advantages and disadvantages of these two packaging materials from the perspective of manufacturers, packagers, end users, disposal, public interest and policy. During 1990 and 1991 these cases of life-cycle assessment came to the forefront of public and analytic attention, [29], [30].

During the late 1980s the problems of disposal of solid wastes by landfill, ocean dumping and incineration became subjects of public and political controversy in the U.S. Existing landfill sites in many states were full and unable to accept more waste from major urban centers. The regulations to limit ground water contamination surrounding the citing and licensing of new landfill sites in many cases prohibited expansion of existing sites or the construction of new ones. Many suitable sites could not be constructed because local citizens simply did not want landfills in the proximity of their cities, towns, and residences. This resulted in widespread interstate and intrastate transport of solid wastes to remaining sites, sometimes for distances as far as 1000 km.

On the east coast, ocean dumping of wastes became more restricted and controversial when wastes began drifting onto beaches, despoiling recreation and scenic areas and raising public health concerns. Incineration also became controversial and more restricted. Air emissions from incineration plants in many cases were not complying with Environmental Protection Agency standards, and even when standards were met, there was public anxiety about odors, accidents, corrosive air emissions, and the safety of permitted levels carcinogenic furan and dioxin emissions.

McDonald's Inc., the world's largest chain of restaurants, became a symbol of packaging disposal problems. McDonald's for several decades had utilized a variety of expanded polystyrene containers (cups, boxes, serving trays) for serving food and beverages. In response to public and political pressure from citizen and environmental advocacy groups, McDonald's engaged in a program to study and reduce the landfill waste produced by its restaurants [31]. In 1991 the decision was made to convert to the use of paper containers in McDonald's restaurants. This decision was based on the prevailing notions that paper containers were always preferable because they were constructed from a renewable resource (trees), could be recycled back into paper products, and were biologically degradable if disposed of in landfills.

Whether or not this decision by McDonald's had a significant impact on either the mass or volume of waste disposal problems, it became a very visible decision that was widely followed by other firms in the food service industry, and users of packaging in general. The change from plastic to paper containers was perceived by customers, regulatory agencies, and the public in general as being "friendly to the environment" and as a positive step in reducing the waste disposal problem [29]. During this time period packaging of all types began appearing with coding systems reporting on its recycled content, and in the case of plastics, coding reporting its type and suitability for recycling [32]. Many thousands of municipalities in the U.S. and Canada began a variety of collection and sorting programs to collect paper, plastic and glass household wastes for recycling into new products [32]. Within two years, the volume of materials collected had significantly exceeded the capacity of existing reprocessing facilities to reutilize the collected materials, resulting in storage of surpluses, and in many cases the carefully collected and sorted materials were buried in landfills, [33], [34].

The first widely publicized challenge to the wisdom of these decisions was published in *Science* in February 1991 by Martin B. Hocking under the title, "Paper Vs. Polystyrene: A Complex Choice" [35]. This "Policy Forum" article offered a basic inventory of the material and energy requirements for paper and plastic container manufacture and an assessment of the disposal options for each. As a standardized example, 8 oz. paper beverage cups vs. 8 oz. polystyrene beverage cups were chosen for the comparison of packaging alternatives. This analysis was performed in the general framework of a life-cycle assessment (although Hocking does not refer to it as such) and reported some surprising and controversial results.

o The petroleum requirements, on a per cup basis, of producing paper and plastic cups were almost the same, despite the fact that the precursor material of the paper cup is wood, and that of the polystyrene cup is entirely petroleum. And, of course, the polystyrene cup consumed no wood in its manufacture.

o The mass of other chemicals required in the production process was almost 40 times more for paper than for polystyrene.

o Air and water emissions were dramatically lower for polystyrene than for paper.

o On a mass basis, polystyrene was less demanding of landfill disposal. On a volume basis, the two utilized about the same landfill resources.

This counter-intuitive report received wide coverage in the national press and television media. The debate over the results and the underlying data continued in four letters published in *Science* the following June [36], [37], [38], [39], and correspondence which Hocking received personally [40]. A full paper was published by Hocking [41] in November 1991 with a more extensive inventory based on improved data and personal communication with industry sources.

While Hocking's full paper does provide a more extensive inventory and calculations in a life-cycle framework, it does not provide complete models of the paper and polystyrene manufacturing processes, their distribution, use and disposal options, including recycling. Process network theory provides a formal tool for constructing such a "full system" model, and for comparing results with less complete and inclusive life-cycle assessments.

4.4 Data for Parameters and Variables

The controversy and correspondence surrounding Hocking's experience with the data for his assessment and the extensive discussions surrounding data collection problems presented in the SETAC report [26] illustrate the problems of finding accurate, consistent data for life-cycle assessments. Data sources fall into the following general categories.

- *Theoretical calculations based on chemical stoichiometric and thermodynamic relationships and material-energy balances.* For material transformations in chemical reactions mass is always conserved, but the actual distribution of yields of products and byproducts may vary due to incomplete reactions or variations in reaction conditions. Theoretical energetic calculations are even more subject to variation from practice because of the difficulty in determining waste heat losses and variations in reaction temperatures and temperatures of incoming and outgoing materials. In cases of some complex reactions, envolving polymers for example, there is no theoretical basis available for energetic calculations.
- *Reference material from books and encyclopedias describing process industries.* These sources can provide useful representative information, but in process industries where technologies are changing, which is frequently the case, even current references may be outdated compared with contemporary practice. In addition, there may normally be significant variations in the design and operation of plants producing the same or similar products.
- *Empirical data from the actual operation of processes.* For life-cycle assessment this is in some respects the most appealing source, but it is also subject to limitations. Because of plant to plant variations in design, operation, and technologies, the most

consistent process data could be expected by obtaining all data from a single plant. It is then necessary to determine how representative the particular plant(s) are of the industry practice as a whole. Normally such data are not published, but must be obtained in cooperation with a particular enterprise, or in some cases industry groups or consulting firms that compile such information. Such data are often considered propriety for competitive reasons, and may not be made available to scientific investigators. Additional problems arise because some process data may simply not be known -- not measured or not available in a tabulated form.

- *In the case of regulated air and water emissions the permitted levels may be used to provide data.* This of course assumes that the plant or processes is in compliance, which may not be true, even at an industry wide level. And of course in many cases actual emissions may be below the permitted levels. However the regulated level may commonly be the only available source of information for many assessments.

In the data reflected in Hocking's work and references, as well as discussions in the SETAC framework, agreement between data sources closer than 10% is considered fortunate.

Hocking's work began within a framework of published data which for his full paper [41] was supplemented by direct personal contact with three spokespersons from each industry in the U.S. and Canada in an attempt to make his assembled data as close to current experience as possible. Thus, his full paper is an invaluable starting point for data for use in a process network model. Hocking's conversions were checked again other reference sources where available. Process data for paper manufacturing in particular has changed substantially from the 1960s to 1980s in published reference material, [41], [42].

However, since Hocking's inventory is not a full system model and is not broken down into a network of component processes, there are a number of important deficiencies in the data presented in his paper. In the models below, the missing information was obtained from reference materials and in a few cases from theoretical calculation. In a few cases where the necessary information was simply not available, informed judgements were employed in approximation.

Conversion between units of mass, energy and fuel types was performed using standard chemical engineering references [28], [42], [43], [44]. Petroleum fuels and feedstocks were all converted to and expressed in kilograms (kg), and electric power in kiloWatt-hours (kWh). All material units are converted to and expressed in kilograms except for water, for which the units are cubic meters (m^3).

5 LIFE-CYCLE ASSESSMENT OF PAPER MANUFACTURING, USE AND DISPOSAL

5.1 Network Diagram of Paper Manufacturing

A network diagram of paper manufacturing including resource materials y_r and products y_0 is given in Figure 4. There are at least three major classes of paper manufacture processes in use. The process diagramed here is the bleached Kraft process, which is predominant in the manufacture of packaging materials because of the high strength of the fiber structure of the paper product (others are sulfite and NSSC).

Paper manufacturing is a complex network of processes. Each of the processes numbered 1 thru 11 in this diagram is in fact composed of anywhere from two to a dozen subprocesses. The diagram shown here is constructed to represent a minimum level of detail necessary for the purpose of this analysis--that is, the life-cycle assessment of the paper product and the manufacturing enterprise producing it. For purposes of other analysis such as the evaluation of specific technological changes of subprocesses, a more detailed model of each process 1 thru 11 shown here could be constructed in greater detail and then incorporated in the level of this process model. Obviously the choice of level of detail is a key modeling decision, and must be chosen to incorporate the information necessary for the purposes of the analysis while ignoring unnecessary lower level detail. More detailed diagrams of the subprocesses of paper manufacture may be found in Austin [42] or many other references on paper manufacture.

Stimulus material flows are represented by dual lines =====>===== with an arrow to indicate the orientation of material flow, and labeled o1 thru o11.

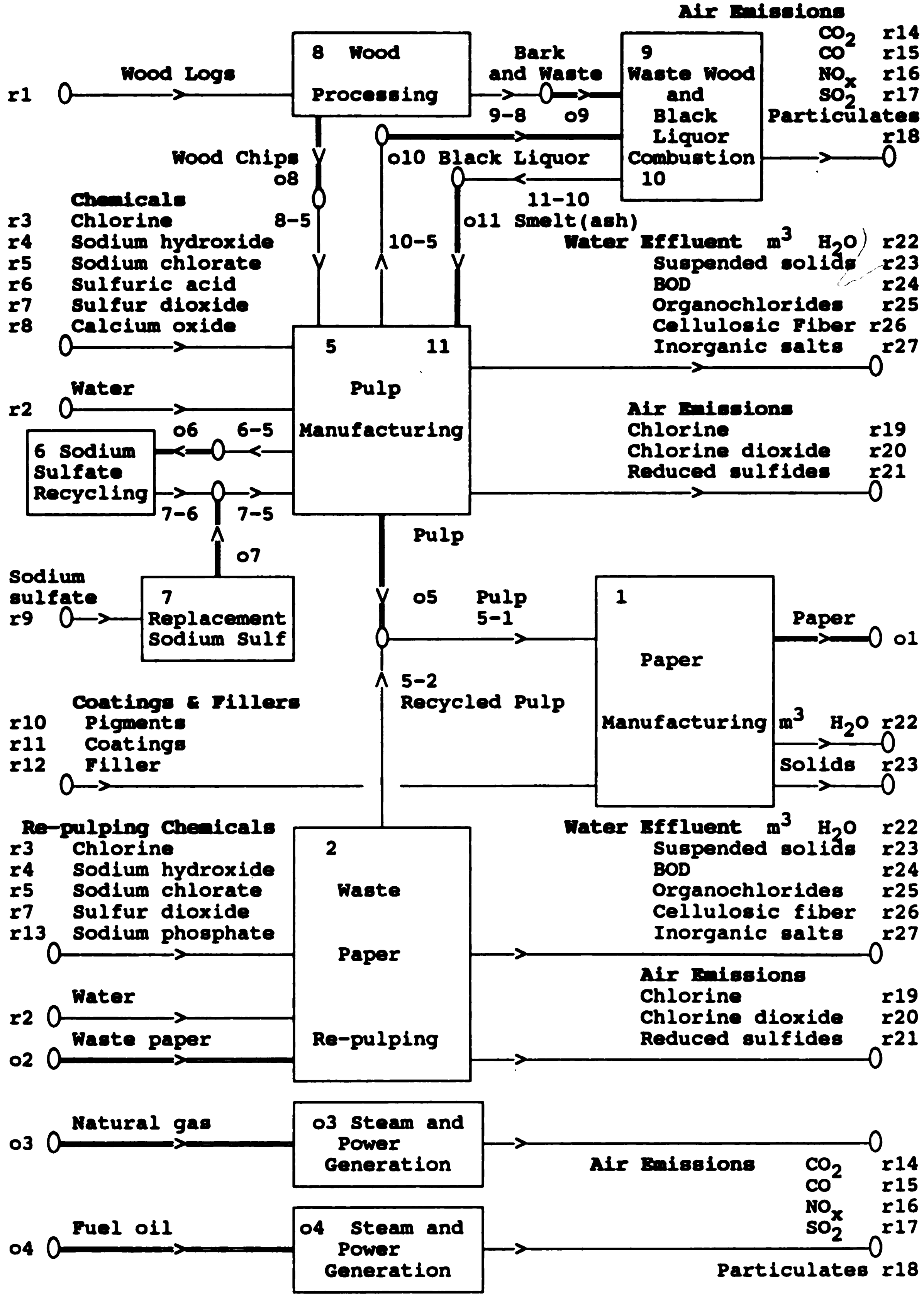

Figure 4 Network Diagram of Paper Manufacturing

Response variables are represented by single lines ———>——— and labeled r1 thru r27 for resources and byproducts and 5-1 thru 11-10 for links between processes. The general direction of material flow is from resources on the left to products and byproducts, including emissions and effluents on the right.

The system boundary chosen here is the paper manufacturing enterprise. Resource chemicals r3 through r13 are taken as the boundary resources for the network. As in Hocking's analysis the manufacture of these resources with their accompanying material and energy requirements is not modeled here, but could be added through the inclusion of models for their manufacture at the next level of analysis. Since these chemicals collectively total about 20% of the weight of the paper produced, the role of their manufacture may be expected to affect the life-cycle analysis, but as will be seen, is not expected to change the conclusions presented. Models for the manufacture of these chemicals as well as the process of wood growth and harvesting can be systematically added as refinements to the life-cycle process network here as required to address other classes of questions.

Wood processing 8, involves the removal of bark and waste, and chipping. The bark and waste are burned in process 9 to generate process steam for pulp manufacturing 5 and 11, and paper manufacturing 1. In pulp manufacturing the wood chips go through a series of cooking and digestion stages to remove lignins from the cellulose, and then chemical washing and bleaching to produce the finished dense liquid pulp. Chemicals r3-r8 are used on a once through basis, but sodium sulfate is recycled, with makeup r9 being required to replace losses. In the pulp manufacturing process a byproduct liquid called black liquor containing lignins is produced. This black liquor is burned for steam generation along with the bark and waste wood in process 10. The chemically rich ash remaining after combustion is recycled back into the pulp manufacturing processes.

Waste paper repulping is represented in process 2. Repulping may or may not take place at the same plant site as virgin pulp manufacture. Some plants are devoted solely to virgin pulp and paper manufacture, some solely to repulping and paper manufacture, and some to both functions. The model presented here is generic to all these cases since setting the coefficients in ***K*** associated with virgin pulp manufacture to zero gives a representation of a 100% repulping plant and vis a versa. Plants producing both virgin wood and recycled paper pulp may be modeled by the selection of stimulus variables o1 and o2. This is very useful since any overall mix of virgin wood and recycled paper can be chosen to represent an industry wide pattern of production in the life-cycle assessment.

This is an important feature to note in the network representation chosen here. The operating decision involves the choice of levels of production of paper o1 and levels of reduction of waste paper o2 at the boundary of the network. The branch stimulus variable pulp from virgin wood o5, is a "make up" variable -- which in the computation of the model automatically calculates the level of virgin wood pulp o5 and accompanying resources required. For this reason, the flow rate of recycled pulp at link 5-2 must be constrained to be less than or equal to the pulp flow rate 5-1. Otherwise flow o5 would be negative and the network would "produce" trees, clearly not a feasible condition !

An alternative network topology for recycled paper pulp could have been chosen; where recycled pulp would be a stimulus variable with a link to paper manufacturing as in the case of pulp o5. In this case, the ratio of virgin wood pulp to recycled pulp would be determined by the relative coefficients of ***K*** for paper manufacturing, process 1. The choice between these two topologies at the enterprise level is an arbitrary choice of the investigator. However the full system model to follow *requires* the topology shown in Figure 4 for the network to satisfy the continuity conditions as will be seen later.

An important insight from this topological requirement is that the ratio of virgin to recycled pulp in the paper product *cannot be controlled by the paper manufacturer* in a full system life-cycle model of the industry, but is determined by the policy or behavior choice for paper disposal -- recycling. The structure of the network requires the paper manufacturer to behave according to the policy rule or behavior imposed at a higher level of network organization.

Processes 3 and 4, for steam and electrical power generation illustrate the *reduction* of material fuels into atmospheric emissions. This is an important and perhaps confusing point that has not been modeled correctly in earlier process network models. While natural gas and fuel oil are energy sources, as *material* fuels they are potential energy sources. Their combustion is an exoenergetic material transformation of potential to thermal energy. As such, both the material transformation and the energy produced must be modeled. Note that electric power *purchased* in addition to the power generated on site by the enterprise does not appear as a process since it is acquired as a kinetic energy form from outside the boundary of the system and thus has no material transformation character. Purchased power generation at a higher level of organization can readily be modeled in the life-cycle analysis presented here simply by specifying that all electric power be generated on site with the appropriate technological parameters.

5.2 Network Model of Paper Manufacturing

Table 1 shows the matrices K_{lb}, K_{lo}, K_{rb}, K_{ro} for the process network describing paper manufacturing corresponding to Figure 4. Comments about the coefficient data will be presented below by referring to processes in general by their number and to specific elements according to their row-column labels.

In wood processing 8, 6% of the mass of wood logs is comprised of bark and waste. Because wood chips are the independent variable, this results in a coefficient of 1.06 for wood logs to wood chips [r1,o8] and .06 for bark and waste to wood chips [9-8,o8]. This illustrates how coefficients k are inverses of the common expression of input-output ratios cited in most discussions in process literature, *i.e.* wood chips to wood logs would have a coefficient of .94. Wood chips are in turn converted to pulp with a coefficient of 2.2. The remaining mass is the lignin content of the wood chips which appears in the black liquor [10-5,o5] with a coefficient of 1.2 and is burned for steam generation in process 10.

Hocking reports an aggregate total for the mass of chemicals [r3-r8,o5]. The coefficients shown here are an arbitrary division of the relative magnitudes judging from information in Austin [42], which yield the same total chemical requirement as given in Hocking [41]. Coefficients [6-5,o5], [7-5,o5], [7-6,o6] and [r9,o7] define the sodium sulfate recycling loop and makeup at the replacement rate described by Hocking [41]. Air emissions r14-r21 are based on aggregate data from Hocking. Since 56% of total energy generation takes place in processes 9, the total emissions have been distributed on this basis between the coefficients for processes 9 and for fuel combustion, processes 3 and 4 to result in the total emission levels given by Hocking.

Table 1 Paper Manufacturing Coefficients

Links	Branches	Pulp o5	Sod. Sulf. o6	Sod. Sulf. o7	Wood Chips o8	Waste &Bark o9	Black Liqr o10	Black Liqr o11	Paper o1	Waste Paper o2	Nat. Gas o3	Fuel Oil o4
Pulp	5-1	0	0	0	0	0	0	0	1	0	0	0
Pulp	5-2	0	0	0	0	0	0	0	0	.83	0	0
Sodium sulfate	6-5	.009	0	0	0	0	0	0	0	0	0	0
Sodium sulfate	7-5	.01	0	0	0	0	0	0	0	0	0	0
Sodium sulfate	7-6	0	1	0	0	0	0	0	0	0	0	0
Wood chips	8-5	2.20	0	0	0	0	0	0	0	0	0	0
Bark & waste	9-8	0	0	0	.06	0	0	0	0	0	0	0
Black liquor	10-5	1.20	0	0	0	0	0	0	0	0	0	0
Smelt (ash)	11-10	0	0	0	0	0	.17	0	0	0	0	0
Wood Logs	r1	0	0	0	1.06	0	0	0	0	0	0	0
Water	r2	.10	0	0	0	0	0	0	0	.05	0	0
Chlorine	r3	.06	0	0	0	0	0	0	0	.03	0	0
Sodium hydroxide	r4	.02	0	0	0	0	0	0	0	.01	0	0
Sodium chlorate	r5	.03	0	0	0	0	0	0	0	.01	0	0
Sulfuric acid	r6	.01	0	0	0	0	0	0	0	0	0	0
Sulfur dioxide	r7	.01	0	0	0	0	0	0	0	.01	0	0
Calcium hydroxide	r8	.01	0	0	0	0	0	0	0	0	0	0
Sodium sulfate	r9	0	0	1	0	0	0	0	0	0	0	0
Pigments	r10	0	0	0	0	0	0	0	0	0	0	0
Coatings	r11	0	0	0	0	0	0	0	0	0	0	0
Filler	r12	0	0	0	0	0	0	0	0	0	0	0
Sodium Phosphate	r13	0	0	0	0	0	0	0	0	0	0	0
CO_2	r14	0	0	0	0	0	0	0	0	0	0	0
CO	r15	0	0	0	0	.028	0	0	0	0	.0001	.0001
NO_x	r16	0	0	0	0	.046	0	0	0	0	.0004	.0005
SO_2	r17	0	0	0	0	.100	0	0	0	0	0	.0044
Particulates	r18	0	0	0	0	.015	0	0	0	0	0	.0005
Chlorine	r19	.0002	0	0	0	0	0	0	0	.0001	0	0
Chlorine dioxide	r20	.0002	0	0	0	0	0	0	0	.0001	0	0
Reduced sulfides	r21	.0015	0	0	0	0	0	0	0	.0008	0	0
m^3 H_2O	r22	.07	0	0	0	0	0	0	.01	.04	0	0
Suspended solids	r23	.01	0	0	0	0	0	0	0	.005	0	0
BOD	r24	.005	0	0	0	0	0	0	0	.003	0	0
Organochlorides	r25	.003	0	0	0	0	0	0	0	.002	0	0
Cellulostic Fiber	r26	.001	0	0	0	0	0	0	0	.001	0	0
Inorganic salts	r27	.06	0	0	0	0	0	0	0	.03	0	0

Note that NO_x and SO_2 coefficients are zero for natural gas combustion since these emissions are very low. Provision is made here for inclusion of CO_2 coefficients for each process. Note that in the examples that follow CO_2 emission rates have been set to zero. CO_2 emissions are a key issue in the global warming controversy which Hocking does not consider analytically. Carbon dioxide emissions will be discussed here in Chapter 7 on Life-cycle Comparison. Water effluent rates r22-r27 are calculated directly from Hocking's levels.

[5-1,o1] reflects the conversion of pulp to paper on a dry weight basis, which is the common industry practice, rather than reference to wet weights which include 10-15% water content [42]. Thus the dry weight coefficient is 1.

In his work Hocking does not consider the process of recycling waste paper into recycled pulp. Austin reports that the repulping of waste paper to recycled pulp operates at a 17% loss [42], resulting in a coefficient of .83 for [5-2,o2]. The chemical requirements for recycling pulp are more difficult to ascertain. Several sources [42], [45], provide descriptions of the repulping processes and the chemicals required, but not the quantities. Repulping requires approximately half the total number of stages of chemical processes that manufacture of pulp from virgin wood requires. It is assumed here that the chemical requirements and water emissions would then also be about half of virgin pulp manufacture. This is a useful operating assumption. Ongoing improvements in data can help refine the model.

Table 2 shows the continuity matrix *A* for the network. In Table 3 various information for variables in the model are entered. The stimulus variables o1 and o2 are specified as described in the previous section.

Table 2 Paper Manufacturing Continuity Matrix

	5-1	5-2	6-5	7-5	7-6	8-5	9-8	10-5	11-10
o5	1	-1	0	0	0	0	0	0	0
o6	0	0	1	0	0	0	0	0	0
o7	0	0	0	1	-1	0	0	0	0
o8	0	0	0	0	0	1	0	0	0
o9	0	0	0	0	0	0	1	0	0
o10	0	0	0	0	0	0	0	1	0
o11	0	0	0	0	0	0	0	0	1

Table 3 Paper Manufacturing Variables

Stimulus Variables

Paper Manufacture	o1	1
Re-pulping	o2	0
Gas Steam & Power	o3	
Oil Steam & Power	o4	

Energy use ratios

Gas In Steam Generation	.00%
Oil In Steam Generation	100.00%
Cogenerated Electric	.00%
Purchased Electric	100.00%

kg Natural Gas/kg Steam	.047
kg Natural Gas/kWh Elect.	.200
kg Fuel Oil/kg Steam	.057
kg Fuel Oil/kWh Elect.	.240

Table 4 Paper Manufacturing Energetic Matrix F_b F_o

Energy Type per unit material		Steam kg	Natural Gas kg	Fuel Oil kg	Elect. Power kWh	Diesel Fuel kg	Direct Labor1 hours	Direct Labor2 hours
Process								
Pulp Manufacturing	o5	8	0	0	.40	0	.0010	0
Sodium S. Recycle	o6	0	0	0	0	0	0	0
Sodium S. Replace	o7	0	0	0	0	0	0	0
Wood Chipping	o8	0	0	0	.09	0	.0005	0
Waste Combustion	o9	-42	0	0	0	0	.0076	0
Waste Combustion	o10	0	0	0	0	0	0	0
Pulp Manufacturing	o11	0	0	0	0	0	0	0
Paper Manufacture	o1	2	0	0	.40	0	.0010	0
Re-pulping	o2	3	0	0	.20	0	.0010	0
Gas Steam & Power	o3	0	0	0	0	0	0	0
Oil Steam & Power	o4	0	0	0	0	0	0	0

This first example specifies o2 as zero, corresponding to the no recycling case which Hocking discusses. Natural gas and fuel oil material rates for o3 and o4 are determined internally in the model, since they are dependent on the energy requirements.

Energy use ratios are specified in the next section. Two options are available; the ratio of use of natural gas to fuel oil for steam and electric power generation, and the ratio of electric power generated on site (cogenerated power) to electric power purchased by the enterprise. The U.S. paper industry as a whole uses about 35% oil and 65% gas for steam generation beyond that provided by combustion of bark and waste [37]. Any ratio can be used in the model, but for the examples which follow 100% oil utilization has been selected to simplify comparisons across models and comparison with petroleum feedstocks. Comparison of oil and gas on a mass basis with natural gas is straightforward, 1 kg of natural gas has the same energy content as 1.2 kg of fuel oil.

The final section of Table 3 gives energy conversion ratios for fuels to steam and electricity. Fuel to steam ratios follow Hocking [41], and are aggregates of low pressure and high pressure steam requirements. Fuel to electric power ratios assume 33% conversion efficiency on a Joule or kWh basis, which is a reasonable historical average for electric power generation. In a cogeneration environment, low pressure process steam is available downstream of the turbine driven electric generation stage. This increases the combined thermal efficiency of steam and electrical power generation. Cogeneration scenarios for different power generation cycles and fuels can readily be described through specification of the four ratios.

Table 4 reports the conversion energy functions F_b and F_o. Total steam and electrical power requirements are those reported by Hocking [41] but are divided between

(

a

ma

disp

processes 5 and 1. As in the case of chemical requirements, the energy requirements for repulping are difficult to ascertain. In the absence of better information assumptions have been made of half the energy requirement relative to the requirements for virgin pulp.

Direct labor hours are reported to be 5 hours per metric ton of finished paper by [46]. For this illustration 4 hours were used as a basis, assuming improvement in labor efficiency have taken place. The total labor time is distributed between the processes as indicated.

Table 5 shows the matrix X_r for the boundary energy costs of the network resource materials y_r. As discussed in the previous section, energy costs involved in making resources r1 through r13 available to the boundary of the network are generally unknown since such accounts are generally not maintained by industries. The largest energy costs can be expected to be associated with wood growth and harvest to produce the wood logs and the production of chlorine compounds. These costs can be systematically included in the life-cycle assessment by extending the boundary of the network to include the corresponding material transformation processes or they can be determined from auxiliary analysis of the network of precursor transformation processes involved in producing these resources.

Table 6 provides for entry of price information for resources, products and energy at the boundary of the network. The purpose of the economic analysis here is to demonstrate *how* process network models can be mapped into economic performance, and to illustrate *how* a full system model in a life-cycle analysis can be utilized by a manufacturing enterprise to evaluate the impact of how changes in product use and disposal effect the economic performance of the enterprise.

Table 5 Paper Manufacturing Matrix X_r

Energy Type per unit material		Natural Gas kg	Fuel Oil kg	Electric Power kW	Diesel Fuel kg	Direct Labor 1 hours	Direct Labor 2 hours
Resource							
Wood Logs	r1	0	0	0	0	0	0
Water	r2	0	0	0	0	0	0
Chlorine	r3	0	0	0	0	0	0
Sodium hydroxide	r4	0	0	0	0	0	0
Sodium chlorate	r5	0	0	0	0	0	0
Sulfuric acid	r6	0	0	0	0	0	0
Sulfur dioxide	r7	0	0	0	0	0	0
Calcium hydroxide	r8	0	0	0	0	0	0
Sodium sulfate	r9	0	0	0	0	0	0
Pigments	r10	0	0	0	0	0	0
Coatings	r11	0	0	0	0	0	0
Filler	r12	0	0	0	0	0	0
Sodium phosphate	r13	0	0	0	0	0	0
CO_2	r14	0	0	0	0	0	0
CO	r15	0	0	0	0	0	0
NO_x	r16	0	0	0	0	0	0
SO_2	r17	0	0	0	0	0	0
Particulates	r18	0	0	0	0	0	0
Chlorine	r19	0	0	0	0	0	0
Chlorine dioxide	r20	0	0	0	0	0	0
Reduced sulfides	r21	0	0	0	0	0	0
m^3 H_2O	r22	0	0	0	0	0	0
Suspended solids	r23	0	0	0	0	0	0
BOD	r24	0	0	0	0	0	0
Organochlorides	r25	0	0	0	0	0	0
Cellulostic Fiber	r26	0	0	0	0	0	0
Inorganic salts	r27	0	0	0	0	0	0

Table 6 Paper Manufacturing Prices

Resource y_r		Price/kg material p_r
Wood Logs	r1	\$.08
Water	r2	\$.00
Chlorine	r3	\$.25
Sodium hydroxide	r4	\$.25
Sodium chlorate	r5	\$.25
Sulfuric acid	r6	\$.25
Sulfur dioxide	r7	\$.25
Calcium hydroxide	r8	\$.25
Sodium sulfate	r9	\$.25
Pigments	r10	\$.25
Coatings	r11	\$.25
Filler	r12	\$.25
Sodium Phosphate	r13	\$.25
CO_2	r14	\$.00
CO	r15	\$.00
NO_x	r16	\$.00
SO_2	r17	\$.00
Particulates	r18	\$.00
Chlorine	r19	\$.00
Chlorine dioxide	r20	\$.00
Reduced sulfides	r21	\$.00
m^3 H_2O	r22	\$.00
Suspended solids	r23	\$.00
BOD	r24	\$.00
Organochlorides	r25	\$.00
Cellulostic Fiber	r26	\$.00
Inorganic salts	r27	\$.00

Products Y_o		Price/kg material p_o
Paper Manufacture	o1	\$.50
Re-pulping	o2	\$.00
Gas Steam & Power	o3	\$.00
Oil Steam & Power	o4	\$.00

Energy	Price/unit energy p_e
Natural Gas / kg	\$.25
Fuel Oil / kg	\$.25
Electric Power / kWh	\$.05
Diesel Fuel / kg	\$.35
Direct Labor 1 / hour	\$12.00
Direct Labor 2 / hour	\$.00

Processing Environment Amortization		\$ / kg material G_b & G_o
Pulp Manufacturing	o5	\$.02
Sodium S. Recycle	o6	\$.00
Sodium S. Replace	o7	\$.00
Wood Chipping	o8	\$.02
Waste Combustion	o9	\$.02
Waste Combustion	o10	\$.00
Pulp Manufacturing	o11	\$.00
Paper Manufacture	o1	\$.02
Re-pulping	o2	\$.02
Gas Steam & Power	o3	\$.02
Oil Steam & Power	o4	\$.02

A detailed and accurate analysis of the economic performance of a paper manufacturing enterprise or of the industry as a whole would require current and accurate prices for resource materials r1 through r13 and the finished paper product o1. These prices are normally the result of negotiation and contracts between firms and information is not generally available from published sources. Firms normally treat this information as proprietary for competitive reasons. Large chemical manufacturers and purchasers often utilize the services of specialized consulting firms and extensive internal marketing and purchasing departments to determine market conditions. This information is considered valuable property by manufacturers and consulting firms alike, and access to is restricted. In the case of feedstock prices for polystyrene manufacture it was possible to obtain some basic information through the efforts of a personal industry contact, but even this limited information required nearly a month of inquiries within his firm and with a consulting firm working under contract [47].

For the illustration here, a price for bleached kraft paper o1 in Table 6 was assumed to be $500 per ton on the basis of personal experience within the industry [48]. This is also about half the wholesale price per kg of finished paper cups [49]. Chemical prices are assumed to be a uniform $250 per ton, again a "ball park" figure for many inorganic chemicals based on personal manufacturing experience [48]. The price of wood logs ($80 / ton) was adjusted to result in an overall cash flow that would be representative of manufacturing industries given the other price information assumptions.

Representative prices for petroleum fuels are readily determined from published sources and distributors prices and then converted to a kg basis. Electric power prices vary by a factor of as much as 3 to 1 depending on region. $.05 / Kwh has been chosen as representative here. Direct labor costs can also be expected to vary widely, but have been assumed to be $12 per hour. For purposes of illustration, processing environment amortization g_b and g_o have been set to $.02 for each component process.

5.3 Enterprise Level Results of Paper Manufacturing

Figure 5 shows the diagram of the manufacturing enterprise illustrated in Figure 4 at the next higher level of organization. All detail has now been consolidated into the expressions for this higher level. Table 7 shows the system matrix K_S relating products y_o to resources y_r and the internal schedule matrix K_b relating the flow rates or products y_o to the flow rates of internal stimulus variables y_b. Flow rates of material variables $\dot{y}_l$, $\dot{y}_r$, $\dot{y}_b$, and $\dot{y}_o$ are presented in Table 8. Note that in this example the flow rate for finished paper o1 has been set at 1.1 kg / unit time. When adjusted for units of measurement, the flow rates given here conform quite closely to Hocking's aggregated figures for paper manufacturing [41].

Energy and economic results for paper manufacturing are presented in Table 9. Some explanation of the Fsst and F_S matrices is required. Fsst represents the system energy requirements including the steam required in addition to that generated internally by processes 9 and 10. This additional steam must also be generated internally by either process 3 or 4. The conversion rates of gas and oil to steam given in Table 3 are used to calculate the fuel requirements, in this case the fuel oil required, .2540 kg fuel oil / kg paper o1, as shown in F_S. After conversion of units, Hocking's Table 1 [41] reports .2168 kg fuel oil / kg paper. Hocking does not report in detail how this particular steam to fuel oil conversion was calculated.

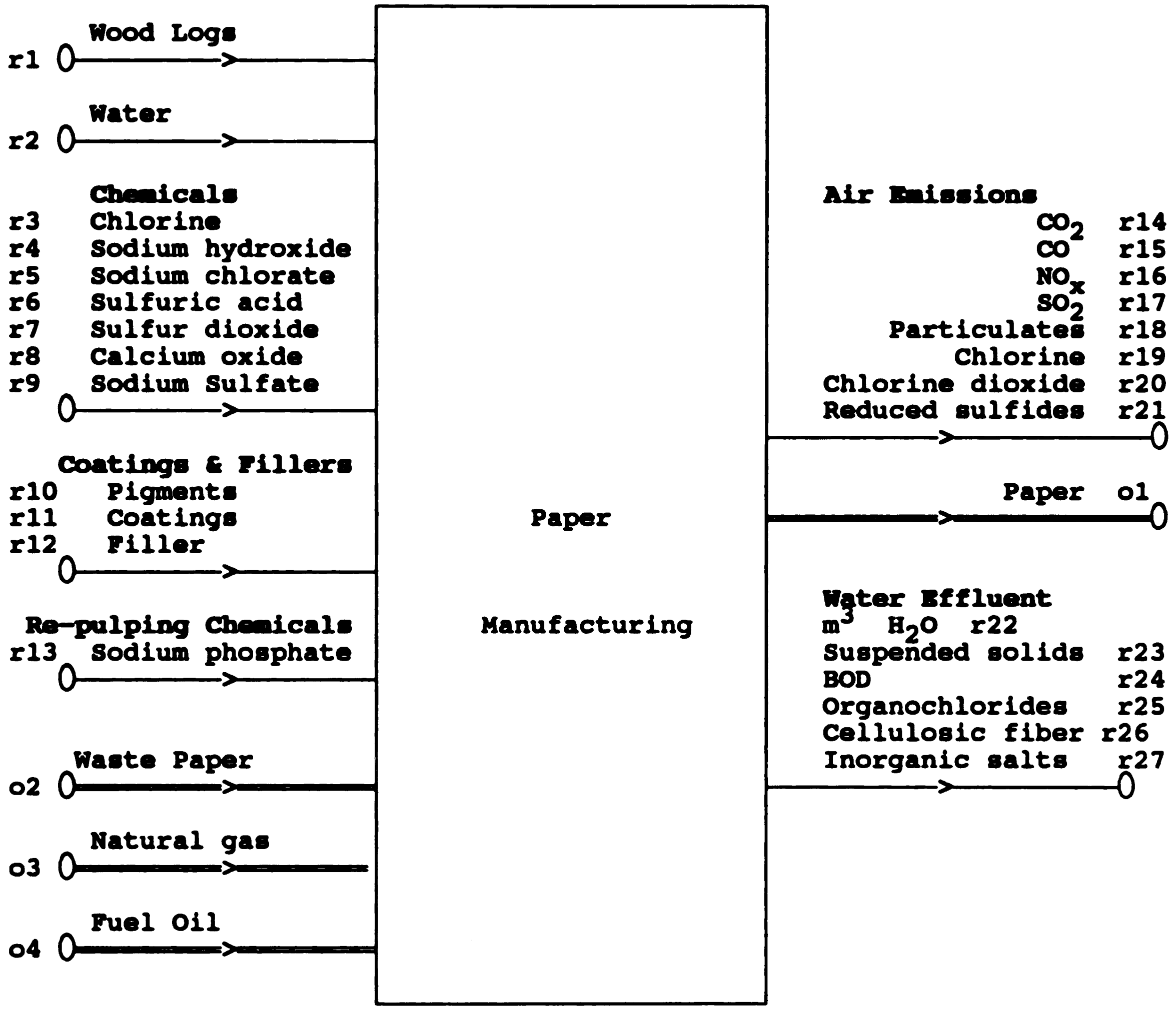

Figure 5 Consolidated Network Diagram of Paper Manufacturing

Table 7 Paper Manufacturing System Matrices

		Paper	Waste Paper	Nat. Gas	Fuel Oil
Schedule Matrix K_b		o1	o2	o3	o4
Pulp Manufacturing	o5	1	-.8300	0	0
Sodium S. Recycle	o6	.0090	-.0075	0	0
Sodium S. Replace	o7	.0010	-.0008	0	0
Wood Chipping	o8	2.2000	-1.8260	0	0
Waste Combustion	o9	.1320	-.1096	0	0
Waste Combustion	o10	1.2000	-.9960	0	0
Pulp Manufacturing	o11	.2040	-.1693	0	0
System Matrix K_s					
Wood Logs	r1	2.3320	-1.9356	0	0
Water	r2	.1000	-.0330	0	0
Chlorine	r3	.0600	-.0198	0	0
Sodium hydroxide	r4	.0200	-.0066	0	0
Sodium chlorate	r5	.0300	-.0149	0	0
Sulfuric acid	r6	.0100	-.0083	0	0
Sulfur dioxide	r7	.0100	.0017	0	0
Calcium hydroxide	r8	.0100	-.0083	0	0
Sodium sulfate	r9	.0010	-.0008	0	0
Pigments	r10	0	0	0	0
Coatings	r11	0	0	0	0
Filler	r12	0	0	0	0
Sodium Phosphate	r13	0	0	0	0
CO_2	r14	0	0	0	0
CO	r15	.0037	-.0031	.0001	.0001
NO_x	r16	.0061	-.0050	.0004	.0005
SO_2	r17	.0132	-.0110	0	.0044
Particulates	r18	.0020	-.0016	0	.0005
Chlorine	r19	.0002	-.0001	0	0
Chlorine dioxide	r20	.0002	-.0001	0	0
Reduced sulfides	r21	.0015	-.0004	0	0
m^3 H_2O	r22	.0800	-.0181	0	0
Suspended solids	r23	.0100	-.0033	0	0
BOD	r24	.0050	-.0012	0	0
Organochlorides	r25	.0030	-.0005	0	0
Cellulostic Fiber	r26	.0010	.0002	0	0
Inorganic salts	r27	.0600	-.0198	0	0

Table 8 Paper Manufacturing Material Flows

Links	y_l	
Pulp	5-1	1.1000
Pulp	5-2	0
Sodium sulfate	6-5	.0099
Sodium sulfate	7-5	.0110
Sodium sulfate	7-6	.0099
Wood chips	8-5	2.4200
Bark & waste	9-8	.1452
Black liquor	10-5	1.3200
Smelt (ash)	11-10	.2244

Branches	y_b	
Pulp Manufacture	o5	1.1000
Sodium S. Recycle	o6	.0099
Sodium S. Replace	o7	.0011
Wood Chipping	o8	2.4200
Waste Combustion	o9	.1452
Waste Combustion	o10	1.3200
Pulp Manufacture	o11	.2244

Resources	y_r	
Wood Logs	r1	2.5652
Water	r2	.1100
Chlorine	r3	.0660
Sodium hydroxide	r4	.0220
Sodium chlorate	r5	.0330
Sulfuric acid	r6	.0110
Sulfur dioxide	r7	.0110
Calcium hydroxide	r8	.0110
Sodium sulfate	r9	.0011
Pigments	r10	0
Coatings	r11	0
Filler	r12	0
Sodium Phosphate	r13	0
CO_2	r14	0
CO	r15	.0041
NO_x	r16	.0068
SO_2	r17	.0157
Particulates	r18	.0023
Chlorine	r19	.0002
Chlorine dioxide	r20	.0002
Reduced sulfides	r21	.0017
m^3 H_2O	r22	.0880
Suspended solids	r23	.0110
BOD	r24	.0055
Organochlorides	r25	.0033
Cellulostic Fiber	r26	.0011
Inorganic salts	r27	.0660

Objects	y_o	
Paper Manufacture	o1	1.1000
Re-pulping	o2	0
Gas Steam & Power	o3	0
Oil Steam & Power	o4	.2794

Table 9 Paper Manufacturing System Energetics

Energy Type per unit material		Steam kg	Natural Gas kg	Fuel Oil kg	Elect. Power kWh	Diesel Fuel kg	Direct Labor1 hours	Direct Labor2 hours
Fsst Matrix								
Paper Manufacture	o1	4.4560	0	0	.9980	0	.0041	0
Re-pulping	o2	.9615	0	0	-.2963	0	-.0016	0
Gas Steam & Power	o3	0	0	0	0	0	0	0
Oil Steam & Power	o4	0	0	0	0	0	0	0
F_s Matrix								
Paper Manufacture	o1		0	.2540	.9980	0	.0041	0
Re-pulping	o2		0	.0548	-.2963	0	-.0016	0
Gas Steam & Power	o3		0	0	0	0	0	0
Oil Steam & Power	o4		0	0	0	0	0	0
X_b Matrix								
Pulp Manufacture	o5	-2.4560	0	0	-.5980	0	-.0031	0
Sodium S. Recycle	o6	0	0	0	0	0	0	0
Sodium S. Replace	o7	0	0	0	0	0	0	0
Wood Chipping	o8	2.5200	0	0	-.0900	0	-.0010	0
Waste Combustion	o9	42	0	0	0	0	-.0076	0
Waste Combustion	o10	0	0	0	0	0	0	0
Pulp Manufacture	o11	0	0	0	0	0	0	0
X_o Matrix								
Paper Manufacture	o1		0	-.2540	-.9980	0	-.0041	0
Re-pulping	o2		0	-.0548	.2963	0	.0016	0
Gas Steam & Power	o3		0	0	0	0	0	0
Oil Steam & Power	o4		0	0	0	0	0	0
Energy e_s			0	.2794	1.0978	0	.0045	0
Energy e_o			0	-.2794	-1.0978	0	-.0045	0
Amortiztion G_s								
Paper Manufacture	o1	$.09						
Re-pulping	o2	($.04)						
Gas Steam & Power	o3	$.02						
Oil Steam & Power	o4	$.02						
Cash Flow c_f		$.13						
Value Added v_s		$.03						

For consistency, the conversion rate used in the model here is the same conversion rate used by Hocking in a later section of his paper. Since all electric power is purchased in the examples shown, electric power requirements are .9980 kWh / kg paper o1. This is in agreement with Hocking [41].

The energy requirements for waste paper repulping o2 are at first surprising, and demonstrate an important feature of the network structure. Notice that the electrical power figure for repulping in F_S is -.2963 kWh, which would at first glance seem that repulping paper is generating electric power. This is not the case. The network structure in Figure 4 shows that recycled pulp *reduces* the virgin pulp requirement for the final paper manufacturing process 1. Thus, the energy requirements in F_S reflect the *reduction* in energy requirements for each kg of waste paper o2 utilized in the production of paper o1, that is .2963 fewer kWh of electrical power are required for each kg of waste paper o2 which is recycled. Notice that the steam and fuel oil requirements actually *increase* by .9615 and .0548 kg respectively for each kg of waste paper that is recycled despite the fact that process 2, waste paper repulping has *lower* steam/fuel oil requirements than process 5, virgin pulp manufacturing. This occurs because when virgin pulp is manufactured, 56% of the total steam energy is generated by the combustion of bark and waste wood from the incoming wood logs. This is an extraordinarily important result which has not been revealed in other analyses. As will be discussed in the section Life-Cycle Comparison of Paper and Plastic, this will result in petroleum consumption for recycling paper *almost identical* to petroleum consumption for virgin paper manufacture, a result that is directly contrary to current assumptions.

5.4 Network Diagram of Paper Use and Disposal

Figure 6 presents a diagram of paper use and disposal. The boundary stimulus variables for use and disposal are the flow of beverages o12, and diesel fuel for transportation o13. Notice that links 1-16, paper, and links 2-18 and 2-17 used cups and waste paper, are interconnected to the higher level network model of paper manufacturing shown in Figure 5 at o1 and o2 respectively. This illustrates a particular choice of modeling topology where the graph in Figure 6 is "added" to the graph of Figure 5.

Alternatively, paper use and disposal could have been modeled as an independent network and then the two models, one for paper manufacture, and the other for use and disposal, could have been combined. Either approach yields the same result for the entire system, and this equivalence illustrates the flexibility in the definition of boundaries and subnetworks available to the investigator. The approach of adding additional processes to the higher level manufacturing model was chosen here since it illustrates how processes can be added in series to create a higher level model. This approach is particularly well suited to life-cycle assessment issues and contemporary practice.

Referring to Figure 6, paper from paper manufacturing is transported to a cup manufacturing facility 15. Adhesive r28 is employed in the manufacture and part of the paper is lost as waste from trimmings [17-15]. Cups then require transport in process 14 and used to serve beverages in process 12. Beverages r29 flow through process 12 and are ultimately the object o12 of the network of paper manufacturing, use and disposal.

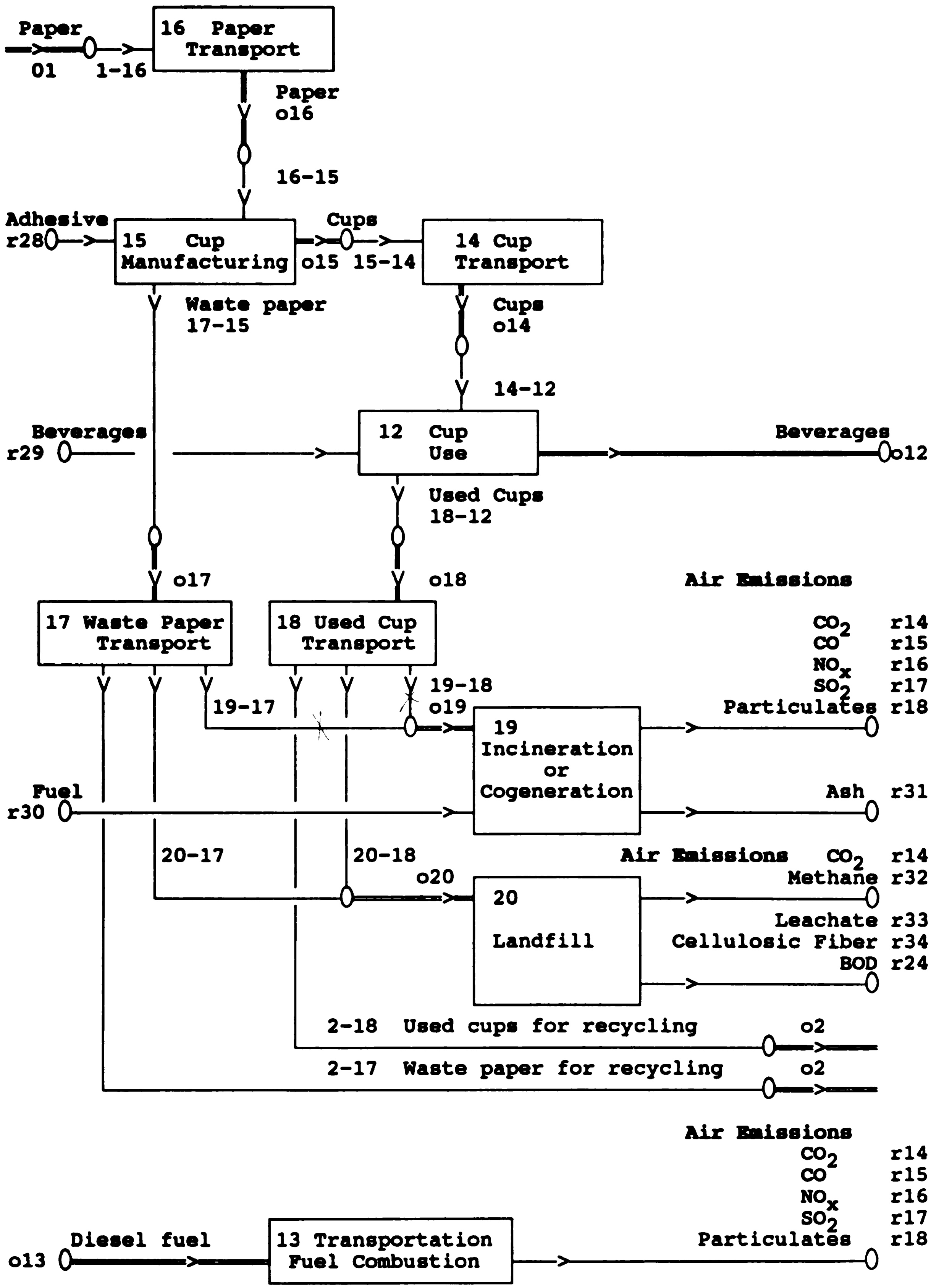

Figure 6 Network Diagram of Paper Use and Disposal

That is, o12 is the independent variable that determines all other material flows and energy costs for the full system. It is important to note that there is nothing about the physics of the system's functioning that causes o12 to be the independent variable. Other variables could have been selected as the object of transformation. For example, ash from incineration could have been chosen as independent with corresponding changes in the network topology to make all interconnections meet the continuity requirements. Recalling however that this is a human designed, engineered and managed system for packaging beverages, the objective clearly is the consumption of beverages, not the disposal of the cup as ash, etc.

In processes 17 and 18 waste paper and used cups are separated for three disposal options and transported to their respective destinations. Those disposal options include processes 19, incineration or burning to generate electrical power and/or steam, cogeneration. Air emissions r14 to r18 and ash r31 are byproducts of either of these combustion options. Supplementary fuel r30, such as fuel oil or natural gas may be required or utilized in incineration or cogeneration. Landfill, process 20, is a second disposal option, with air emissions r14 and r32, landfill mass of cellulosic fiber r34, liquid leachate r33 which may contaminate ground water, and biochemical oxygen demand, BOD r24 which may accompany decomposition. Recycling is the third disposal option, links 2-17 and 2-18 which are connected to paper manufacturing by stimulus variable o2 in Figure 5.

Process 13 describes the combustion of diesel fuel by truck or railroad locomotives for the transportation processes 14, 16, 17 and 18. It is important to note that the combustion of fuel in process 13 is a separate processes from the transport processes themselves, 14, 16, 17 and 18. That is, the diesel fuel is not a component of the objects of transformation, paper, cups, waste paper, etc. However, the quantity of diesel fuel combusted is related to the transport distances, as will be discussed in the following section.

5.5 Network Model of Paper Manufacturing, Use and Disposal

Table 10 shows the matrices $\boldsymbol{K}_{lb}$, $\boldsymbol{K}_{lo}$, $\boldsymbol{K}_{rb}$, $\boldsymbol{K}_{ro}$ for the process network describing paper manufacturing, use and disposal corresponding to the interconnected networks of Figure 5 and Figure 6. Comments about the coefficient data will be presented below by referring processes in general by their number and to specific elements according to their row-column labels.

In Table 10, the network model of paper manufacturing illustrated in Figure 5 is aggregated with the model of paper use and disposal illustrated in Figure 6. The first feature to notice is how the system matrix for paper manufacturing $\boldsymbol{K}_S$ given in Table 7 has been incorporated into the model. The ordering of columns of $\boldsymbol{K}_{lb}$, $\boldsymbol{K}_{lo}$ has been chosen with the stimulus variables connecting the lower level system to the higher level system, o1 and o2, as the first two columns in Table 10. Thus the first two columns of $\boldsymbol{K}_S$ given in Table 7 become the first two columns and first 27 rows of the matrix $\boldsymbol{K}_{lo}$. Similarly, columns 3 and 4 of the matrix $\boldsymbol{K}_S$ become the second and third columns of matrix $\boldsymbol{K}_{ro}$ corresponding to o3 and o4.

Now that paper manufacturing has been incorporated into the model, what remains in the remainder of the matrix is to describe the coefficients relating to the processes for paper use and disposal.

Table 10 Paper Manufacturing, Use and Disposal Coefficients

Links	Branches	Paper o1	Waste Paper o2	Cups o14	Cups o15	Paper o16	Waste Paper o17	Waste Cups o18	Waste Paper o19	Waste Paper o20	Beverages o12	Nat. Gas o3	Fuel Oil o4	Diesel Fuel o13
Paper	1-16	0	0	0	0	1	0	0	0	0	0	0	0	0
Paper	16-15	0	0	0	1.10	0	0	0	0	0	0	0	0	0
Waste Paper	17-15	0	0	0	.10	0	0	0	0	0	0	0	0	0
Cups	15-14	0	0	1	0	0	0	0	0	0	0	0	0	0
Cups	14-12	0	0	0	0	0	0	0	0	0	1	0	0	0
Used Cups	18-12	0	0	0	0	0	0	0	0	0	1	0	0	0
Incin.Waste Paper	19-17	0	0	0	0	0	0	0	0	0	0	0	0	0
Incin.Used Cups	19-18	0	0	0	0	0	0	0	0	0	0	0	0	0
Landfill Waste Pap	20-17	0	0	0	0	0	1	0	0	0	0	0	0	0
Landfill Used Cups	20-18	0	0	0	0	0	0	1	0	0	0	0	0	0
Recyl.Waste Paper	2-17	0	0	0	0	0	0	0	0	0	0	0	0	0
Recyl.Used Cups	2-18	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood Logs	r1	2.3320	-1.9356	0	0	0	0	0	0	0	0	0	0	0
Water	r2	.1000	-.0330	0	0	0	0	0	0	0	0	0	0	0
Chlorine	r3	.0600	-.0198	0	0	0	0	0	0	0	0	0	0	0
Sodium hydroxide	r4	.0200	-.0066	0	0	0	0	0	0	0	0	0	0	0
Sodium chlorate	r5	.0300	-.0149	0	0	0	0	0	0	0	0	0	0	0
Sulfuric acid	r6	.0100	-.0083	0	0	0	0	0	0	0	0	0	0	0
Sulfur dioxide	r7	.0100	.0017	0	0	0	0	0	0	0	0	0	0	0
Calcium hydroxide	r8	.0100	-.0083	0	0	0	0	0	0	0	0	0	0	0
Sodium sulfate	r9	.0010	-.0008	0	0	0	0	0	0	0	0	0	0	0
Pigments	r10	0	0	0	0	0	0	0	0	0	0	0	0	0
Coatings	r11	0	0	0	0	0	0	0	0	0	0	0	0	0
Filler	r12	0	0	0	0	0	0	0	0	0	0	0	0	0
Sodium Phosphate	r13	0	0	0	0	0	0	0	0	0	0	0	0	0
CO_2	r14	0	0	0	0	0	0	0	0	0	0	0	0	0
CO	r15	.0037	-.0031	0	0	0	0	0	.028	0	0	.0001	.0001	.078
NO_x	r16	.0061	-.0050	0	0	0	0	0	.046	0	0	.0004	.0005	.020
SO_2	r17	.0132	-.0110	0	0	0	0	0	.100	0	0	0	.0044	0
Particulates	r18	.0020	-.0016	0	0	0	0	0	.015	0	0	0	.0005	.001
Chlorine	r19	.0002	-.0001	0	0	0	0	0	0	0	0	0	0	0
Chlorine dioxide	r20	.0002	-.0001	0	0	0	0	0	0	0	0	0	0	0
Reduced sulfides	r21	.0015	-.0004	0	0	0	0	0	0	0	0	0	0	0
m^3 H_2O	r22	.0800	-.0181	0	0	0	0	0	0	0	0	0	0	0
Suspended solids	r23	.0100	-.0033	0	0	0	0	0	0	0	0	0	0	0
BOD	r24	.0050	-.0012	0	0	0	0	0	0	0	0	0	0	0
Organochlorides	r25	.0030	-.0005	0	0	0	0	0	0	0	0	0	0	0
Cellulostic Fiber	r26	.0010	.0002	0	0	0	0	0	0	0	0	0	0	0
Inorganic salts	r27	.0600	-.0198	0	0	0	0	0	0	0	0	0	0	0
Adhesive	r28	0	0	0	0	0	0	0	0	0	0	0	0	0
Beverages	r29	0	0	0	0	0	0	0	0	0	1	0	0	0
Incineration Fuel	r30	0	0	0	0	0	0	0	0	0	0	0	0	0
Ash	r31	0	0	0	0	0	0	0	.03	0	0	0	0	0
Methane	r32	0	0	0	0	0	0	0	0	0	0	0	0	0
Leachate	r33	0	0	0	0	0	0	0	0	0	0	0	0	0
Cellulostic Fiber	r34	0	0	0	0	0	0	0	0	1	0	0	0	0

In transport processes 14 and 16, and cup use, 12, there is no transformation of the product in material form, so coefficients for these processes are 1 for [15-14,o14], [1-16,o16], [14-12,o12] and [18-12,o12]. In process 15, cup manufacturing, 10% of the paper from manufacturing the cup is lost to waste trimmings due to the cylindrical shape of the bottom and the tapered shape of the cup body. The coefficients for [16-15,o15] and [17-15,o15] reflect this loss. Hocking [41] does not include these losses in his calculations, which is important since this increases the total paper requirement per beverage serving and material and energy requirements by 10%.

In this particular example, the case of 100% landfill disposal is being examined. Thus coefficients [20-17,o17] and [20-18,o18] are set to 1, and coefficients for incineration and recycling are set to zero. Later cases will examine 100% incineration, power cogeneration, and recycling disposal options, as well as mixed disposal alternatives where disposal is distributed between the three options. The selection of the coefficients associated with transport processes 17 and 18 determines the distribution.

The incineration of waste paper in process 19 results in residuals r14 through r18. These coefficients are assumed to be the same as those for the combustion of waste bark and black liquor in paper manufacturing. More specific figures could be used to reflect differing combustion technologies available for incineration or power cogeneration. Ash, r31, is also a byproduct.

The landfill of waste paper in process 20 may result in five types of residuals, carbon dioxide r14, BOD (biological oxygen demand) r24, methane r32, leachate r33, and cellulosic fiber r34. Landfill disposal is performed in a wide variety of geographic and climatic sites, with a variety of technologies. Under some conditions buried organic wastes may decompose and under others may remain relative inert, Hocking [41], Cavaney [38]. If decomposition occurs, the primary air emissions are CO_2 and methane in varying concentrations depending on the availability of oxygen (BOD) within the landfill substrate. Some landfill technologies deliberately manage the decomposition process to produce methane which is then captured and stored for use as a fuel. Leachate refers to the liquid that drains from the landfill site and may contaminate underground water supplies or surface water. The model can accommodate these variations in landfill conditions, but since representative data are not available for this widely variable processes, here the case of an inert disposal site is represented by assuming that all landfilled waste paper results in landfill mass.

Residuals from the combustion of diesel fuel for transportation o13 consist of air emissions r14 through r18. These coefficients are calculated from the U.S. Environmental Protection Agency limits on air emissions for diesel trucks [50]. These limits went into effect in 1986 and are currently in force.

Table 11 shows the continuity interconnection matrix for the network. Note that o1 and o2 from the network diagram of paper manufacturing are connected to links 1-16 and 2-17, 2-18 respectively. In table 12 information for various variables in the model are entered. For this aggregated model, the stimulus variable beverage servings, o12, is the overall stimulus for the network. The weight per cup used here is the 8.3 grams used in Hocking's example, which represents a typical 8 oz. paper coffee cup. For evaluation of other package types the appropriate weight per package can be entered. The first group of comparisons are to be on the basis of equal weights of packaging material, so the weight of cups has been specified as 1.0 kg, which yields 120 beverage servings.

Table 11 Paper Manufacturing, Use, Disposal Continuity Matrix

	1-16	16-15	17-15	15-14	14-12	18-12	19-17	19-18	20-17	20-18	2-17	2-18
o1	1	0	0	0	0	0	0	0	0	0	0	0
o2	0	0	0	0	0	0	0	0	0	0	1	1
o14	0	0	0	0	1	0	0	0	0	0	0	0
o15	0	0	0	1	0	0	0	0	0	0	0	0
o16	0	1	0	0	0	0	0	0	0	0	0	0
o17	0	0	1	0	0	0	0	0	0	0	0	0
o18	0	0	0	0	0	1	0	0	0	0	0	0
o19	0	0	0	0	0	0	1	1	0	0	0	0
o20	0	0	0	0	0	0	0	0	1	1	0	0

Table 12 Paper Manufacturing, Use, Disposal Variables

Stimulus Variables

Number of beverage serving	o12	120
Weight per cup g		8.30
Weight of cups kg	o14	1.00
Natural gas kg	o3	
Fuel Oil kg	o4	
Diesel Fuel kg	o13	

Disposal Policy	Waste Paper	Used Cups
% Incineration/Cogen.	.00%	.00%
% Landfill	100.00%	100.00%
% Recycled	.00%	.00%

Table 13 Paper Manufacturing, Use, Disposal Energetic Matrix F_b F_o

Energy Type per unit material		kg fuel/ freight unit-km	kg material/ freight unit	km of transport	Steam kg	Natural Gas kg	Fuel Oil kg	Elect. Power kWh	Diesel Fuel kg	Direct Labor1 hours	Direct Labor1 hours
Process											
Paper Manufacture	o1				0	0	.2540	.9980	0	.0041	0
W.Paper Repulping	o2				0	0	.0548	-.2963	0	-.0016	0
Cup Transport	o14	.35	10000	300	0	0	0	0	.0105	.0005	0
Cup Manufacturing	o15				0	0	0	.001	0	.0010	0
Paper Transport	o16	.35	20000	1000	0	0	0	0	.0175	.0008	0
W.Paper Transport	o17	.35	20000	1000	0	0	0	0	.0175	.0008	0
U.Cup Transport	o18	.35	20000	1000	0	0	0	0	.0175	.0008	0
Incineration	o19				0	0	0	-1.85	0	.0010	0
Landfill	o20				0	0	0	0	0	.0010	0
Beverage Servings	o12				0	0	0	0	0	0	0
Natural Gas	o3				0	0	0	0	0	0	0
Fuel Oil	o4				0	0	0	0	0	0	0
Diesel Fuel	o13				0	0	0	0	0	0	0

Later comparisons will be made on the basis of equal numbers of beverage servings. The material rates for natural gas, fuel oil, and diesel fuel combustion, o3, o4, and o13 are determined internally in the model from the energy requirements as discussed below. Finally, a disposal policy can be specified for both waste paper and used cups. These disposal policy choices are automatically reflected in the coefficients of Table 10.

In Table 13 the energetic matrices F_b and F_o are given. The first two rows corresponding to o1 and o2 specify coefficients from the lower level model of paper manufacturing, that is the first two rows of the matrix F_S for the network model of paper manufacturing given in Table 9. The rows corresponding to transport processes, o14, o16, o17, and o18 allow entry in the model of data about the transport processes. In the first column, the specific fuel consumption of the transportation unit is entered. The metric coefficient of .35 kg fuel/freight unit-km corresponds to the more familiar 7 miles per gallon fuel consumption of a typical semi-truck in English (SAE) units [48]. Alternative specific fuel consumption rates could be specified to evaluate rail or ship transport. The second column corresponds to the weight of material carried each freight unit, or truckload in this case. Note that the transport of paper, waste paper and used paper, o16, o17, and o18 assumes 20000 kg. per truckload, since this corresponds to the legal weight limit under federal trucking regulations. However the process of transporting cups assumes only 10000 kg per truckload since the volume of finished cups constrains the weight that can be transported per vehicle [48].

In the third column of Table 13 the distance of transport is specified. The figures chosen here of 1000 km for paper, waste paper, and used cup transport are thought to be realistic in the absence of representative industry wide data. In North America, paper manufacture is concentrated in three geographic zones, the Pacific Northwest, Ontario and Quebec, and the South Eastern U.S. A 1000 km radius from each of these regions encompasses much of the industrial and population centers of the continent. A distance of 1000 km has also been chosen as an average for waste paper and used cup transport. Incineration and power cogeneration plants are widely spaced geographically, and increasingly major portions of municipal wastes from population centers are being trucked across several states due to scarcity of landfill sites [30]. Paper repulping plants, whether combined with virgin pulp manufacture or operating solely from recycled paper are also geographically widely spaced. The transport of finished cups is assumed to be 300 km on an average since there are many cup manufacturers distributed more densely throughout urban regions. The eighth column, diesel fuel kg / unit material, is computed using the data in the first three columns. Direct labor time in the ninth column is based on an average speed of 70 km/hr for each truck.

Cup manufacturing, o15 is a reasonably simple process involving electrically driven automated machinery and is assumed to have a nominal electrical requirement and labor requirement. If electrical power cogeneration takes place in the incineration processes there will be electric power produced. Here 1.85 kWh per kg of waste paper or used cups is assumed based on 20 M Joules of recoverable heat per kg of paper [41] and a typical power conversion efficiency of 33%. In the absence of better data, reasonable assumptions have been made for direct labor requirements.

No energy has been assumed for process 12, cup use, but an *extremely* comprehensive life-cycle assessment could include the energy required to warm or cool the beverage for consumption! The processes of fuel combustion o3, o4 and o13 produce energy that is utilized by other processes at conversion efficiencies that are included in the computations for the entries in F_b, but do not themselves have energetic requirements except for possibly *indirect* labor which is not an energetic transformation cost.

Table 14 shows the matrix X_0 for the energetic costs of materials brought to the boundary of the entire system. This is the same as the matrix X_0 for paper manufacturing given in Table 5 with the addition of resources and residuals r28 through r34.

Table 14 Paper Manufacturing, Use, Disposal Matrix X_r

Energy Type per unit material		Natural Gas kg	Fuel Oil kg	Electric Power kW	Diesel Fuel kg	Direct Labor 1 hours	Direct Labor 2 hours
Resource							
Wood Logs	r1	0	0	0	0	0	0
Water	r2	0	0	0	0	0	0
Chlorine	r3	0	0	0	0	0	0
Sodium hydroxide	r4	0	0	0	0	0	0
Sodium chlorate	r5	0	0	0	0	0	0
Sulfuric acid	r6	0	0	0	0	0	0
Sulfur dioxide	r7	0	0	0	0	0	0
Calcium hydroxide	r8	0	0	0	0	0	0
Sodium sulfate	r9	0	0	0	0	0	0
Pigments	r10	0	0	0	0	0	0
Coatings	r11	0	0	0	0	0	0
Filler	r12	0	0	0	0	0	0
Sodium Phosphate	r13	0	0	0	0	0	0
CO_2	r14	0	0	0	0	0	0
CO	r15	0	0	0	0	0	0
NO_x	r16	0	0	0	0	0	0
SO_2	r17	0	0	0	0	0	0
Particulates	r18	0	0	0	0	0	0
Chlorine	r19	0	0	0	0	0	0
Chlorine dioxide	r20	0	0	0	0	0	0
Reduced sulfides	r21	0	0	0	0	0	0
m^3 H_2O	r22	0	0	0	0	0	0
Suspended solids	r23	0	0	0	0	0	0
BOD	r24	0	0	0	0	0	0
Organochlorides	r25	0	0	0	0	0	0
Cellulostic Fiber	r26	0	0	0	0	0	0
Inorganic salts	r27	0	0	0	0	0	0
Adhesive	r28	0	0	0	0	0	0
Beverages	r29	0	0	0	0	0	0
Incineration Fuel	r30	0	0	0	0	0	0
Ash	r31	0	0	0	0	0	0
Methane	r32	0	0	0	0	0	0
Leachate	r33	0	0	0	0	0	0
Cellulostic Fiber	r34	0	0	0	0	0	0

5.6 Life-cycle Level Results of Paper Manufacturing, Use and Disposal

Figure 7 shows a diagram for the complete network of paper manufacturing, use and disposal combining the network of manufacturing process of Figure 5 with the use and disposal processes of Figure 6. Table 15 shows the system matrix K_S for Figure 7 relating products y_o to resources y_r and the internal schedule matrix K_b relating the flow rates or products y_o to the flow rates of internal stimulus variables y_b. Flow rates of material variables $\dot{y}_l$, $\dot{y}_r$, $\dot{y}_b$, and $\dot{y}_o$ are presented in Table 16. Table 17 reports the energetic costs for the entire network. Notice that in this example the energy per unit material F_S and X_o are the same as the total energy e_s and e_o since the analysis is based on one unit (kg) of paper packaging material and the boundary energies at lower levels have all been specified as zero. A more detailed discussion of the material flows and energetic costs shown in these tables will be given in the chapter on comparisons of the life-cycle results of paper and polystyrene packaging to follow.

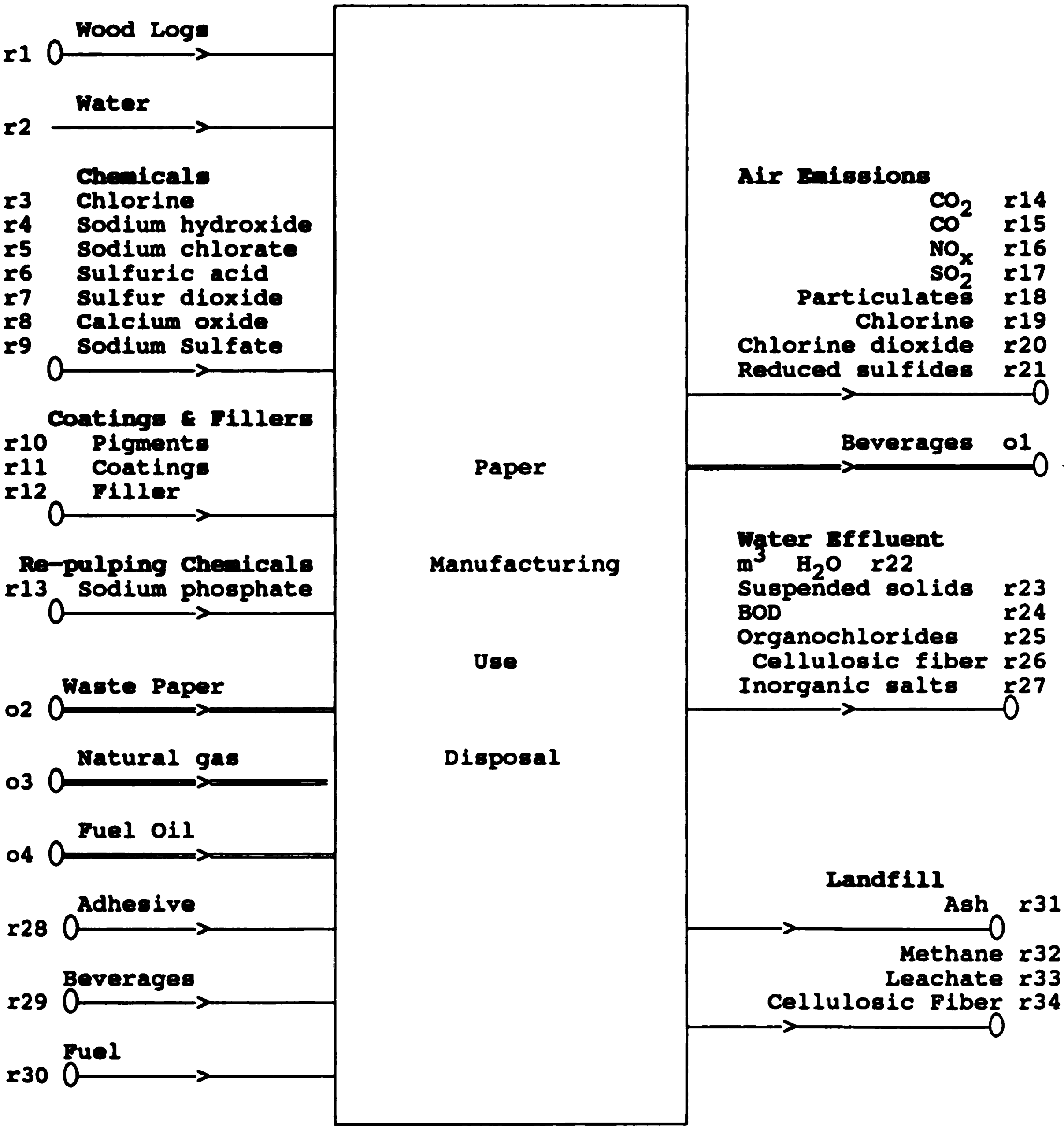

Figure 7 Consolidated Diagram of Paper Manufacturing, Use and Disposal

Table 15 Paper Manufacturing, Use, Disposal System Matrices

Schedule Matrix K_b		Bever-ages o12	Nat. Gas o3	Fuel Oil o4	Diesel Fuel o13
Paper Manufacture	o1	1.1000	0	0	0
W.Paper Repulping	o2	0	0	0	0
Cup Transport	o14	1	0	0	0
Cup Manufacturing	o15	1	0	0	0
Paper Transport	o16	1.1000	0	0	0
W.Paper Transport	o17	.1000	0	0	0
U.Cup Transport	o18	1	0	0	0
Incineration	o19	0	0	0	0
Landfill	o20	1.1000	0	0	0
System Matrix K_r					
Wood Logs	r1	2.5652	0	0	0
Water	r2	.1100	0	0	0
Chlorine	r3	.0660	0	0	0
Sodium hydroxide	r4	.0220	0	0	0
Sodium chlorate	r5	.0330	0	0	0
Sulfuric acid	r6	.0110	0	0	0
Sulfur dioxide	r7	.0110	0	0	0
Calcium hydroxide	r8	.0110	0	0	0
Sodium sulfate	r9	.0011	0	0	0
Pigments	r10	0	0	0	0
Coatings	r11	0	0	0	0
Filler	r12	0	0	0	0
Sodium Phosphate	r13	0	0	0	0
CO_2	r14	0	0	0	0
CO	r15	.0041	.0001	.0001	.0780
NO_x	r16	.0067	.0004	.0005	.0200
SO_2	r17	.0145	0	.0044	0
Particulates	r18	.0022	0	.0005	.0010
Chlorine	r19	.0002	0	0	0
Chlorine dioxide	r20	.0002	0	0	0
Reduced sulfides	r21	.0017	0	0	0
m^3 H_2O	r22	.0880	0	0	0
Suspended solids	r23	.0110	0	0	0
BOD	r24	.0055	0	0	0
Organochlorides	r25	.0033	0	0	0
Cellulostic Fiber	r26	.0011	0	0	0
Inorganic salts	r27	.0660	0	0	0
Adhesive	r28	0	0	0	0
Beverages	r29	1	0	0	0
Incineration Fuel	r30	0	0	0	0
Ash	r31	0	0	0	0
Methane	r32	0	0	0	0
Leachate	r33	0	0	0	0
Cellulostic Fiber	r34	1.1000	0	0	0

Table 16 Paper Manufacturing, Use, Disposal Material Flows

Links	y_l		*Branches*	y_b	
Paper	1-16	1.1000	Paper Manufacture	o1	1.1000
Paper	16-15	1.1000	W.Paper Repulping	o2	0
Waste Paper	17-15	.1000	Cup Transport	o14	1
Cups	15-14	1	Cup Manufacturing	o15	1
Cups	14-12	1	Paper Transport	o16	1.1000
Used Cups	18-12	1	W.Paper Transport	o17	.1000
Incin.Waste Paper	19-17	0	U.Cup Transport	o18	1
Incin.Used Cups	19-18	0	Incineration	o19	0
Land Used Cups	20-17	.1000	Landfill	o20	1.1000
Land Used Cups	20-18	1			
Recyl.Waste Paper	2-17	0			
Recyl.Used Cups	2-18	0			

Resources	y_r		*Objects*	y_o	
Wood Logs	r1	2.5652	Beverage Servings	o12	1
Water	r2	.1100	Natural Gas	o3	0
Chlorine	r3	.0660	Fuel Oil	o4	.2794
Sodium hydroxide	r4	.0220	Diesel Fuel	o13	.0490
Sodium chlorate	r5	.0330			
Sulfuric acid	r6	.0110			
Sulfur dioxide	r7	.0110			
Calcium hydroxide	r8	.0110			
Sodium sulfate	r9	.0011			
Pigments	r10	0			
Coatings	r11	0			
Filler	r12	0			
Sodium Phosphate	r13	0			
CO_2	r14	0			
CO	r15	.0079			
NO_x	r16	.0078			
SO_2	r17	.0157			
Particulates	r18	.0024			
Chlorine	r19	.0002			
Chlorine dioxide	r20	.0002			
Reduced sulfides	r21	.0017			
m^3 H_2O	r22	.0880			
Suspended solids	r23	.0110			
BOD	r24	.0055			
Organochlorides	r25	.0033			
Cellulostic Fiber	r26	.0011			
Inorganic salts	r27	.0660			
Adhesive	r28	0			
Beverages	r29	1			
Incineration Fuel	r30	0			
Ash	r31	0			
Methane	r32	0			
Leachate	r33	0			
Cellulostic Fiber	r34	1.1000			

Table 17 Paper Manufacturing, Use, Disposal System Energetics

Energy Type per unit material		Steam kg	Natural Gas kg	Fuel Oil kg	Elect. Power kWh	Diesel Fuel kg	Direct Labor1 hours	Direct Labor2 hours
F_{sat} Matrix								
Beverage Servings	o12	0	0	.2794	1.0988	.0490	.0089	0
Natural Gas	o3	0	0	0	0	0	0	0
Fuel Oil	o4	0	0	0	0	0	0	0
Diesel Fuel	o13	0	0	0	0	0	0	0
F_s Matrix								
Beverage Servings	o12		0	.2794	1.0988	.0490	.0089	0
Natural Gas	o3		0	0	0	0	0	0
Fuel Oil	o4		0	0	0	0	0	0
Diesel Fuel	o13		0	0	0	0	0	0
X_b Matrix								
Paper Manufacture	o1	0	0	-.2540	-.9980	0	-.0041	0
W.Paper Repulping	o2	0	0	-.0548	.2963	0	.0016	0
Cup Transport	o14	0	0	-.2794	-1.0988	-.0315	-.0071	0
Cup Manufacturing	o15	0	0	-.2794	-1.0988	-.0210	-.0066	0
Paper Transport	o16	0	0	-.2540	-.9980	-.0175	-.0049	0
W.Paper Transport	o17	0	0	0	0	-.0175	-.0018	0
U.Cup Transport	o18	0	0	0	0	-.0175	-.0018	0
Incineration	o19	0	0	0	1.8500	0	-.0010	0
Landfill	o20	0	0	0	0	0	-.0010	0
X_o Matrix								
Beverage Servings	o12	0	-.2794	-1.0988	-.0490	-.0089	0	0
Natural Gas	o3	0	0	0	0	0	0	0
Fuel Oil	o4	0	0	0	0	0	0	0
Diesel Fuel	o13	0	0	0	0	0	0	0
Energy e_s			0	.2794	1.0988	.0490	.0089	0
Energy e_o			0	-.2794	-1.0988	-.0490	-.0089	0

6 LIFE-CYCLE ASSESSMENT OF POLYSTYRENE MANUFACTURING, USE AND DISPOSAL

6.1 Network Diagram of Polystyrene Manufacturing

A diagram of polystyrene manufacturing including resource materials y_r and products y_0 is given in Figure 8. The secondary feedstocks in the production of polystyrene are ethylene manufactured in process 10 and benzene which is manufactured in process 12. There are a number of precursor chemical options and processes for both ethylene and benzene manufacture, Austin [42], Hocking [41]. The precursor chemicals illustrated here are propane, r1, and ethane r2. Propane and ethane are themselves products of the cracking of petroleum or natural gas via a number of process options. The analysis presented here illustrates how information about the energy $\dot{X}_r$ required to bring these primary feedstocks to the boundary of the enterprise can be utilized in both the enterprise level analysis and life-cycle assessment without explicitly modeling the refinery cracking process.

Benzene manufacture produces a number of marketable byproducts; toluene, aromatics and other fractions, r8 through r10. Similarly, ethylene manufacture results in hydrocarbon byproducts, r11, with a variety of potential uses. Since ethylene and benzene have a wide variety of uses, they may typically be produced at one petrochemical plant or facility, and transported via processes 9 and 11 to another location for the manufacture of ethylbenzene and polystyrene.

Within the petrochemical and plastic industries there are a wide variety of enterprise structures, Girouard [47]. Large integrated manufacturers operate facilities producing the series of products from ethylene and benzene to finished styrene beads.

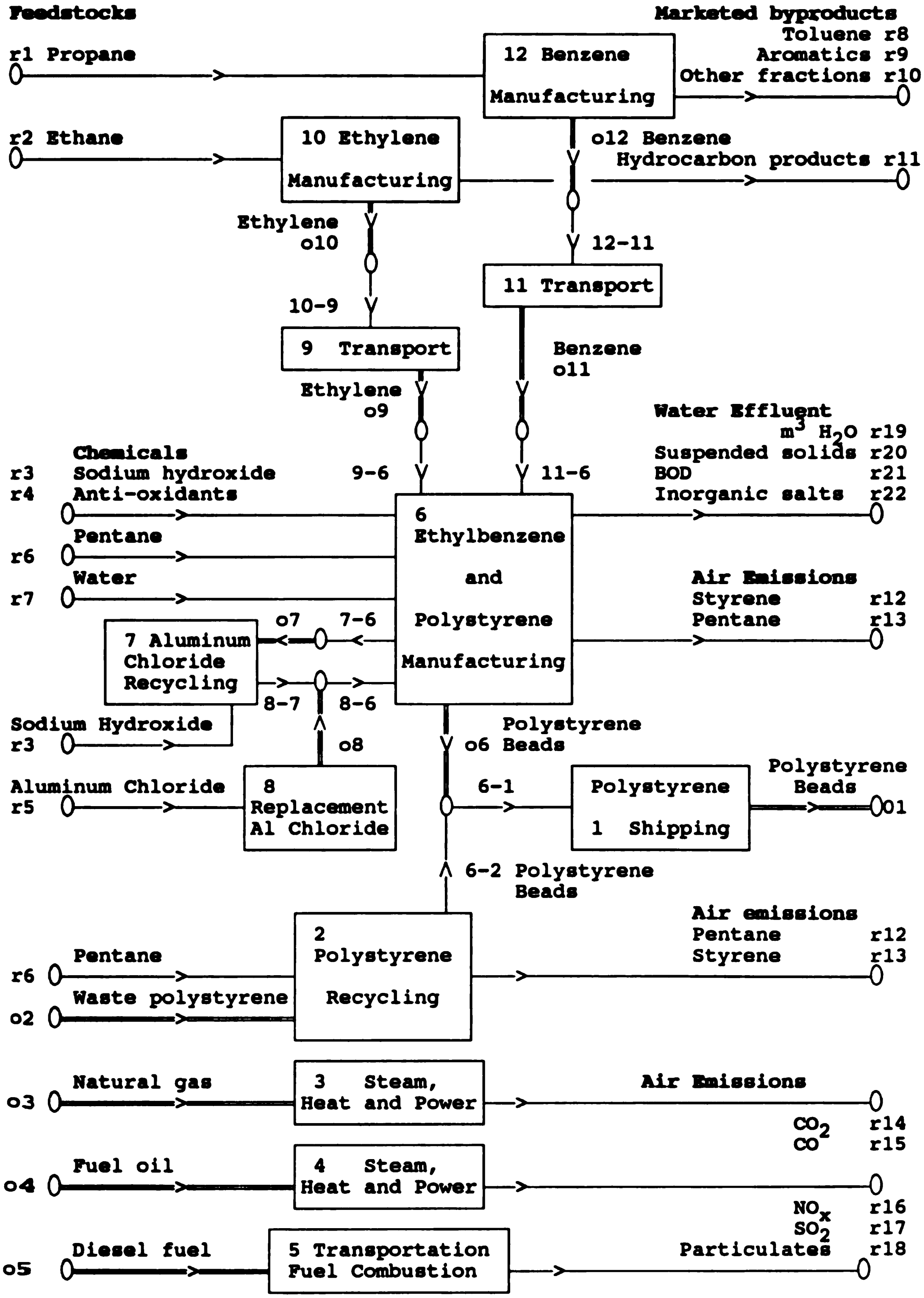

Figure 8 Network Diagram of Polystyrene Manufacturing

Other manufacturers may purchase ethylene and benzene from petrochemical manufacturers and produce ethylbenzene and polystyrene as in process 6 of Figure 8. The enterprise model illustrated here is that of an integrated manufacturer.

Relatively small amounts of other chemicals are used in polystyrene manufacture. Sodium hydroxide and aluminum chloride, r3 and r5 are employed, with most of the aluminum chloride being recycled in the process 7, Hocking [41]. It is important to note that the continuity of the network topology requires that replacement aluminum chloride is introduced in process 8 through the stimulus variable o8. Anti-oxidants r4 can be introduced to improve the properties of polystyrene for recycling Girouard [47]. Pentane gas introduced into the product gives the solid polystyrene beads the ability to "foam" or expand into the familiar cellular structure when manufacturing the finished packaging product.

Water effluents include the cubic volume of water, suspended solids, biochemical oxygen demand (BOD), and inorganic salts, r19 through r22. Air emissions consist of styrene gas and pentane which may escape during the production process. The escaped pentane is a flammable gas which can be captured and burned as a fuel. This scenario is not modeled here.

Polystyrene recycling, process 2, is a simple processes compared with waste paper repulping. Used polystyrene foam is shredded with grinding machinery into a granular or powder form and then re-extruded through a tapered auger heated to 300 to 450 degrees Fahrenheit. The only energy requirement is electric power for mechanical work and heating the auger body. Pentane is introduced as during virgin polystyrene manufacture.

As in the case of the repulping of paper, the branch stimulus variable o6, polystyrene beads, is a "makeup" variable. For a given level of waste polystyrene o2, the model calculates the level of virgin polystyrene beads o6 and accompanying resources required. Polystyrene shipping, o1, is simply a process which maintains the network continuity. As in the case of paper manufacture, the flow rate of recycled polystyrene beads 6-2, must be constrained to be less than or equal to the flow rate 6-1. Otherwise the flow o6 would be negative and the system would "produce" propane and ethane, clearly not a feasible condition.

The generation of steam, heat, and power in processes 3 and 4, and the combustion of transportation fuel in process 5 are all analogous to those processes in the discussion of paper manufacture.

6.2 Network Model of Polystyrene Manufacturing

Table 18 shows the matrices $\boldsymbol{K}_{lb}$, $\boldsymbol{K}_{lo}$, $\boldsymbol{K}_{rb}$, $\boldsymbol{K}_{ro}$ for the process network describing polystyrene manufacturing as given in Figure 8. The coefficients for processes 6, 10 and 12 are derived from the information presented by Hocking [41]. Unfortunately Hocking's aggregated data and associated diagrams, calculations and discussions are not in the rigorous framework required by process network theory. Considerable care taken when utilizing data in this type of format for calculation of coefficients to be incorporated in a process network model. References by Austin [42] and Erskine [43] were utilized to resolve uncertainties in the derivations presented by Hocking. Ethylbenzene and polystyrene manufacture is a series of reaction processes with unreacted components being internally fed back, achieving high levels of conversion efficiency.

Table 18 Polystyrene Manufacturing Coefficients

Links	Branches	Polysty Beads o6	Alum. Chlor o7	Alum. Chlor o8	Ethy-lene o9	Ethy-lene o10	Ben-zene o11	Ben-zene o12	Polyst Beads o1	Waste Polyst o2	Nat. Gas o3	Fuel Oil o4	Diesel Fuel o5
Polystyrene beads	6-1	0	0	0	0	0	0	0	1	0	0	0	0
Polystyrene beads	6-2	0	0	0	0	0	0	0	0	1	0	0	0
Aluminum chloride	7-6	.089	0	0	0	0	0	0	0	0	0	0	0
Aluminum chloride	8-6	.10	0	0	0	0	0	0	0	0	0	0	0
Aluminum chloride	8-7	0	1	0	0	0	0	0	0	0	0	0	0
Ethylene	9-6	.27	0	0	0	0	0	0	0	0	0	0	0
Ethylene	10-9	0	0	0	1	0	0	0	0	0	0	0	0
Benzene	11-6	.86	0	0	0	0	0	0	0	0	0	0	0
Benzene	12-11	0	0	0	0	0	1	0	0	0	0	0	0
Propane	r1	0	0	0	0	0	0	5	0	0	0	0	0
Ethane	r2	0	0	0	0	1.28	0	0	0	0	0	0	0
Sodium hydroxide	r3	.011	.124	0	0	0	0	0	0	0	0	0	0
Anti-oxidents	r4	0	0	0	0	0	0	0	0	0	0	0	0
Aluminum chloride	r5	0	0	1	0	0	0	0	0	0	0	0	0
Pentane	r6	.04	0	0	0	0	0	0	0	.04	0	0	0
Water	r7	.14	0	0	0	0	0	0	0	0	0	0	0
Toluene	r8	0	0	0	0	0	0	1.20	0	0	0	0	0
Aromatics	r9	0	0	0	0	0	0	.95	0	0	0	0	0
Other fractions	r10	0	0	0	0	0	0	1.45	0	0	0	0	0
Hydrocarbon prod.	r11	0	0	0	0	.28	0	0	0	0	0	0	0
Styrene	r12	.003	0	0	0	0	0	0	0	0	0	0	0
Pentane	r13	0	0	0	0	0	0	0	0	0	0	0	0
CO_2	r14	0	0	0	0	0	0	0	0	0	0	0	0
CO	r15	0	0	0	0	0	0	0	0	0	.0001	.0001	.078
NO_x	r16	0	0	0	0	0	0	0	0	0	.0004	.0005	.020
SO_2	r17	0	0	0	0	0	0	0	0	0	0	.0044	0
Particulates	r18	0	0	0	0	0	0	0	0	0	0	.0005	.001
m^3 H_2O	r19	.14	0	0	0	0	0	0	0	0	0	0	0
Suspended solids	r20	.0005	0	0	0	0	0	0	0	0	0	0	0
BOD	r21	.0002	0	0	0	0	0	0	0	0	0	0	0
Inorganic salts	r22	.02	0	0	0	0	0	0	0	0	0	0	0

Coefficients [9-6,06] and [11-6,o6] reflect the conversion of ethylene and benzene to finished polystyrene beads. The coefficients for aluminum chloride describe the recycling loop whereby 11% of the recycled flow rate is required for makeup.

Transport processes 9 and 11 and the polystyrene shipping process 1 all have coefficients of one. The coefficients in column o12 reflect the proportions of resource propane and byproducts r8-r10 of benzene production. Likewise column o10 reflects the coefficients for ethylene production. The remaining resource and residual coefficients for process 6 are found in column o6. Air emission rates for natural gas, fuel oil, and diesel fuel combustion are the same as those utilized in the model of paper manufacture, use and disposal.

Table 19 shows the interconnection matrix for the network. In Table 20 stimulus variables o1 and o2 are specified. In this first example, recycling of waste polystyrene is set to zero. Fuel combustion stimulus variables o3, o4 and o5 are determined internally in the model according to the energy requirements. Energy use ratios and conversion rates between energy forms are specified as before in the paper manufacture model.

Table 21 reports the conversion energy functions F_b and F_o for the network. Steam, fuel oil and electric power requirements are derived from Hocking [41]. Transportation diesel fuel is calculated according to the same procedure as in the paper use and disposal example. For the sake of comparison, manufacturing labor requirements are assumed to be 4 hours per metric ton of polystyrene, as in the case of paper manufacture. The recycling of polystyrene, o2, requires a small amount of electric power for shredding and a larger amount for heating the polystyrene to a glass and then molten state.

Table 19 Polystyrene Manufacturing Continuity Matrix

	6-1	6-2	7-6	8-6	8-7	9-6	10-9	11-6	12-11
o6	1	-1	0	0	0	0	0	0	0
o7	0	0	1	0	0	0	0	0	0
o8	0	0	0	1	-1	0	0	0	0
o9	0	0	0	0	0	1	0	0	0
o10	0	0	0	0	0	0	1	0	0
o11	0	0	0	0	0	0	0	1	0
12	0	0	0	0	0	0	0	0	1

Table 20 Polystyrene Manufacturing Variables

Stimulus Variables

Polystyrene Manufacture	o1	1
Waste Polystyrene	o2	0
Gas Steam, Heat & Power	o3	
Oil Steam, Heat & Power	o4	
Diesel Fuel - Transport	o5	
Energy use ratios		
Gas In Steam Generation		.00%
Oil In Steam Generation		100.00%
Cogenerated Electric		.00%
Purchased Electric		100.00%
kg Natural Gas/kg Steam		.047
kg Natural Gas/kWh Elect.		.200
kg Fuel Oil/kg Steam		.057
kg Fuel Oil/kWh Elect.		.240

Table 21 Polystyrene Manufacturing Energetic Matrix F_b F_o

Energy Type per unit material / Process		kg fuel/ freight unit-km	kg material/ freight unit	km of transport	Steam kg	Natural Gas kg	Fuel Oil kg	Elect. Power kWh	Diesel Fuel kg	Direct Labor1 hours	Direct Labor2 hours
Polystyrene Mfg.	o6				3.28	0	0	.28	0	.0010	0
Al.Chloride Recycle	o7				0	0	0	0	0	0	0
Al.Chloride Replace	o8				0	0	0	0	0	0	0
Ethylene Transport	o9	.35	20000	1000	0	0	0	0	.0175	.0008	0
Ethylene Manufacture	o10				2.65	0	.17	0	0	.0010	0
Benzene Transport	o11	.35	20000	1000	0	0	0	0	.0175	.0008	0
Benzene Manufacture	o12				2.65	0	.17	0	0	.0010	0

Polystyrene Shipping	o1				0	0	0	0	0	0	0
Polystyrene Recycle	o2				0	0	0	.14	0	.0010	0
Gas Steam,Heat&Power	o3				0	0	0	0	0	0	0
Oil Steam,Heat&Power	o4				0	0	0	0	0	0	0
Diesel Fuel Combust.	o5				0	0	0	0	0	0	0

The specific heat of polystyrene at standard reference temperature is available from standard reference sources [51]. However the specific heat required to bring polystyrene to melting is a far more complex matter, and illustrates how difficult it can be to use theoretical information to derive energy requirements for processes. In fact the energetics of phase transitions of non-cross linked plastics such as polystyrene through glass to molten states is not understood theoretically, despite having been the subject of research spanning decades [52]. Lacking empirical data measuring the power consumption of an extruder in operation, an assumption has been made that polystyrene recycling requires half the electrical energy of virgin polystyrene manufacture.

Table 22 gives the matrix X_r for the boundary energy costs of the network resource materials y_r. The boundary energetic costs for the minor resource materials r3 through r6 are unknown. However estimates are available for the energies x_{rs} for the two primary feedstocks, propane and ethane. The actual requirements are highly variable depending on the facility and technology. The coefficients shown here follow Hocking's approximation of 15% hydrocarbon requirement for fueling the cracking processes.

Table 23 provides for the entry of price information for resources, products and energetic resources. As discussed in the paper manufacturing example, operational price information is difficult to obtain for propriety reasons. The assumed prices used here are reasonable approximations of prices obtained by Girouard [47] in January 1992, and illustrate *how* process network models can be mapped into economic performance of the enterprise. It should be noted that byproducts r8 through r11 have economic value and may be marketed by the enterprise or used in other manufacturing operations. Thus they are assigned *negative* prices at the boundary of the network.

Table 22 Polystyrene Manufacturing Matrix X_r

Energy Type per unit material		Natural Gas kg	Fuel Oil kg	Electric Power kW	Diesel Fuel kg	Direct Labor 1 hours	Direct Labor 2 hours
Resource							
Propane	r1	0	.056	0	0	0	0
Ethane	r2	0	.056	0	0	0	0
Sodium hydroxide	r3	0	0	0	0	0	0
Anti-oxidents	r4	0	0	0	0	0	0
Aluminum chloride	r5	0	0	0	0	0	0
Pentane	r6	0	0	0	0	0	0
Water	r7	0	0	0	0	0	0
Toluene	r8	0	0	0	0	0	0
Aromatics	r9	0	0	0	0	0	0
Other fractions	r10	0	0	0	0	0	0
Hydrocarbon prod.	r11	0	0	0	0	0	0
Styrene	r12	0	0	0	0	0	0
Pentane	r13	0	0	0	0	0	0
CO_2	r14	0	0	0	0	0	0
CO	r15	0	0	0	0	0	0
NO_x	r16	0	0	0	0	0	0
SO_2	r17	0	0	0	0	0	0
Particulates	r18	0	0	0	0	0	0
m^3 H_2O	r19	0	0	0	0	0	0
Suspended solids	r20	0	0	0	0	0	0
BOD	r21	0	0	0	0	0	0
Inorganic salts	r22	0	0	0	0	0	0

Table 23 Polystyrene Manufacturing Prices

Resource y_r		Price/kg material p_r
Propane	r1	$.25
Ethane	r2	$.25
Sodium hydroxide	r3	$.25
Anti-oxidents	r4	$.00
Aluminum chloride	r5	$.25
Pentane	r6	$.25
Water	r7	$.00
Toluene	r8	($.25)
Aromatics	r9	($.25)
Other fractions	r10	($.25)
Hydrocarbon prod.	r11	($.25)
Styrene	r12	$.00
Pentane	r13	$.00
CO_2	r14	$.00
CO	r15	$.00
NO_x	r16	$.00
SO_2	r17	$.00
Particulates	r18	$.00
m^3 H_2O	r19	$.00
Suspended solids	r20	$.00
BOD	r21	$.00
Inorganic salts	r22	$.00

Products Y_o		Price/kg material p_o
Polystyrene Beads	o1	$.70
Waste Polystyrene	o2	$.00
Natural Gas	o3	$.00
Fuel Oil	o4	$.00
Diesel Fuel	o5	$.00

Energy	Price/unit energy p_e
Natural Gas / kg	$.25
Fuel Oil / kg	$.25
Electric Power / kWh	$.05
Diesel Fuel / kg	$.35
Direct Labor 1 / hour	$12.00
Direct Labor 2 / hour	$.00

Processing Environment Amortization		$ / kg material G_b & G_o
Polystyrene Mfg.	o6	.02
Al.Chloride Recycle	o7	0
Al.Chloride Replace	o8	0
Ethylene Transport	o9	.02
Ethylene Manufacture	o10	.02
Benzene Transport	o11	.02
Benzene Manufacture	o12	.02
Polystyrene Shipping	o1	0
Polystyrene Recycle	o2	.02
Gas Steam,Heat&Power	o3	.02
Oil Steam,Heat&Power	o4	.02
Diesel Fuel Combust.	o5	.02

It should be noted also that fuels, natural gas, fuel oil and diesel fuel, are priced as energies only, not as combustion materials o3, o4 and o5. To assign prices to both of these roles in the model would result in double counting of their economic cost. For purposes of illustration, processing environment amortization has been set to \$.02.

6.3 Enterprise Level Results of Polystyrene Manufacturing

Figure 9 shows the diagram of the manufacturing enterprise illustrated in Figure 8 at the next higher level of organization. Table 24 shows the system matrix $\boldsymbol{K}_S$ relating products $\boldsymbol{y}_o$ to $\boldsymbol{y}_r$ and the internal schedule matrix $\boldsymbol{K}_b$ relating the flow rates of products $\boldsymbol{y}_o$ to the flow rates of internal stimulus variables $\boldsymbol{y}_b$. Flow rates of material variables $\dot{\boldsymbol{y}}_l$, $\dot{\boldsymbol{y}}_r$, $\dot{\boldsymbol{y}}_b$ and $\dot{\boldsymbol{y}}_o$ are presented in Table 25.

Energetic and economic results for polystyrene manufacturing are presented in Table 26. The topology for the production of recycled versus virgin polystyrene beads is the same topology as for paper manufacture. Thus recycling *reduces* the energy requirements for each kg of waste polystyrene o2 utilized in the production of polystyrene beads o1. Since no steam, natural gas, fuel oil, or diesel fuel are used in polystyrene recycling, the reduction in these energy forms is exactly equal to the quantities utilized in virgin polystyrene manufacture. Under the assumption that electrical power requirements are half for the recycled material o2, the kWh of electricity are reduced accordingly in Fsst and $\boldsymbol{F}_S$. After conversion of units, the fuel oil (petroleum) energy requirement shown in $\boldsymbol{X}_o$ of .8053 kg / kg of polystyrene is in close agreement with .7923 kg / kg given by Hocking. Electric power requirements of .28 kWh / kg of polystyrene are also consistent with Hocking [41].

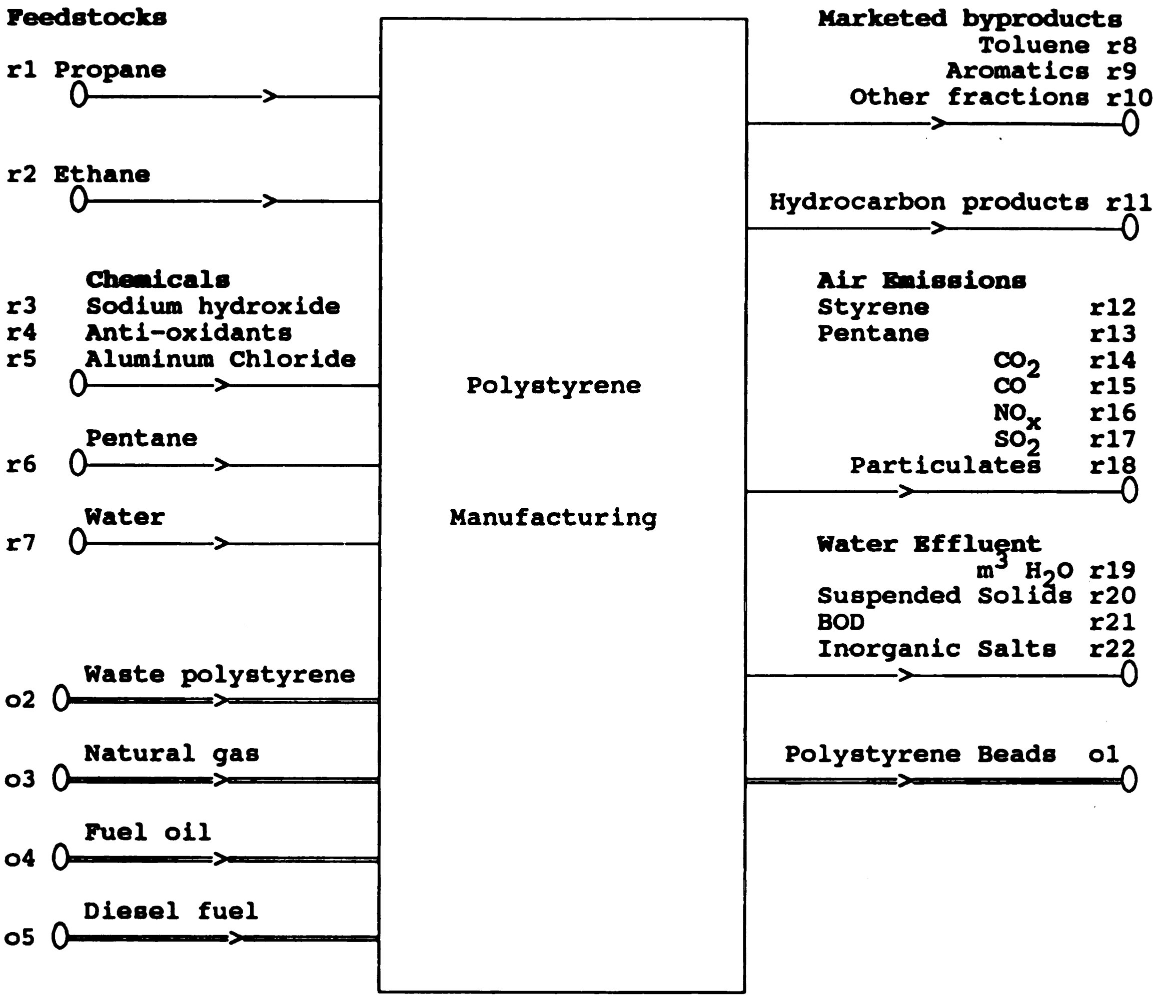

Figure 9 Consolidated Network Diagram of Polystyrene Manufacturing

Table 24 Polystyrene Manufacturing System Matrices

Schedule Matrix K_b		Polyst Beads o1	Waste Polyst o2	Nat. Gas o3	Fuel Oil o4	Diesel Fuel o5
Polystyrene Mfg.	o6	1	-1	0	0	0
Al.Chloride Recycle	o7	.0890	-.0890	0	0	0
Al.Chloride Replace	o8	.0110	-.0110	0	0	0
Ethylene Transport	o9	.2700	-.2700	0	0	0
Ethylene Manufacture	o10	.2700	-.2700	0	0	0
Benzene Transport	o11	.8600	-.8600	0	0	0
Benzene Manufacture	o12	.8600	-.8600	0	0	0
System Matrix K_S						
Propane	r1	4.3000	-4.3000	0	0	0
Ethane	r2	.3456	-.3456	0	0	0
Sodium hydroxide	r3	.0220	-.0220	0	0	0
Anti-oxidents	r4	0	0	0	0	0
Aluminum chloride	r5	.0110	-.0110	0	0	0
Pentane	r6	.0400	0	0	0	0
Water	r7	2.5000	-2.5000	0	0	0
Toluene	r8	1.0320	-1.0320	0	0	0
Aromatics	r9	.8170	-.8170	0	0	0
Other fractions	r10	1.2470	-1.2470	0	0	0
Hydrocarbon prod.	r11	.0756	-.0756	0	0	0
Styrene	r12	.0030	-.0030	0	0	0
Pentane	r13	0	0	0	0	0
CO_2	r14	0	0	0	0	0
CO	r15	0	0	.0001	.0001	.08
NO_x	r16	0	0	.0004	.0005	.02
SO_2	r17	0	0	0	.0044	0
Particulates	r18	0	0	0	.0005	.00
m^3 H_2O	r19	2.5000	-2.5000	0	0	0
Suspended solids	r20	.0005	-.0005	0	0	0
BOD	r21	.0002	-.0002	0	0	0
Inorganic salts	r22	.0150	-.0150	0	0	0

Table 25 Polystyrene Manufacturing Material Flows

Links		y_l
Polystyrene beads	6-1	1
Polystyrene beads	6-2	0
Aluminum chloride	7-6	.0890
Aluminum chloride	8-6	.1000
Aluminum chloride	8-7	.0890
Ethylene	9-6	.2700
Ethylene	10-9	.2700
Benzene	11-6	.8600
Benzene	12-11	.8600

Branches		y_b
Polystyrene Mfg.	o6	1
Al.Chloride Recycle	o7	.0890
Al.Chloride Replace	o8	.0110
Ethylene Transport	o9	.2700
Ethylene Manufacture	o10	.2700
Benzene Transport	o11	.8600
Benzene Manufacture	o12	.8600

Resources		y_r
Propane	r1	4.3000
Ethane	r2	.3456
Sodium hydroxide	r3	.0220
Anti-oxidents	r4	0
Aluminum chloride	r5	.0110
Pentane	r6	.0400
Water	r7	2.5000
Toluene	r8	1.0320
Aromatics	r9	.8170
Other fractions	r10	1.2470
Hydrocarbon prod.	r11	.0756
Styrene	r12	.0030
Pentane	r13	0
CO_2	r14	0
CO	r15	.0016
NO_x	r16	.0007
SO_2	r17	.0024
Particulates	r18	.0003
m^3 H_2O	r19	2.5000
Suspended solids	r20	.0005
BOD	r21	.0002
Inorganic salts	r22	.0150
Suspended solids	r23	.0110
BOD	r24	.0055
Organochlorides	r25	.0033
Cellulostic Fiber	r26	.0011
Inorganic salts	r27	.0660

Objects		y_o
Polystyrene Shipping	o1	1
Polystyrene Recycle	o2	0
Gas Steam,Heat&Power	o3	0
Oil Steam,Heat&Power	o4	.5452
Diesel Fuel Combust.	o5	.0198

Table 26 Polystyrene Manufacturing System Energetics

Energy Type per unit material	Steam kg	Natural Gas kg	Fuel Oil kg	Elect. Power kWh	Diesel Fuel kg	Direct Labor1 hours	Direct Labor2 hours
Fsat Matrix							
Polystyrene Shipping o1	6.1945	0	.1921	.2800	.0198	.0030	0
Polystyrene Recycle o2	-6.1945	0	-.1921	-.1400	-.0198	-.0020	0
Gas Steam,Heat&Power o3	0	0	0	0	0	0	0
Oil Steam,Heat&Power o4	0	0	0	0	0	0	0
Diesel Fuel Combust. o5	0	0	0	0	0	0	0
F_s Matrix							
Polystyrene Shipping o1		0	.5452	.2800	.0198	.0030	0
Polystyrene Recycle o2		0	-.5452	-.1400	-.0198	-.0020	0
Gas Steam,Heat&Power o3		0	0	0	0	0	0
Oil Steam,Heat&Power o4		0	0	0	0	0	0
Diesel Fuel Combust. o5		0	0	0	0	0	0
X_b Matrix							
Polystyrene Mfg. o6	-6.1945	0	-.4523	-.2800	-.0198	-.0030	0
Al.Chloride Recycle o7	0	0	0	0	0	0	0
Al.Chloride Replace o8	0	0	0	0	0	0	0
Ethylene Transport o9	-2.6500	0	-.2417	0	-.0175	-.0018	0
Ethylene Manufacture o10	-2.6500	0	-.2417	0	0	-.0010	0
Benzene Transport o11	-2.6500	0	-.4500	0	-.0175	-.0018	0
Benzene Manufacture o12	-2.6500	0	-.4500	0	0	-.0010	0
X_o Matrix							
Polystyrene Shipping o1		0	-.8053	-.2800	-.0198	-.0030	0
Polystyrene Recycle o2		0	.8053	.1400	.0198	.0020	0
Gas Steam,Heat&Power o3		0	0	0	0	0	0
Oil Steam,Heat&Power o4		0	0	0	0	0	0
Diesel Fuel Combust. o5		0	0	0	0	0	0
Energy e_s		0	.5452	.2800	.0198	.0030	0
Energy e_o		0	-.8053	-.2800	-.0198	-.0030	0
Amortiztion G_s							
Polystyrene Shipping o1	$.07						
Polystyrene Recycle o2	($.05)						
Gas Steam,Heat&Power o3	$.02						
Oil Steam,Heat&Power o4	$.02						
Diesel Fuel Combust. o5	$.02						
Cash Flow c_f	$.12						
Value Added v_s	$.04						

6.4 Diagram of Polystyrene Manufacturing, Use and Disposal

Figure 10 is a network diagram of polystyrene use and disposal. The boundary stimulus variables for use and disposal are the flow of beverages o13, and diesel fuel for transportation o5. Notice that links 1-16, polystyrene, and link 2-17, used cups and waste polystyrene, are connected to the network model for polystyrene manufacturing shown in Figure 9 at o1 and o2 respectively. This illustrates a particular choice of modeling topology where the network in Figure 9 is "added" to the graph of Figure 10.

Polystyrene beads from polystyrene manufacturing are transported to a cup manufacturing facility, process 15. Cup manufacturing consists of heating the beads in a molding machine which expands, or "foams" the polystyrene into the familiar cup form. No polystyrene is wasted in the processes, but some pentane from the foaming process is lost to the atmosphere. Cups must then be transported to the point of use in process 13. Beverages, o13, are the stimulus variable for the overall network of manufacture, use and disposal. In processes 17 used cups are separated for three disposal options and transported to their respective destinations, incineration or cogeneration 18, landfill 19, or the recycling link 2-17. Transportation fuel combustion takes place in process 5.

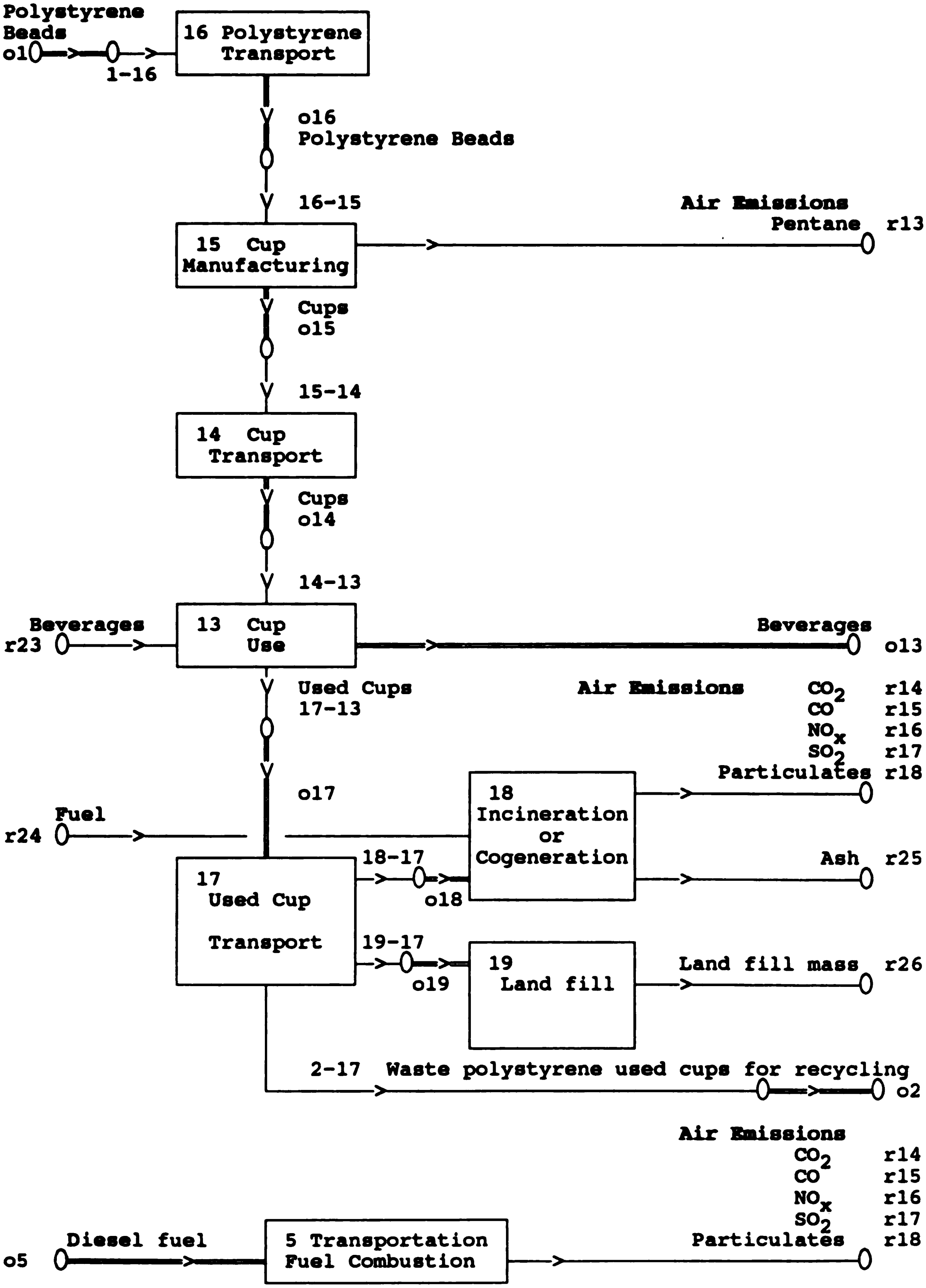

Figure 10 Network Diagram of Polystyrene Use and Disposal

6.5 Network Model of Polystyrene Manufacturing, Use and Disposal

Table 27 shows the matrices K_{lb}, K_{lo}, K_{rb}, K_{ro} for the process network describing polystyrene manufacturing corresponding to Figure 10. Comments about the coefficient data will be presented below by referring processes in general by their number and to specific elements according to their row-column labels.

In this table, the network model of polystyrene manufacturing illustrated in Figure 9 is aggregated with the model of paper use and disposal illustrated in Figure 10. The first feature to notice is how the system matrix for polystyrene manufacturing K_S given in Table 24 has been incorporated into the model. The ordering of columns of K_{lb}, K_{lo} has been chosen with the stimulus variables connecting the lower level system to the higher level system, o1 and o2, as the first two columns. Thus the first two columns of K_S given in Table 24 become the first two columns and 22 rows of the matrix K_{lo}. Similarly, columns 3, 4 and 5 of the matrix K_S become the second, third and fourth columns of matrix K_{ro} corresponding to o3, o4 and o5.

Now that polystyrene manufacturing has been incorporated into the model, what remains in the remainder of the matrix is to describe the coefficients relating to the processes for polystyrene use and disposal. In transport processes 14 and 16, and cup use, 13, there is no transformation of the product in material form, so coefficients for these processes are 1, [15-14,o14], [1-16,o16], [14-13,o13] and [17-13,o13]. In process 15, cup manufacturing, none of the polystyrene from manufacturing the cup is lost so [16-15,o15] is one. In this particular example, the case of 100% landfill disposal is being examined. Thus coefficients [19-17,o17] is set to 1, and coefficients for incineration and recycling are set to zero.

Table 27 Polystyrene Manufacturing, Use, Disposal Coefficients

Links	Branches	Polyst Beads o1	Waste Polyst o2	Cups o14	Cups o15	Polyst Beads o16	Used Cups o17	Used Cups o18	Used Cups o19	Bever-ages o13	Nat. Gas o3	Fuel Oil o4	Diesel Fuel o5
Cups	14-13	0	0	0	0	0	0	0	0	1	0	0	0
Cups	15-14	0	0	1	0	0	0	0	0	0	0	0	0
Polystyrene beads	16-15	0	0	0	1	0	0	0	0	0	0	0	0
Polystyrene beads	1-16	0	0	0	0	1	0	0	0	0	0	0	0
Used cups	17-13	0	0	0	0	0	0	0	0	1	0	0	0
Incin. used cups	18-17	0	0	0	0	0	0	0	0	0	0	0	0
Landfill used cups	19-17	0	0	0	0	0	1	0	0	0	0	0	0
Recycle used cups	2-17	0	0	0	0	0	0	0	0	0	0	0	0
Propane	r1	4.3000	-4.3000	0	0	0	0	0	0	0	0	0	0
Ethane	r2	.3456	-.3456	0	0	0	0	0	0	0	0	0	0
Sodium hydroxide	r3	.0220	-.0220	0	0	0	0	0	0	0	0	0	0
Anti-oxidents	r4	0	0	0	0	0	0	0	0	0	0	0	0
Aluminum chloride	r5	.0110	-.0110	0	0	0	0	0	0	0	0	0	0
Pentane	r6	.0400	0	0	0	0	0	0	0	0	0	0	0
Water	r7	2.5000	-2.5000	0	0	0	0	0	0	0	0	0	0
Toluene	r8	1.0320	-1.0320	0	0	0	0	0	0	0	0	0	0
Aromatics	r9	.8170	-.8170	0	0	0	0	0	0	0	0	0	0
Other fractions	r10	1.2470	-1.2470	0	0	0	0	0	0	0	0	0	0
Hydrocarbon prod.	r11	.0756	-.0756	0	0	0	0	0	0	0	0	0	0
Styrene	r12	.0030	-.0030	0	0	0	0	0	0	0	0	0	0
Pentane	r13	0	0	0	.04	0	0	0	0	0	0	0	0
CO_2	r14	0	0	0	0	0	0	0	0	0	0	0	0
CO	r15	0	0	0	0	0	0	.028	0	0	.0001	.0001	.0780
NO_x	r16	0	0	0	0	0	0	.046	0	0	.0004	.0005	.0200
SO_2	r17	0	0	0	0	0	0	.100	0	0	0	.0044	0
Particulates	r18	0	0	0	0	0	0	.015	0	0	0	.0005	.0010
m^3 H_2O	r19	2.5000	-2.5000	0	0	0	0	0	0	0	0	0	0
Suspended solids	r20	.0005	-.0005	0	0	0	0	0	0	0	0	0	0
BOD	r21	.0002	-.0002	0	0	0	0	0	0	0	0	0	0
Inorganic salts	r22	.0150	-.0150	0	0	0	0	0	0	0	0	0	0
Beverages	r23	0	0	0	0	0	0	0	0	1	0	0	0
Fuel	r24	0	0	0	0	0	0	0	0	0	0	0	0
Ash	r25	0	0	0	0	0	0	.03	0	0	0	0	0
Landfill mass	r26	0	0	0	0	0	0	0	1	0	0	0	0

Later cases will examine 100% incineration, power cogeneration, and recycling disposal options, as well as mixed disposal alternatives where disposal is distributed between the three options. The selection of the coefficients associated with transport process 17 determines the distribution.

Incineration of waste polystyrene in process 18 results in residuals r14 through r18 and ash r18. These coefficients are assumed to be the same as those for the combustion of waste bark and black liquor in paper manufacturing. More specific figures could be used to reflect differing combustion technologies available for incineration or power cogeneration. The landfill of waste polystyrene in process 19 is essentially chemically and biologically inert, so the only resulting residual is the landfill mass of polystyrene. Residuals from the combustion of diesel fuel for transportation o13 consist of air emissions r14 through r18.

Table 28 shows the continuity interconnection matrix for the network. Note that o1 and o2 from the network model of polystyrene manufacturing are connected to links 1-16 and 2-17 respectively. In table 29 information for various variables in the model are entered. For this aggregated model, the stimulus variable beverage servings, o12, is the overall stimulus for the network. The weight per cup used here is the 2.4 grams used in Hocking's example, which represents a typical 8 oz. polystyrene coffee cup. For evaluation of other package types the appropriate weight per package can be entered. The first group of comparisons are to be on the basis of equal weights of packaging material, so the weight of cups has been specified as 1.0 kg, which yields 417 beverage servings. Later comparisons will be made on the basis of equal number of beverage servings.

Table 28 Polystyrene Manufacturing, Use, Disposal Continuity Matrix

	14-13	15-14	16-15	1-16	17-13	18-17	19-17	2-17
o1	0	0	0	1	0	0	0	0
o2	0	0	0	0	0	0	0	1
o14	1	0	0	0	0	0	0	0
o15	0	1	0	0	0	0	0	0
o16	0	0	1	0	0	0	0	0
o17	0	0	0	0	1	0	0	0
o18	0	0	0	0	0	1	0	0
o19	0	0	0	0	0	0	1	0

Table 29 Polystyrene Manufacturing, Use, Disposal Variables

Stimulus Variables

Number of beverage servings		417
Weight per cup g		2.40
Weight of cups kg	o13	1.00
Natural gas kg	o3	
Fuel Oil kg	o4	
Diesel Fuel kg	o5	

Disposal Policy	Used Cups
% Incineration/Cogen.	.00%
% Landfill	100.00%
% Recycled	.00%

Table 30 Polystyrene Manufacturing, Use, Disposal Energetic Matrix F_b F_o

Energy Type per unit material / Process		kg fuel/ freight unit-km	kg material/ freight unit	km of transport	Steam kg	Natural Gas kg	Fuel Oil kg	Elect. Power kWh	Diesel Fuel kg	Direct Labor1 hours	Direct Labor2 hours
Polystyrene shipping	o1				0	0	.5452	.2800	.0198	.0030	0
Polystyrene recycle	o2				0	0	-.5452	-.1400	-.0198	-.0020	0
Cup transport	o14	.35	2500	300	0	0	0	0	.0420	.0018	0
Cup manufacturing	o15				0	0	0	.070	0	.0010	0
Polystyrene trans.	o16	.35	20000	1000	0	0	0	0	.0175	.0008	0
Used cup transport	o17	.35	20000	1000	0	0	0	0	.0175	.0008	0
Incineration/cogen.	o18				0	0	0	-3.700	0	.0010	0
Landfill	o19				0	0	0	0	0	.0010	0
Cup Use	o13				0	0	0	0	0	0	0
Gas Steam,Heat&Power	o3				0	0	0	0	0	0	0
Oil Steam,Heat&Power	o4				0	0	0	0	0	0	0
Diesel Fuel Combust.	o5				0	0	0	0	0	0	0

Table 31 Polystyrene Manufacturing, Use, Disposal Matrix X_r

Energy Type per unit material		Natural Gas kg	Fuel Oil kg	Electric Power kW	Diesel Fuel kg	Direct Labor 1 hours	Direct Labor 2 hours
Resource							
Propane	r1	0	.056	0	0	0	0
Ethane	r2	0	.056	0	0	0	0
Sodium hydroxide	r3	0	0	0	0	0	0
Anti-oxidents	r4	0	0	0	0	0	0
Aluminum chloride	r5	0	0	0	0	0	0
Pentane	r6	0	0	0	0	0	0
Water	r7	0	0	0	0	0	0
Toluene	r8	0	0	0	0	0	0
Aromatics	r9	0	0	0	0	0	0
Other fractions	r10	0	0	0	0	0	0
Hydrocarbon prod.	r11	0	0	0	0	0	0
Styrene	r12	0	0	0	0	0	0
Pentane	r13	0	0	0	0	0	0
CO_2	r14	0	0	0	0	0	0
CO	r15	0	0	0	0	0	0
NO_x	r16	0	0	0	0	0	0
SO_2	r17	0	0	0	0	0	0
Particulates	r18	0	0	0	0	0	0
m^3 H_2O	r19	0	0	0	0	0	0
Suspended solids	r20	0	0	0	0	0	0
BOD	r21	0	0	0	0	0	0
Inorganic salts	r22	0	0	0	0	0	0
Beverages	r23	0	0	0	0	0	0
Fuel	r24	0	0	0	0	0	0
Ash	r25	0	0	0	0	0	0
Landfill mass	r26	0	0	0	0	0	0

The material rates for natural gas, fuel oil, and diesel fuel combustion, o3, o4, and o5 are determined internally in the model from the energy requirements as discussed below. Finally, a disposal policy can be specified for both waste polystyrene and used cups. These disposal policy choices are automatically reflected in the coefficients of Table 27.

In Table 30 the energetic matrices F_b and F_o are given. The first two rows corresponding to o1 and o2, specify coefficients from the lower level model of polystyrene manufacturing, *i.e.* the first two rows of the matrix F_S for the network model of polystyrene manufacturing given in Table 26. The rows corresponding to transport processes, o14, o16 and o17 allow entry in the model of data about the transport processes. In the first column, the specific fuel consumption of the transportation unit is entered. The metric coefficient of .35 kg fuel/freight unit-km corresponds to the more familiar 7 miles per gallon fuel consumption of a typical semi-truck in English (SAE) units [48]. Alternative specific fuel consumption rates can be specified to evaluate rail or ship transport. The second column corresponds to the weight of material carried by each freight unit, or truckload in this case. Notice that the transport of polystyrene, waste polystyrene and used polystyrene, o16 and o17 assumes 20000 kg. per truckload, since this corresponds to the legal weight limit under federal trucking regulations. For the case of waste polystyrene, this assumes that the polystyrene foam has been shredded or compacted at the recycling collection site to increase its shipping density before transport. However the process of transporting cups assumes only 2500 kg per truckload since the volume of finished cups constrains the weight that can be transported per vehicle [48].

In the third column of Table 30 the distance of transport is specified. The figures chosen here of 1000 km for polystyrene and used cup transport are thought to be realistic in the absence of representative industry wide data. Personal experience in the trucking where polystyrene beads were hauled under contract indicates that these are reasonable figures under the industries geographic structure [48]. Incineration and power cogeneration plants are widely distributed geographically, and increasingly major portions of municipal wastes from population centers are being trucked across several states due to scarcity of landfill sites [48]. Polystyrene recycling plants, whether combined with virgin polystyrene manufacture or operating solely from recycled polystyrene are also geographically widely distributed. The transport of finished cups is assumed to be 300 km on an average since there are many cup manufacturers distributed more densely throughout urban regions. The coefficient in the eighth column, diesel fuel kg / unit material, is computed using the data in the first three columns. Direct labor time in the ninth column is computed based on an average speed of 70 km / hr for each truck.

Cup manufacturing, o15 is a reasonably simple process involving electrically driven automated machinery and is assumed to have a nominal electrical requirement and labor requirement. If electrical power cogeneration takes place in the incineration processes there will be electric power produced. Here 3.7 kWh per kg of waste polystyrene or used cups is assumed based on 40 M Joules of recoverable heat per kg of polystyrene [41] and a typical power conversion efficiency of 33%. In the absence of better data, reasonable assumptions have been made for direct labor requirements.

No energy has been assumed for process 13, cup use, but an *extremely* comprehensive life-cycle assessment could include the energy required to warm or cool the beverage for consumption! The processes of fuel combustion o3, o4 and o5 produce energy that is utilized by other processes at conversion efficiencies that are included in the computations for the entries in $\boldsymbol{F}_b$, but do not themselves have energetic requirements except for possibly *indirect* labor which is not an energetic transformation cost.

Table 31 shows the matrix $\boldsymbol{X}_o$ for the energetic costs of materials brought to the boundary of the entire system. This is the same as the matrix $\boldsymbol{X}_o$ for polystyrene manufacturing given in Table 22 with the addition of resources and residuals r23 through r26.

6.6 Life-cycle Level Results of Polystyrene Manufacturing, Use and Disposal

Figure 11 shows a diagram for the complete network of polystyrene manufacturing, use and disposal combining the network of manufacturing process of Figure 9 with the processes of Figure 10. Table 32 shows the system matrix $\boldsymbol{K}_S$ for Figure 11 relating products $\boldsymbol{y}_o$ to resources $\boldsymbol{y}_r$ and the internal schedule matrix $\boldsymbol{K}_b$ relating the flow rates or products $\boldsymbol{y}_o$ to the flow rates of internal stimulus variables $\boldsymbol{y}_b$. Flow rates of material variables $\dot{\boldsymbol{y}}_l$, $\dot{\boldsymbol{y}}_r$, $\dot{\boldsymbol{y}}_b$, and $\dot{\boldsymbol{y}}_o$ are presented in Table 33. Table 34 reports the energy costs for the entire network. Notice that in this example the energy per unit material $\boldsymbol{F}_S$ and $\boldsymbol{X}_o$ are the same as the total energy $\boldsymbol{e}_s$ and $\boldsymbol{e}_o$ since the analysis is based on one unit (kg) of polystyrene packaging material and the boundary energies at lower levels have all been specified as zero. A more detailed discussion of the material flows and energy costs shown in these tables will be given in the chapter on life cycle comparisons to follow.

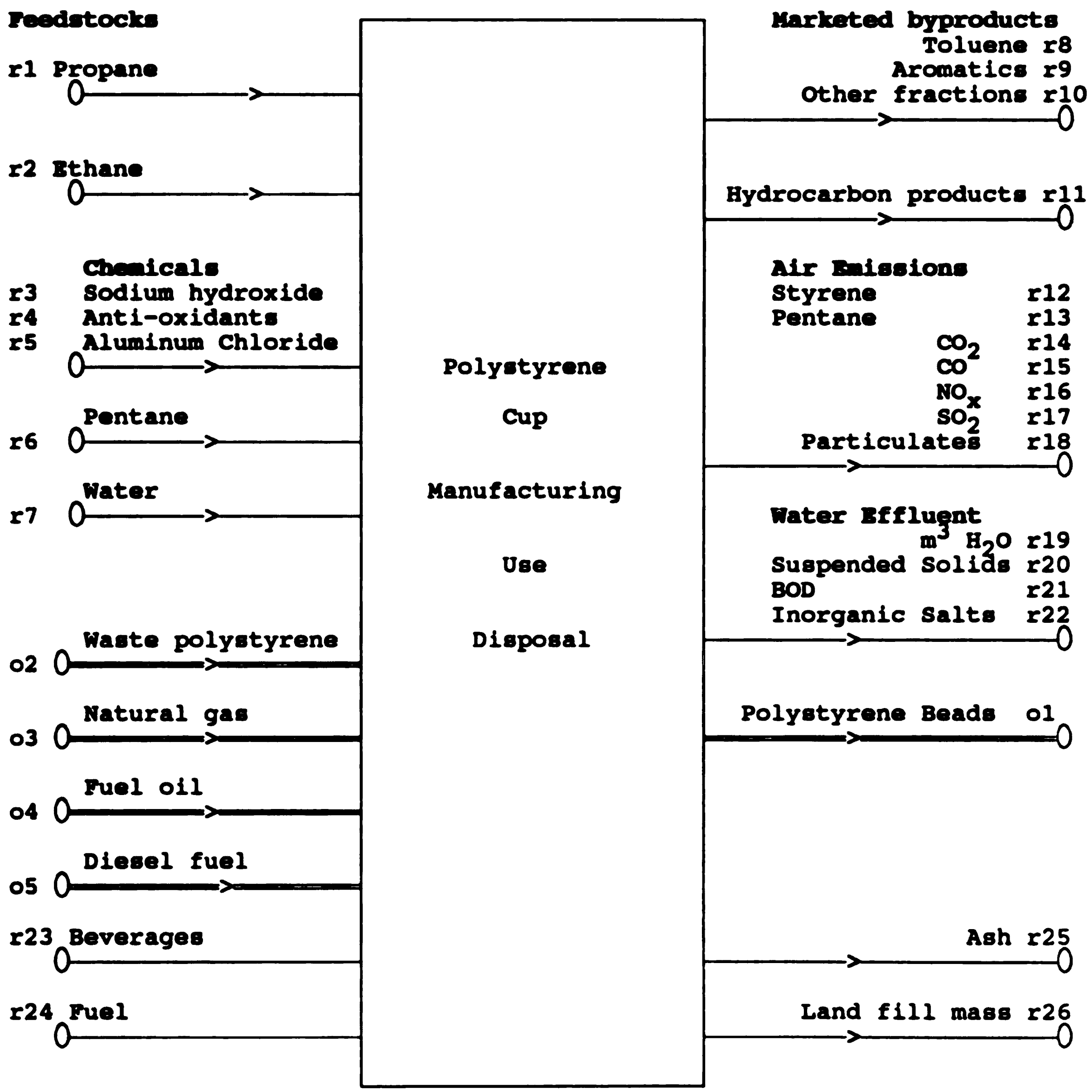

Figure 11 Consolidated Diagram of Polystyrene Manufacturing, Use and Disposal

Table 32 Polystyrene Manufacturing, Use, Disposal System Matrices

Schedule Matrix K_b		Beverages o13	Nat. Gas o3	Fuel Oil o4	Diesel Fuel o5
Polystyrene shipping	o1	1	0	0	0
Polystyrene recycle	o2	0	0	0	0
Cup transport	o14	1	0	0	0
Cup manufacturing	o15	1	0	0	0
Polystyrene trans.	o16	1	0	0	0
Used cup transport	o17	1	0	0	0
Incineration/cogen.	o18	0	0	0	0
Landfill	o19	1	0	0	0
System Matrix K_r					
Propane	r1	4.3000	0	0	0
Ethane	r2	.3456	0	0	0
Sodium hydroxide	r3	.0220	0	0	0
Anti-oxidents	r4	0	0	0	0
Aluminum chloride	r5	.0110	0	0	0
Pentane	r6	.0400	0	0	0
Water	r7	2.5000	0	0	0
Toluene	r8	1.0320	0	0	0
Aromatics	r9	.8170	0	0	0
Other fractions	r10	1.2470	0	0	0
Hydrocarbon prod.	r11	.0756	0	0	0
Styrene	r12	.0030	0	0	0
Pentane	r13	.0400	0	0	0
CO_2	r14	0	0	0	0
CO	r15	0	.0001	.0001	.0780
NO_x	r16	0	.0004	.0005	.0200
SO_2	r17	0	0	.0044	0
Particulates	r18	0	0	.0005	.0010
m^3 H_2O	r19	2.5000	0	0	0
Suspended solids	r20	.0005	0	0	0
BOD	r21	.0002	0	0	0
Inorganic salts	r22	.0150	0	0	0
Beverages	r23	1	0	0	0
Fuel	r24	0	0	0	0
Ash	r25	0	0	0	0
Landfill mass	r26	1	0	0	0

Table 33 Polystyrene Manufacturing, Use, Disposal Material Flows

Links	y_l		*Branches*	y_b	
Cups	14-13	1	Polystyrene ship	o1	1
Cups	15-14	1	Polystyrene recycle	o2	0
Polystyrene beads	16-15	1	Cup transport	o14	1
Polystyrene beads	1-16	1	Cup manufacturing	o15	1
Used cups	17-13	1	Polystyrene trans.	o16	1
Incin. used cups	18-17	0	Used cup transport	o17	1
Landfill used cups	19-17	1	Incineration/cogen.	o18	0
Recycle used cups	2-17	0	Landfill	o19	1

Resources	y_r		*Objects*	y_o	
Propane	r1	4.3000	Beverage Servings	o13	1
Ethane	r2	.3456	Natural Gas	o3	0
Sodium hydroxide	r3	.0220	Fuel Oil	o4	.5452
Anti-oxidents	r4	0	Diesel Fuel	o5	.0968
Aluminum chloride	r5	.0110			
Pentane	r6	.0400			
Water	r7	2.5000			
Toluene	r8	1.0320			
Aromatics	r9	.8170			
Other fractions	r10	1.2470			
Hydrocarbon prod.	r11	.0756			
Styrene	r12	.0030			
Pentane	r13	.0400			
CO_2	r14	0			
CO	r15	.0076			
NO_x	r16	.0022			
SO_2	r17	.0024			
Particulates	r18	.0004			
m^3 H_2O	r19	2.5000			
Suspended solids	r20	.0005			
BOD	r21	.0002			
Inorganic salts	r22	.0150			
Beverages	r23	1			
Fuel	r24	0			
Ash	r25	0			
Landfill mass	r26	1			

Table 34 Polystyrene Manufacturing, Use, Disposal System Energetics

Energy Type per unit material		Steam kg	Natural Gas kg	Fuel Oil kg	Elect. Power kWh	Diesel Fuel kg	Direct Labor1 hours	Direct Labor2 hours
Fsst Matrix								
Beverage Servings	o13	0	0	.5452	.3500	.0968	.0084	0
Natural Gas	o3	0	0	0	0	0	0	0
Fuel Oil	o4	0	0	0	0	0	0	0
Diesel Fuel	o5	0	0	0	0	0	0	0
F_s Matrix								
Beverage Servings	o13		0	.5452	.3500	.0968	.0084	0
Natural Gas	o3		0	0	0	0	0	0
Fuel Oil	o4		0	0	0	0	0	0
Diesel Fuel	o5		0	0	0	0	0	0
X_b Matrix								
Polystyrene ship	o1	0	0	-.8054	-.2800	-.0198	-.0030	0
Polystyrene recycle	o2	0	0	.8054	.1400	.0198	.0020	0
Cup transport	o14	0	0	-.8054	-.3500	-.0793	-.0066	0
Cup manufacturing	o15	0	0	-.8054	-.3500	-.0373	-.0048	0
Polystyrene trans.	o16	0	0	-.8054	-.2800	-.0373	-.0038	0
Used cup transport	o17	0	0	0	0	-.0175	-.0018	0
Incineration/cogen.	o18	0	0	0	3.7000	0	-.0010	0
Landfill	o19	0	0	0	0	0	-.0010	0
X_o Matrix								
Beverage Servings	o13		0	-.8054	-.3500	-.0968	-.0084	0
Natural Gas	o3		0	0	0	0	0	0
Fuel Oil	o4		0	0	0	0	0	0
Diesel Fuel	o5		0	0	0	0	0	0
Energy e_s			0	.5452	.3500	.0968	.0084	0
Energy e_o			0	.8054	.3500	.0968	.0084	0

7 LIFE-CYCLE COMPARISON OF PAPER AND POLYSTYRENE

7.1 Disposal and Recycling Alternatives

Table 35 through 40 present the results of alternative cases of disposal and recycling of paper and polystyrene packaging materials. These results are presented in a format which allows direct comparison of resources, residuals and energetic requirements for each of the cases.

Two broad classes of alternative cases are presented; 1) comparisons on a basis of equal *mass* of packaging material, and 2) comparisons on a *per package* basis. Examination on both of these basis is valuable. The per unit mass cases illustrate the results where equal weights of material are required to perform the same packaging task. The per unit package cases illustrate how the results and life-cycle assessment are effected by the technical characteristics and merits of the material in its use for packaging. In the case of cups for beverages, for example, the technical characteristics of the two materials allow the same or similar packaging function to be performed by a polystyrene cup composed of 2.4 grams of polystyrene as is performed by a paper cup composed of 8.3 grams of paper.

A total of six disposal and recycling cases are examined for each of these two broad classes of alternatives. Referring to Table 35 through 38, these cases are indexed in columns as cases A, B, C, D. Tables 39 and 40 show cases E and F. Cases A through D are "polar" cases, that is cases where all or the material is disposed of using the same alternative. Case A examines the example most analogous to Hocking's analysis, the case of 100% landfill disposal. In this case all used paper and polystyrene packaging is disposed of by landfill, including the waste paper trimmings from cup manufacture.

Table 35 Resource and Energetic Comparisons on an Equal Mass Basis

Paper Cup Manufacture, Use and Disposal

Disposal Case:			A	B	C	D
Incineration disposal			0%	100%	0%	0%
Electric Generation dispsl.			0%	0%	100%	0%
Landfill disposal			100%	0%	0%	0%
Recycling disposal			0%	0%	0%	100%
Products y_o		P_o				
Beverage Servings			120	120	120	120
Paper Cups-kg	o12		1	1	1	1
Paper-kg	o1	$.50	1.10	1.10	1.10	1.10
Paper Recycle-kg	o2		0	0	0	1.10
Paper Manufacture Cash Flow			$.13	$.13	$.13	$.34
Paper Mfg. Value Added			$.03	$.03	$.03	$.27
System Energy y_o * X_o		P_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	.279	.279	.279	.340
Electric Power - kWh		$.05	1.099	1.099	-.936	.773
Diesel Fuel - kg		$.35	.049	.049	.049	.049
Direct Labor 1 hours		$12.0	.009	.009	.009	.006
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r		P_r				
Wood Logs	r1	$.10	2.57	2.57	2.57	.44
Water	r2	$.00	.11	.11	.11	.07
Chlorine	r3	$.25	.066	.066	.066	.044
Sodium hydroxide	r4	$.25	.022	.022	.022	.015
Sodium chlorate	r5	$.25	.033	.033	.033	.017
Sulfuric acid	r6	$.25	.011	.011	.011	.002
Sulfur dioxide	r7	$.25	.011	.011	.011	.013
Calcium hydroxide	r8	$.25	.011	.011	.011	.002
Sodium sulfate	r9	$.25	.0011	.0011	.0011	.0002
Pigments	r10	$.25	0	0	0	0
Coatings	r11	$.25	0	0	0	0
Filler	r12	$.25	0	0	0	0
Sodium Phosphate	r13	$.25	0	0	0	0
CO_2	r14	$.00	0	0	0	0
CO	r15	$.00	.0079	.0387	.0387	.0045
NO_x	r16	$.00	.0078	.0584	.0584	.0024
SO_2	r17	$.00	.0157	.1257	.1257	.0039
Particulates	r18	$.00	.0024	.0189	.0189	.0007
Chlorine	r19	$.00	.0002	.0002	.0002	.0001
Chlorine dioxide	r20	$.00	.0002	.0002	.0002	.0001
Reduced sulfides	r21	$.00	.0017	.0017	.0017	.0012
m^3 H_2O	r22	$.00	.09	.09	.09	.07
Suspended solids	r23	$.00	.011	.011	.011	.007
BOD	r24	$.00	.0055	.0055	.0055	.0042
Organochlorides	r25	$.00	.0033	.0033	.0033	.0028
Cellulostic Fiber	r26	$.00	.0011	.0011	.0011	.0013
Inorganic salts	r27	$.00	.0660	.0660	.0660	.0442
Adhesive	r28	$.25	0	0	0	0
Beverages	r29	$.00	1	1	1	1
Incineration Fuel	r30	$.00	0	0	0	0
Ash	r31	$.00	0	.0330	.0330	0
Methane	r32	$.00	0	0	0	0
Leachate	r33	$.00	0	0	0	0
Cellulostic Fiber	r34	$.00	1.10	0	0	0

Polystyrene Cup Manfacturing, Use and Disposal

Disposal Case:			A	B	C	D
			0%	100%	0%	0%
			0%	0%	100%	0%
			100%	0%	0%	0%
			0%	0%	0%	100%
Products y_o		P_o				
Beverage Servings			417	417	417	417
Plastic cups-kg	o13		1	1	1	1
Polystyrene-kg	o1	$.70	1	1	1	1
Polyst.Recycle-kg	o2		0	0	0	1
Polystyrene Mfg. Cash Flow			$.12	$.12	$.12	$.67
Polystyrene Mfg. Value Added			$.04	$.04	$.04	$.65
System Energy y_o * X_o		P_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	.805	.805	.805	0
Electric Power - kWh		$.05	.35	.35	-3.35	.21
Diesel Fuel - kg		$.35	.097	.097	.097	.077
Direct Labor 1 hours		$12.0	.008	.008	.008	.005
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r		P_r				
Propane	r1	$.25	4.30	4.30	4.30	0
Ethane	r2	$.25	.346	.346	.346	0
Sodium hydroxide	r3	$.25	.022	.022	.022	0
Anti-oxidents	r4	$.00	0	0	0	0
Aluminum chloride	r5	$.25	.011	.011	.011	0
Pentane	r6	$.25	.040	.040	.040	.040
Water	r7	$.00	.140	.140	.140	0
Toluene	r8	($.25)	1.032	1.032	1.032	0
Aromatics	r9	($.25)	.817	.817	.817	0
Other fractions	r10	($.25)	1.247	1.247	1.247	0
Hydrocarbon prod.	r11	($.25)	.076	.076	.076	0
Styrene	r12	$.00	.003	.003	.003	0
Pentane	r13	$.00	.040	.040	.040	.040
CO_2	r14	$.00	0	0	0	0
CO	r15	$.00	.008	.036	.036	.006
NO_x	r16	$.00	.0022	.0482	.0482	.0015
SO_2	r17	$.00	.0024	.1024	.1024	0
Particulates	r18	$.00	.0004	.0154	.0154	.0001
m^3 H_2O	r19	$.00	2.5	2.5	2.5	0
Suspended solids	r20	$.00	.0005	.0005	.0005	0
BOD	r21	$.00	.0002	.0002	.0002	0
Inorganic salts	r22	$.00	.015	.015	.015	0
Beverages	r23	$.00	1	1	1	1
Fuel	r24	$.00	0	0	0	0
Ash	r25	$.00	0	.03	.03	0
Landfill mass	r26	$.00	1	0	0	0

Table 36 Crude Oil Equivalent Comparison on an Equal Mass Basis

Paper Cup Manufacture, Use and Disposal

			A	B	C	D
Disposal Case:			A	B	C	D
Incineration disposal			0%	100%	0%	0%
Electric Generation dispsl.			0%	0%	100%	0%
Landfill disposal			100%	0%	0%	0%
Recycling disposal			0%	0%	0%	100%
Products y_o		P_o				
Beverage Servings			120	120	120	120
Paper Cups-kg	o12		1	1	1	1
Paper-kg	o1	$.50	1.10	1.10	1.10	1.10
Paper Recycle-kg	o2		0	0	0	1.10
Paper Manufacture Cash Flow			$.13	$.13	$.13	$.34
Paper Mfg. Value Added			$.03	$.03	$.03	$.27
System Energy $y_o * X_o$		P_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	.279	.279	.279	.340
Electric Power - kWh		$.05	1.099	1.099	-.936	.773
Diesel Fuel - kg		$.35	.049	.049	.049	.049
Direct Labor 1 hours		$12.0	.009	.009	.009	.006
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r						
Wood Logs	r1		2.57	2.57	2.57	.44
Incineration Fuel	r30		0	0	0	0
Methane	r32		0	0	0	0
Energy Conversion Rates						
kg Crude Oil:						
/kg Natural Gas	o3	.98				
/kg Fuel Oil	o4	1.18				
/kWh Electric		.28				
/kg Diesel Fuel	o13	1.18				
Feedstock and Byproduct Conversion Rates						
kg Crude Oil:						
/kg Wood Logs	r1	0				
/kg Incin. Fuel	r30	-1.18				
/kg Methane	r32	-.98				
Energy - kg Crude Oil			.697	.697	.122	.676
Feedstock - kg Crude Oil			0	0	0	0
Total - kg Crude Oil			.697	.697	.122	.676

Polystyrene Cup Manfacturing, Use and Disposal

			A	B	C	D
Disposal Case:			A	B	C	D
Incineration disposal			0%	100%	0%	0%
Electric Generation dispsl.			0%	0%	100%	0%
Landfill disposal			100%	0%	0%	0%
Recycling disposal			0%	0%	0%	100%
Products y_o		P_o				
Beverage Servings			417	417	417	417
Plastic cups-kg	o13		1	1	1	1
Polystyrene-kg	o1	$.70	1	1	1	1
Polyst.Recycle-kg	o2		0	0	0	1
Polystyrene Mfg. Cash Flow			$.12	$.12	$.12	$.67
Polystyrene Mfg. Value Added			$.04	$.04	$.04	$.65
System Energy $y_o * X_o$		P_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	.805	.805	.805	0
Electric Power - kWh		$.05	.35	.35	-3.35	.21
Diesel Fuel - kg		$.35	.097	.097	.097	.077
Direct Labor 1 hours		$12.0	.008	.008	.008	.005
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r						
Propane	r1		4.30	4.30	4.30	0
Ethane	r2		.346	.346	.346	0
Pentane	r6		.040	.040	.040	.040
Toluene	r8		1.032	1.032	1.032	0
Aromatics	r9		.817	.817	.817	0
Other fractions	r10		1.247	1.247	1.247	0
Hydrocarbon prod.	r11		.076	.076	.076	0
Incineration Fuel	r24		0	0	0	0
Energy Conversion Rates						
kg Crude Oil:						
/kg Natural Gas	o3	.98				
/kg Fuel Oil	o4	1.18				
/kWh Electric		.28				
/kg Diesel Fuel	o5	1.18				
Feedstock and Byproduct Conversion Rates						
kg Crude Oil:						
/kg Propane	r1	.98				
/kg Ethane	r2	.98				
/kg Pentane	r6	.98				
/kg Toulene	r8	-.98				
/kg Aromatics	r9	-.98				
/kg Fractions	r10	-.98				
/kg HC Products	r11	-.98				
/kg Incin. Fuel	r24	1.18				
Energy - kg Crude Oil			1.160	1.160	.116	.150
Feedstock - kg Crude Oil			1.484	1.484	1.484	.039
Total - kg Crude Oil			2.645	2.645	1.600	.189

Table 37 Resource and Energetic Comparisons on the Basis of Servings

Paper Cup Manufacture, Use and Disposal

Disposal Case:			A	B	C	D
Incineration disposal			0%	100%	0%	0%
Electric Generation dispsl.			0%	0%	100%	0%
Landfill disposal			100%	0%	0%	0%
Recycling disposal			0%	0%	0%	100%
Products y_o		p_o				
Beverage Servings			1000	1000	1000	1000
Paper Cups-kg	o12		8.30	8.30	8.30	8.30
Paper-kg	o1	$.50	9.13	9.13	9.13	9.13
Paper Recycle-kg	o2		0	0	0	9.13
Paper Manufacture Cash Flow			$1.05	$1.05	$1.05	$2.78
Paper Mfg. Value Added			$.22	$.22	$.22	$2.26
System Energy $y_o * X_o$		p_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	2.319	2.319	2.319	2.820
Electric Power - kWh		$.05	9.120	9.120	-7.770	6.415
Diesel Fuel - kg		$.35	.407	.407	.407	.407
Direct Labor 1 hours		$12.0	.074	.074	.074	.050
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r		p_r				
Wood Logs	r1	$.10	21.29	21.29	21.29	3.62
Water	r2	$.00	.91	.91	.91	.61
Chlorine	r3	$.25	.548	.548	.548	.367
Sodium hydroxide	r4	$.25	.183	.183	.183	.122
Sodium chlorate	r5	$.25	.274	.274	.274	.138
Sulfuric acid	r6	$.25	.091	.091	.091	.016
Sulfur dioxide	r7	$.25	.091	.091	.091	.107
Calcium hydroxide	r8	$.25	.091	.091	.091	.016
Sodium sulfate	r9	$.25	.0091	.0091	.0091	.0017
Pigments	r10	$.25	0	0	0	0
Coatings	r11	$.25	0	0	0	0
Filler	r12	$.25	0	0	0	0
Sodium Phosphate	r13	$.25	0	0	0	0
CO_2	r14	$.00	0	0	0	0
CO	r15	$.00	.0656	.3212	.3212	.0374
NO_x	r16	$.00	.0647	.4847	.4847	.0199
SO_2	r17	$.00	.1303	1.0433	1.0433	.0324
Particulates	r18	$.00	.0199	.1569	.1569	.0058
Chlorine	r19	$.00	.0017	.0017	.0017	.0008
Chlorine dioxide	r20	$.00	.0017	.0017	.0017	.0008
Reduced sulfides	r21	$.00	.0141	.0141	.0141	.0100
m^3 H_2O	r22	$.00	.73	.73	.73	.57
Suspended solids	r23	$.00	.091	.091	.091	.061
BOD	r24	$.00	.0457	.0457	.0457	.0349
Organochlorides	r25	$.00	.0274	.0274	.0274	.0232
Cellulostic Fiber	r26	$.00	.0091	.0091	.0091	.0108
Inorganic salts	r27	$.00	.5478	.5478	.5478	.3669
Adhesive	r28	$.25	0	0	0	0
Beverages	r29	$.00	8.3	8.3	8.3	8.3
Incineration Fuel	r30	$.00	0	0	0	0
Ash	r31	$.00	0	.2739	.2739	0
Methane	r32	$.00	0	0	0	0
Leachate	r33	$.00	0	0	0	0
Cellulostic Fiber	r34	$.00	9.13	0	0	0

Polystyrene Cup Manfacturing, Use and Disposal

Disposal Case:			A	B	C	D
			0%	100%	0%	0%
			0%	0%	100%	0%
			100%	0%	0%	0%
			0%	0%	0%	100%
Products y_o		p_o				
Beverage Servings			1000	1000	1000	1000
Plastic cups-kg	o13		2.40	2.40	2.40	2.40
Polystyrene-kg	o1	$.70	2.40	2.40	2.40	2.40
Polyst.Recycle-kg	o2		0	0	0	2.40
Polystyrene Mfg. Cash Flow			$.29	$.29	$.29	$1.61
Polystyrene Mfg. Value Added			$.10	$.10	$.10	$1.56
System Energy $y_o * X_o$		p_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	1.933	1.933	1.933	0
Electric Power - kWh		$.05	.84	.84	-8.04	.50
Diesel Fuel - kg		$.35	.232	.232	.232	.185
Direct Labor 1 hours		$12.0	.020	.020	.020	.013
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r		p_r				
Propane	r1	$.25	10.32	10.32	10.32	0
Ethane	r2	$.25	.829	.829	.829	0
Sodium hydroxide	r3	$.25	.053	.053	.053	0
Anti-oxidents	r4	$.00	0	0	0	0
Aluminum chloride	r5	$.25	.026	.026	.026	0
Pentane	r6	$.25	.096	.096	.096	.096
Water	r7	$.00	.336	.336	.336	0
Toluene	r8	($.25)	2.477	2.477	2.477	0
Aromatics	r9	($.25)	1.961	1.961	1.961	0
Other fractions	r10	($.25)	2.993	2.993	2.993	0
Hydrocarbon prod.	r11	($.25)	.181	.181	.181	0
Styrene	r12	$.00	.007	.007	.007	0
Pentane	r13	$.00	.096	.096	.096	.096
CO_2	r14	$.00	0	0	0	0
CO	r15	$.00	.0182	.0854	.0854	.0144
NO_x	r16	$.00	.0053	.1157	.1157	.0036
SO_2	r17	$.00	.0058	.2458	.2458	0
Particulates	r18	$.00	.0010	.0370	.0370	.0002
m^3 H_2O	r19	$.00	6	6	6	0
Suspended solids	r20	$.00	.0012	.0012	.0012	0
BOD	r21	$.00	.0005	.0005	.0005	0
Inorganic salts	r22	$.00	.036	.036	.036	0
Beverages	r23	$.00	2.4	2.4	2.4	2.4
Fuel	r24	$.00	0	0	0	0
Ash	r25	$.00	0	.072	.072	0
Landfill mass	r26	$.00	2.4	0	0	0

Table 38 Crude Oil Equivalent Comparisons on the Basis of Servings

Paper Cup Manufacture, Use and Disposal

			A	B	C	D
Disposal Case:			A	B	C	D
Incineration disposal			0%	100%	0%	0%
Electric Generation dispsl.			0%	0%	100%	0%
Landfill disposal			100%	0%	0%	0%
Recycling disposal			0%	0%	0%	100%
Products y_o		p_o				
Beverage Servings			1000	1000	1000	1000
Paper Cups-kg	o12		8.30	8.30	8.30	8.30
Paper-kg	o1	$.50	9.13	9.13	9.13	9.13
Paper Recycle-kg	o2		0	0	0	9.13
Paper Manufacture Cash Flow			$1.05	$1.05	$1.05	$2.78
Paper Mfg. Value Added			$.22	$.22	$.22	$2.26
System Energy $y_o * X_o$		p_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	2.319	2.319	2.319	2.820
Electric Power - kWh		$.05	9.120	9.120	-7.770	6.415
Diesel Fuel - kg		$.35	.407	.407	.407	.407
Direct Labor 1 hours		$12.0	.074	.074	.074	.050
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r						
Wood Logs	r1		21.33	21.33	21.33	3.65
Incineration Fuel	r30		0	0	0	0
Methane	r32		0	0	0	0

Energy Conversion Rates
kg Crude Oil:

/kg Natural Gas	o3	.98
/kg Fuel Oil	o4	1.18
/kWh Electric		.28
/kg Diesel Fuel	o13	1.18

Feedstock and Byproduct Conversion Rates
kg Crude Oil:

/kg Wood Logs	r1	0
/kg Incin. Fuel	r30	-1.18
/kg Methane	r32	-.98

	A	B	C	D
Energy - kg Crude Oil	5.782	5.782	1.013	5.607
Feedstock - kg Crude Oil	0	0	0	0
Total - kg Crude Oil	5.782	5.782	1.013	5.607

Polystyrene Cup Manfacturing, Use and Disposal

			A	B	C	D
Disposal Case:			A	B	C	D
Incineration disposal			0%	100%	0%	0%
Electric Generation dispsl.			0%	0%	100%	0%
Landfill disposal			100%	0%	0%	0%
Recycling disposal			0%	0%	0%	100%
Products y_o		p_o				
Beverage Servings			1000	1000	1000	1000
Plastic cups-kg	o13		2.40	2.40	2.40	2.40
Polystyrene-kg	o1	$.70	2.40	2.40	2.40	2.40
Polyst.Recycle-kg	o2		0	0	0	2.40
Polystyrene Mfg. Cash Flow			$.29	$.29	$.29	$1.61
Polystyrene Mfg. Value Added			$.10	$.10	$.10	$1.56
System Energy $y_o * X_o$		p_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	1.933	1.933	1.933	0
Electric Power - kWh		$.05	.84	.84	-8.04	.50
Diesel Fuel - kg		$.35	.232	.232	.232	.185
Direct Labor 1 hours		$12.0	.020	.020	.020	.013
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r						
Propane	r1		10.32	10.32	10.32	0
Ethane	r2		.83	.83	.83	0
Pentane	r6		.10	.10	.10	.10
Toluene	r8		2.48	2.48	2.48	0
Aromatics	r9		1.96	1.96	1.96	0
Other fractions	r10		2.99	2.99	2.99	0
Hydrocarbon prod.	r11		.18	.18	.18	0
Fuel	r24		0	0	0	0

Energy Conversion Rates
kg Crude Oil:

/kg Natural Gas	o3	.98
/kg Fuel Oil	o4	1.18
/kWh Electric		.28
/kg Diesel Fuel	o5	1.18

Feedstock and Byproduct Conversion Rates
kg Crude Oil:

/kg Propane	r1	.98
/kg Ethane	r2	.98
/kg Pentane	r6	.98
/kg Toulene	r8	-.98
/kg Aromatics	r9	-.98
/kg Fractions	r10	-.98
/kg HC Products	r11	-.98
/kg Incin. Fuel	r24	1.18

	A	B	C	D
Energy - kg Crude Oil	2.785	2.785	.277	.360
Feedstock - kg Crude Oil	3.562	3.562	3.562	.094
Total - kg Crude Oil	6.347	6.347	3.840	.454

Table 39 Resource and Energetic Comparisons for Mixed Disposal Options

Paper Cup Manufacture, Use and Disposal

Disposal Case:			E	F	E	F
Incineration disposal			10%	0%	10%	0%
Electric Generation dispsl.			10%	50%	10%	50%
Landfill disposal			70%	0%	70%	0%
Recycling disposal			10%	50%	10%	50%
Products y_o		P_o				
Beverage Servings			120	120	1000	1000
Paper Cups-kg	o12		1	1	8.30	8.30
Paper-kg	o1	$.50	1.10	1.10	9.13	9.13
Paper Recycle-kg	o2		.20	.60	1.66	4.98
Paper Manufacture Cash Flow			$.16	$.24	$1.37	$2.00
Paper Mfg. Value Added			$.07	$.16	$.59	$1.33
System Energy y_o * X_o		P_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	.290	.312	2.410	2.592
Electric Power - kWh		$.05	.856	-.004	7.101	-.033
Diesel Fuel - kg		$.35	.049	.049	.407	.407
Direct Labor 1 hours		$12.0	.008	.007	.070	.061
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r		P_r				
Wood Logs	r1	$.10	2.18	1.40	18.08	11.65
Water	r2	$.00	.103	.090	.858	.749
Chlorine	r3	$.25	.062	.054	.515	.449
Sodium hydroxide	r4	$.25	.021	.018	.172	.149
Sodium chlorate	r5	$.25	.030	.024	.249	.200
Sulfuric acid	r6	$.25	.009	.006	.077	.050
Sulfur dioxide	r7	$.25	.011	.012	.094	.100
Calcium hydroxide	r8	$.25	.009	.006	.077	.050
Sodium sulfate	r9	$.25	.0009	.0006	.0075	.0050
Pigments	r10	$.25	0	0	0	0
Coatings	r11	$.25	0	0	0	0
Filler	r12	$.25	0	0	0	0
Sodium Phosphate	r13	$.25	0	0	0	0
CO_2	r14	$.00	0	0	0	0
CO	r15	$.00	.0129	.0201	.1071	.1668
NO_x	r16	$.00	.0160	.0278	.1328	.2307
SO_2	r17	$.00	.0336	.0593	.2789	.4922
Particulates	r18	$.00	.0051	.0089	.0423	.0739
Chlorine	r19	$.00	.0002	.0002	.0017	.0017
Chlorine dioxide	r20	$.00	.0002	.0002	.0017	.0017
Reduced sulfides	r21	$.00	.0016	.0014	.0133	.0116
m^3 H_2O	r22	$.00	.084	.077	.701	.640
Suspended solids	r23	$.00	.010	.009	.085	.075
BOD	r24	$.00	.0053	.0048	.0440	.0398
Organochlorides	r25	$.00	.0032	.0030	.0266	.0249
Cellulostic Fiber	r26	$.00	.0011	.0012	.0091	.0100
Inorganic salts	r27	$.00	.0620	.0541	.5146	.4490
Adhesive	r28	$.25	0	0	0	0
Beverages	r29	$.00	1	1	8.3	8.3
Incineration Fuel	r30	$.00	0	0	0	0
Ash	r31	$.00	.0060	.0150	.0498	.1245
Methane	r32	$.00	0	0	0	0
Leachate	r33	$.00	0	0	0	0
Cellulostic Fiber	r34	$.00	.70	0	5.81	0

Polystyrene Cup Manfacturing, Use and Disposal

Disposal Case:			E	F	E	F
			10%	0%	10%	0%
			10%	50%	10%	50%
			70%	0%	70%	0%
			10%	50%	10%	50%
Products y_o		P_o				
Beverage Servings			417	417	1000	1000
Plastic cups-kg	o13		1	1	2.40	2.40
Polystyrene-kg	o1	$.70	1	1	2.40	2.40
Polyst.Recycle-kg	o2		.10	.50	.24	1.20
Polystyrene Mfg. Cash Flow			$.17	$.40	$.42	$.95
Polystyrene Mfg. Value Added			$.10	$.35	$.25	$.83
System Energy y_o * X_o		P_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	.725	.403	1.740	.966
Electric Power - kWh		$.05	-.034	-1.570	-.082	-3.768
Diesel Fuel - kg		$.35	.095	.087	.228	.209
Direct Labor 1 hours		$12.0	.008	.007	.019	.017
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r		P_r				
Propane	r1	$.25	3.8700	2.1500	9.2880	5.1600
Ethane	r2	$.25	.3110	.1728	.7464	.4147
Sodium hydroxide	r3	$.25	.0198	.0110	.0475	.0264
Anti-oxidents	r4	$.00	0	0	0	0
Aluminum chloride	r5	$.25	.0099	.0055	.0238	.0132
Pentane	r6	$.25	.0400	.0400	.0960	.0960
Water	r7	$.00	.0300	.0700	.1200	.1800
Toluene	r8	($.25)	.9288	.5160	2.2291	1.2384
Aromatics	r9	($.25)	.7353	.4085	1.7647	.9804
Other fractions	r10	($.25)	1.1223	.6235	2.6935	1.4964
Hydrocarbon prod.	r11	($.25)	.0680	.0378	.1632	.0907
Styrene	r12	$.00	.0027	.0015	.0065	.0036
Pentane	r13	$.00	.0400	.0400	.0960	.0960
CO_2	r14	$.00	0	0	0	0
CO	r15	$.00	.0130	.0208	.0312	.0499
NO_x	r16	$.00	.0113	.0249	.0271	.0598
SO_2	r17	$.00	.0222	.0512	.0533	.1229
Particulates	r18	$.00	.0033	.0077	.0079	.0185
m^3 H_2O	r19	$.00	2.2500	1.2500	5.4000	3
Suspended solids	r20	$.00	.0005	.0003	.0012	.0007
BOD	r21	$.00	.0002	.0001	.0005	.0002
Inorganic salts	r22	$.00	.0135	.0075	.0324	.0180
Beverages	r23	$.00	1	1	2.4000	2.4000
Fuel	r24	$.00	0	0	0	0
Ash	r25	$.00	.0060	.0150	.0144	.0360
Landfill mass	r26	$.00	.7000	0	1.6800	0

Table 40 Crude Oil Equivalent Comparison for Mixed Disposal Options

Paper Cup Manufacture, Use and Disposal

Disposal Case:			E	F	E	F
Incineration disposal			10%	0%	10%	0%
Electric Generation dispsl.			10%	50%	10%	50%
Landfill disposal			70%	0%	70%	0%
Recycling disposal			10%	50%	10%	50%
Products y_o		P_o				
Beverage Servings			120	120	1000	1000
Paper Cups-kg	o12		1	1	8.30	8.30
Paper-kg	o1	$.50	1.10	1.10	9.13	9.13
Paper Recycle-kg	o2		.20	.60	1.66	4.98
Paper Manufacture Cash Flow			$.16	$.24	$1.37	$2.00
Paper Mfg. Value Added			$.07	$.16	$.59	$1.33
System Energy $y_o * X_o$		P_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	.290	.312	2.410	2.592
Electric Power - kWh		$.05	.856	-.004	7.101	-.033
Diesel Fuel - kg		$.35	.049	.049	.407	.407
Direct Labor 1 hours		$12.0	.008	.007	.070	.061
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r						
Wood Logs	r1		2.18	1.40	18.08	11.65
Incineration Fuel	r30		0	0	0	0
Methane	r32		0	0	0	0
Energy Conversion Rates						
kg Crude Oil:						
/kg Natural Gas	o3	.98				
/kg Fuel Oil	o4	1.18				
/kWh Electric		.28				
/kg Diesel Fuel	o13	1.18				
Feedstock and Byproduct Conversion Rates						
kg Crude Oil:						
/kg Wood Logs	r1	0				
/kg Incin. Fuel	r30	-1.18				
/kg Methane	r32	-.98				
Energy - kg Crude Oil			.641	.424	5.319	3.519
Feedstock - kg Crude Oil			0	0	0	0
Total - kg Crude Oil			.641	.424	5.319	3.519

Polystyrene Cup Manufacturing, Use and Disposal

Disposal Case:			E	F	E	F
Incineration disposal			10%	0%	10%	0%
Electric Generation dispsl.			10%	50%	10%	50%
Landfill disposal			70%	0%	70%	0%
Recycling disposal			10%	50%	10%	50%
Products y_o		P_o				
Beverage Servings			417	417	1000	1000
Plastic cups-kg	o13		1	1	2.40	2.40
Polystyrene-kg	o1	$.70	1	1	2.40	2.40
Polyst.Recycle-kg	o2		.10	.50	.24	1.20
Polystyrene Mfg. Cash Flow			$.17	$.40	$.42	$.95
Polystyrene Mfg. Value Added			$.10	$.35	$.25	$.83
System Energy $y_o * X_o$		P_e				
Natural Gas - kg		$.25	0	0	0	0
Fuel Oil - kg		$.25	.725	.403	1.740	.966
Electric Power - kWh		$.05	-.034	-1.570	-.082	-3.768
Diesel Fuel - kg		$.35	.095	.087	.228	.209
Direct Labor 1 hours		$12.0	.008	.007	.019	.017
Direct Labor 2 hours		$.00	0	0	0	0
System Resources y_r						
Propane	r1		3.8700	2.1500	9.2880	5.1600
Ethane	r2		.3110	.1728	.7464	.4147
Pentane	r6		.0400	.0400	.0960	.0960
Toluene	r8		.9288	.5160	2.2291	1.2384
Aromatics	r9		.7353	.4085	1.7647	.9804
Other fractions	r10		1.1223	.6235	2.6935	1.4964
Hydrocarbon prod.	r11		.0680	.0378	.1632	.0907
Fuel	r24		0	0	0	0
Energy Conversion Rates						
kg Crude Oil:						
/kg Natural Gas	o3	.98				
/kg Fuel Oil	o4	1.18				
/kWh Electric		.28				
/kg Diesel Fuel	o5	1.18				
Feedstock and Byproduct Conversion Rates						
kg Crude Oil:						
/kg Propane	r1	.98				
/kg Ethane	r2	.98				
/kg Pentane	r6	.98				
/kg Toulene	r8	-.98				
/kg Aromatics	r9	-.98				
/kg Fractions	r10	-.98				
/kg HC Products	r11	-.98				
/kg Incin. Fuel	r24	1.18				
Energy - kg Crude Oil			.955	.133	2.291	.318
Feedstock - kg Crude Oil			1.340	.762	3.216	1.828
Total - kg Crude Oil			2.294	.894	5.507	2.147

Case B examines 100% incineration of used packaging and waste paper trimmings. Case C examines the option where 100% of used packaging and waste paper trimmings are burned to generate electric power. Case D examines 100% recycling of both used packaging and of waste paper trimmings.

Cases E and F in Tables 39 and 40 examine two scenarios for the use of mixed disposal policies, one case approximating current practice, and another case approximating a realistic medium term policy scenario. During the period of 1990-1992 disposal practices have been changing rapidly with the advent of widespread municipal and volunteer recycling programs for paper, plastic and glass. It is difficult to assess what the exact level of materials being recycled may be at the time this dissertation is written. Many materials are accumulating in inventories for lack of reprocessing facilities or markets for end products [33]. One estimate reports over 36% of paper in general being recycled in 1991 [34]. Case E is based on reasonable assumptions about what disposal policies may have looked like during the 1980's. This case specifies 10% incineration, 10% disposal through electric power generation, 70% disposal through landfill, and 10% disposal through recycling. Case F examines a scenario which might practically be attained as a policy objective; 50% use in electrical generation and 50% recycling. In these mixed disposal cases it has been assumed that all waste paper trimmings from paper cup manufacture are recycled.

7.2 Comparison of Resource Requirements

Referring to Tables 35, 37 and 39, resource and residual material flows $\dot{y}_r$ are given for each disposal alternative in columns A, B, C, D, E and F for both paper and polystyrene. Cases A, B and C (zero recycling) all result in identical resource requirements and emissions. On either a mass basis, Table 35, or a volume basis, Table 37, the inputs of inorganic chemicals r1-r8 for paper manufacture are distinctly lower in quantity and variety than those for polystyrene manufacture, r3-r5. Air emissions, and water effluent, r14-r27 and r32 for paper, and r12-r22 for polystyrene, are also substantially lower for polystyrene. Notice that methane emissions from landfill disposal, r32, and leachate r33, are not modeled here due to the great variability caused by differing landfill sites and lack of data. As discussed earlier, CO_2 emissions have not been modeled at this point of analysis, but will be discussed in a separate section below. The landfill mass and volume after compaction are nearly the same for paper and polystyrene on a unit mass basis, Table 35, r34 and r26. But on a per unit package basis, Table 37, polystyrene has an advantage of requiring about 1/4 of the landfill resources.

The use of recycling disposal, in cases D, E and F, Tables 35, 37 and 39, reduces or eliminates the inorganic chemical resource requirements, air emissions, water effluents, and landfill requirements for all but a few variables, which remain similar or unchanged. The effect of recycling is most dramatic for the 100% recycling of polystyrene where many resources and effluents are eliminated completely.

The primary resource flow for paper production, wood logs r1, remains unchanged for cases A, B and C, but is reduced by 83% in case D, 100% recycling, and by lesser but important amounts in the mixed disposal cases E and F. Thus recycling can conserve forest resources. The primary feedstocks for polystyrene manufacture are propane and ethane, r1 and r2, with marketable byproducts r8-r11. These flows remain constant for disposal cases A, B and C and are completely eliminated in case D of 100% recycling. Mixed disposal cases E and F produce intermediate results.

Water, r2, is a primary resource in paper production for both process use and for cooling. In polystyrene production water is used for cooling. On a mass basis water requirements are nearly the same for both products in cases A, B and C. Cooling water requirements for polystyrene are eliminated for 100% recycling.

7.3 Comparison of Energy Requirements

System energy is defined as the total energy requirements of the network, $\dot{y}_0 * X_0$. In all of these example cases fuel oil has been chosen as the combustion energy source. The fuel oil requirements for cases A, B and C are identical. Paper manufacture requires 10% more fuel oil than reported by Hocking since his analysis neglected the material loss due to waste paper trimmings in cup manufacture. Polystyrene fuel requirements are very close to those reported by Hocking [41]. Note that on a mass basis in Table 37, polystyrene manufacture requires almost three times as much fuel oil, but that on a per unit package basis (per cup) the requirement is about 15% less for polystyrene. Essentially, the manufacture of polystyrene cups uses less petroleum energy than paper cups, and does not require the harvest of trees. This is the dramatic result that caused such widespread interest and controversy in Hocking's original analysis [35]. However, Hocking's work did not include a full system life-cycle network assessment, including transportation, use, disposal and recycling options which follow.

In case D 100% recycling is examined. On both a mass basis and a per cup basis, Tables 35 and 37, no fuel oil is required for the production of recycled polystyrene material. But fuel oil required for recycled paper manufacture actually *increases* by 21% compared to manufacture of virgin paper. This is a most surprising and profound result of this processes network analysis, and is directly contrary to the current beliefs of policy makers, paper manufacturers, and the public. How this happens can be understood by considering the material and energy cycles in the paper network. In virgin paper manufacture, 56% of the energy is derived from the combustion of waste wood and bark and the combustion of lignins in the byproduct "black liquor" associated with pulp manufacturing in processes 9 and 10. These energy sources have been "stripped off" from the remaining cellulose fiber that constitutes the paper product. Thus repulping paper in process 2 does not contribute any energy from the combustion of waste byproducts. Despite the lower fuel oil requirement for repulping paper in process 2 this results in a *net increase* in fuel oil energy. The mixed disposal cases for paper, E and F in Table 39, also result in net increases of fuel oil requirements compared to the landfill, electric power generation and incineration cases. Thus from the standpoint of fuel oil requirements, recycling is always preferred for polystyrene. On the other hand, landfill, incineration or electric power generation are equally preferred for paper. With regard to the choice between materials, on a mass basis paper is preferred to polystyrene for cases A, B and C, but in case D polystyrene is preferred. On a per cup basis, polystyrene is always preferred, with 100% recycling of polystyrene dominating all alternatives.

Electric power requirements are also of great interest. For cases A and B, landfill and incineration disposal, electric power requirements are the same; 1.099 kWh for paper and about one third the amount, .35 kWh for polystyrene on a mass basis in Table 35.

On a per cup basis in Table 37, polystyrene requires less than 1/10 of the electric power of paper. In case C, where all waste paper and polystyrene is burned to generate electric power, there is actually a *net production* of electric power by the full system of manufacture, use and disposal. On a mass basis in Table 35, case C produces .936 kWh of electric power for paper and over three times as much, 3.35 kWh for polystyrene. On a per cup basis in Table 37, electric power production is almost equal at 7.77 kWh and 8.04 kWh respectively. Examining case D, 100% recycling, reveals that electric power consumption is reduced by about 1/3 compared with landfill and incineration cases A and B. Thus from the standpoint of electric power, the optimum disposal case is always combustion for power generation with recycling the second choice, and polystyrene is always preferred to paper.

Diesel fuel for transportation in the full system model amounts to about 10-20% of the quantity of fuel oil petroleum required for manufacture, depending on the case. This is important to note since it was supposed before beginning the analysis that transportation fuel might dominate the fuel requirements of manufacturing. Even under the assumptions of relatively long transportation distances in this model, and the use of highway truck rather than more efficient rail transportation, diesel fuel still plays a relatively minor role. On a mass basis, polystyrene uses about twice as much transportation fuel as paper because of the assumptions for ethane and benzene and the lower density of polystyrene. On a per cup basis, polystyrene uses about half as much diesel fuel. Recycling reduces the diesel fuel requirements slightly by eliminating ethane and benzene transport requirements.

Under the assumptions presented here, paper and polystyrene have about the same direct labor requirements on a mass basis, but polystyrene has one third the labor requirement on a per cup basis. Labor requirements fall by about 1/3 under the recycling case D.

7.4 Comparison of Crude Oil Equivalent Energy Use

It is apparent from the discussions in the previous two sections that comparison of trade offs in material and energy resource utilization is complex. No choice of product or disposal option dominates under all criteria. The choice depends very much on the available resource bases.

In an economy like France, without available forest resources or petroleum and with abundant nuclear power, polystyrene with 100% recycling would be chosen on either a mass basis or a per cup basis. This option eliminates the forest resource requirement with a modest electrical power and petroleum requirement. Such a choice could also apply to an economy like Saudi Arabia, without forests, but with currently abundant petroleum.

In an economy like Sweden, with extensive forest resources, but no petroleum and a policy to eliminate nuclear power generation, or an economy like Canada or Russia with extensive forests and currently abundant petroleum, or an economy like the U.S. with limited forests and nuclear power and little remaining petroleum, the choice becomes far more complex. The analysis is complicated further since petroleum-based ethane and propane are feedstocks for polystyrene manufacture and useful petroleum-based byproducts are produced also.

One way to consolidate the analysis is to convert all energy and feedstocks to crude oil equivalents and then compare the crude oil petroleum requirements and forest resource requirements of the two products and their disposal alternatives. This has been done in Tables 36, 38 and 40. System energy and primary resources are presented as in Tables 35, 37 and 39, and conversion rates for natural gas, fuel oil, electric power and diesel fuel to crude oil equivalents are shown as derived from Erskine [43] and Austin [42]. This analysis assumes that all electric power is generated by petroleum combustion rather than nuclear generation. This is currently a reasonable case to explore since nuclear power plants currently account for less than 10% of world power generation and few new nuclear plants are being built. In the bottom three lines of each table the crude oil equivalents for the energy requirements, the feedstock resources, and the total crude oil equivalents are presented.

Table 36 shows this information per kg mass of packaging material. Referring first to the paper case, it is clear that option C, electric power generation, and option D, 100% recycling, are the preferable choices. Option C has the lowest crude oil requirement, at .122 kg but requires 2.57 kg of wood logs. Option D has nearly the same crude oil requirement, .676 kg, as A and B, but requires only 1/6 of the wood resources, .44 kg. For polystyrene the 100% recycling option D clearly dominates all others, requiring only .189 kg of petroleum. The choice between paper and polystyrene now comes into focus also. If forest resources are constrained or not available, polystyrene option D with its crude oil requirement of .189 kg would be chosen. Compared to polystyrene D, the 100% recycling of paper, option D, should never be chosen since it requires 3.5 times the crude oil and .44 kg of wood logs in addition. However with a resource base with abundant forests it may be desirable to choose paper option C, electric power generation, over polystyrene option D. In this case the 2.57 kg of wood logs are being utilized to reduce the crude oil requirement for the packaging material from .189 kg to .122 kg.

This illustrates another very important result. With the technology modeled here, the energy required for paper manufacture *cannot* be supplied only from the wood being harvested for the material requirement, even if all of the waste paper is combusted for energy retrieval -- an additional .122 kg of crude oil equivalent energy is required. This energy could be attained by harvesting more trees for steam generation or the displacement of crude oil powered electrical power generation to provide equivalent transportation fuel. But paper production in itself is not energetically self sufficient as modeled here. Hocking notes that some modern paper production facilities attain as much as 70% of their process energy from waste wood and bark, rather than the average of 56% used here. Under these conditions, option C would come close to be energetically self sustained through the harvest of trees alone on a life-cycle basis, but only if the paper products are burned for combustion fuel after use, not if they are recycled. Recycling, option D, simply substitutes petroleum for a reduced wood requirement. At a time when industry, policy makers and the public have assumed that paper should always be recycled, and are engaging in large scale programs to recycle paper, this is perhaps the most dramatic finding of this research.

Table 38 compares crude oil equivalents on a per cup basis. Paper with disposal options A and B has nearly the same crude oil requirement as polystyrene under options A and B, but of course polystyrene does not require the harvest of trees. As before, paper options C and D reflect a trade off between minimizing petroleum requirements and the amount of wood harvested. Because of the lower mass required per cup, polystyrene option D uses .454 kg of crude oil, about half the 1.013 kg of crude oil required by paper option C, and does not require the harvest of trees. So on a per package basis (per cup) 100% recycling of polystyrene is always the preferred product and disposal option, irrespective of the resource base.

Mixed disposal cases E and F are shown in Table 40. Crude oil and wood requirements are always lower for case F, so it is always preferred to case E for either paper or polystyrene, on either a mass basis or a per cup basis. On a mass basis, paper case F requires .424 kg of crude oil and 1.4 kg of wood versus .894 kg of crude oil for polystyrene case F, resulting in a trade off between forest resources and petroleum. On a per cup basis, polystyrene case F is always preferred since it has about 60% of the energy requirement of paper case F, but requires no wood.

Compared with polystyrene case F, polystyrene case D, 100% recycling, is always preferred on both a mass and per cup basis. Paper case F is an intermediate case between paper C and D, and reflects the same trade off between the use of petroleum and wood.

7.5 Comparison of Carbon Dioxide Emissions

The role of carbon dioxide (CO_2) in atmospheric change and the threat of global warming is of great contemporary importance. As reported earlier, carbon dioxide emissions were not incorporated as coefficients in the examples presented here. CO_2 data for each of the individual combustion process is difficult to obtain in a consistent fashion and was not included in Hocking's analysis. However, the crude oil equivalent data provide a comprehensive and accurate means to compare CO_2 emissions for the products and disposal options. Since petroleum products and natural gas are all hydrocarbons, the release of energy in combustion converts these hydrocarbon chains into carbon dioxide and water. (Carbon monoxide may also be produced, but it reacts in the atmosphere to form CO_2 in a relative short time). So, in general, the carbon dioxide released will be directly proportional to the crude oil equivalent mass of fuel undergoing combustion, and thus to the energy produced.

For polystyrene this allows a very simple comparison. Polystyrene manufacture has two petroleum requirements, process energy and petroleum feedstocks. All of the process energy fuel will be converted proportionally to carbon dioxide. Part of the mass of the feedstock may convert to CO_2 during process reactions, with the remainder forming the mass of the finished product. In Table 36 the total crude oil for polystyrene case A is 2.645 kg. Of this, a mass of 1.0 kg remains in the used cup. In the landfill case, this 1.0 kg is buried and will not release CO_2. Thus the net CO_2 released to the atmosphere is proportional to 1.645. In cases B and C the waste polystyrene is burned, and CO_2 will be released proportionally to the total crude oil equivalent of 2.645 and 1.6 respectively. (In case C, the generation of electric power by burning the waste polystyrene reduced the fuel oil required for power generation). In case D, 100% recycling, the only CO_2 released will come from the combustion energy of .150 kg. On either a mass basis or a per cup basis (Table 38), 100% recycling will always be preferred, resulting in 5-10% of the CO_2 emissions of the other alternatives.

In paper manufacture and use there are two CO_2 emission sources to consider; combustion of petroleum for process energy, and the growth, combustion and disposal of wood and paper. CO_2 emissions for process energy will be proportional to the crude oil equivalent for process energy, which for paper is the same as the total kg of crude oil equivalent. Case C, electric generation disposal is clearly the preferred option, having about 20% of the CO_2 emissions of the other alternatives.

Accounting for CO_2 emissions related to wood is more complex. Referring to Table 36, in case A, landfill disposal, 2.57 kg of wood logs are harvested for each 1.1 kg of paper. Ignoring the relatively minor loss of cellulose mass in water effluent, this means that a total of 1.47 kg of wood mass has been burned in processes 9 and 10 internal to the manufacturing enterprise. The remaining 1.1 kg is buried in the landfill as waste paper. If wood is being grown at the same rate as it is being harvested, the CO_2 uptake by the growing trees will be proportional to 2.57. The CO_2 released by combustion will be in the same proportion to 1.47. If the conditions in the landfill are such that all of the 1.1 kg of waste paper decomposes aerobically into CO_2, then there will be a neutral CO_2 balance for the system as a whole and no net change in atmospheric CO_2. If more wood is harvested than is regrown, there will be a net increase in CO_2 levels since the inventory of CO_2 trapped in the forest wood will be released into the atmosphere. (This argument ignores the controversy surrounding the dynamics of CO_2 cycles in the biosphere -- increased atmospheric CO_2 levels may cause increased rates of plant growth, pushing the system toward a new equilibrium). Likewise, if the landfill conditions are anaerobic such that decomposition does not take place, the CO_2 fixed in the 1.1 kg of waste paper will be removed from the cycle of the biosphere, resulting in a net reduction of atmospheric CO_2 levels.

Cases B and C both call for combustion of the 1.1 kg of waste paper, releasing the same amount of CO_2 as had originally been fixed in the growth of this 1.1 kg of wood mass. In case D, 100% recycling, the .44 kg of wood mass required for make up of losses in repulping is partially combusted in processes 9 and 10 and partially lost as water effluent in repulping. This lost effluent can be expected to decompose, so again the net CO_2 change in the atmosphere will be neutral if wood is grown at the same rate as it is harvested.

If the above scenarios for the CO_2 cycle for wood are taken to be neutral, then the comparison of materials becomes a comparison of the emissions from petroleum combustion. On a mass basis, for paper the preferred choice is C at .122 kg, and for polystyrene the preferred choice is D at .150 kg, approximately the same. On a per cup basis polystyrene again has clearly superior CO_2 emissions at .360 kg for case D, while paper is proportional to 1.013 kg in case C.

Thus from the perspective of CO_2 emissions, it may be concluded that under conditions of sustained wood regrowth and complete combustion or decomposition of waste paper, recycling polystyrene is equivalent to or preferred to electrical power generation with waste paper.

7.6 Comparison of Economic Results

In Tables 35, 37 and 39 the cash flow and value added are given for each of the disposal options. Cases A, B and C all report the same result for each product respectively since these disposal options do not effect the material and energy flows of the manufacturing enterprise itself. It is interesting to note the figures for case D, 100% recycling. Under the price assumptions used here, recycling always results in a dramatic increase in both cash flow and value added. This occurs primarily because the waste paper and polystyrene materials, o2, for recycling have a price of $.00; that is they are free. This in fact corresponds to market conditions of the last several years for paper and plastics. In some cases, manufacturers are being *paid* to take recyclable materials in the face of rising landfill disposal costs and lack of availability of sites. As recently as 1979, better quality used news print was purchased for $80 per ton. In 1991 manufacturers were being paid $20 per ton to take it [48]. In the case of polystyrene cash flow and value added are further enhanced by the reduction in energy required to produce product from recycled material. The recycling of paper does not enjoy this advantage.

8 CONCLUSIONS AND POLICY IMPLICATIONS FOR THE USE OF PAPER AND POLYSTYRENE PACKAGING MATERIALS

It is believed that the application of the above paradigm is essential for the future success of manufacturing enterprises of all types and the successful functioning of the national and global economies which encompass them. *Specifically, during the decade and century ahead economies and the enterprises of which they are composed will function in a world with ever scarcer energy and material resources and the design and production of products will be further constrained by their life cycles and disposal or recycling within the economic system and stress-sensitive natural environments.* These challenges require the development of an integrated theory for the analysis of alternative designs and production processes which explicitly incorporates the flows and stocks of materials, energy, and knowledge/skill specific human time, and provides a consistent framework for analysis of product designs, production processes, enterprise management and life-cycle assessment.

The complexity of trading off the merits and demerits in a life-cycle assessment is illustrated by the results and discussion presented in the preceding sections. Certainly several conclusions are quite direct.

- On the basis of water effluents, polystyrene causes only a fraction of the loading incurred by paper.
- Air emissions are similar per kg of virgin packaging material produced, primarily because of the combustion of fuels for process and transportation energy. Refinery emissions have not been accounted for in this analysis, but since the crude oil

equivalent use of petroleum is so similar (per kg), these too should be comparable. Polystyrene recycling, requiring relatively little energy and materials is clearly a superior choice by this criterion.

- Either landfill burial or incineration of either product is very wasteful of petroleum and of forest resources in the case of paper. Unfortunately these disposal methods account for the majority of past and current practice. Although generation of electric power from municipal waste is practiced in the U.S., it seemingly deserves a far greater role in both petroleum conservation and landfill abatement. As this is written, it remains a mystery why coal burning electric utilities are not firing their boilers with the enormous supplies of free used newsprint that are being collected; much of which is being hauled to landfills for lack of repulping capacity. Co-fueling of coal fired power plants with paper should be straightforward and could be expected to decrease emissions, especially of sulfur. Burning polystyrene and mixed municipal waste cleanly can be done, but requires more specialized combustion technology.
- There is a distinct trade-off of forest resources for petroleum required for the most favorable paper alternatives, electric power generation and recycling. This trade off does not seem to be appreciated in the literature nor in the decisions of policy makers and the industry.
- On a per kg basis, recycling polystyrene uses 50% more petroleum than paper, but has no wood requirement. Because of its superior mechanical properties and low density for some types of packaging functions, recycling polystyrene will be a clear choice for those functions where the per container weight is lower.

- The discussion of petroleum requirements applies directly to CO_2 emissions. The lower the petroleum requirement the lower will be carbon dioxide loading. This assumes that wood is grown at the same rate it is harvested [38], [53].
- Other sources of cellulose fiber such as hemp [39] may prove more efficient than the wood varieties now employed, and should be analyzed in a life-cycle context.
- Paper cups currently sell (at wholesale) for 2-3 times the price of polystyrene cups [49]. In examining the resource requirements, it is apparent why this is so. Recall that the cash flow and value added calculations are on the basis of kg of product produced.
- Transportation fuels play a relatively minor role in petroleum use and emissions in these life-cycle assessments, 10-20%, even under the liberal assumptions for transportation distances and the use of fuel inefficient truck transport. This is a surprising result that is contrary to what was anticipated before the analysis.
- For drinking beverages, neither product is necessary, and could be eliminated entirely. Ceramic eating and drinking vessels have been found in the earliest known human habitats, and were still rather popular until the 1960's. And humans obviously have utilized and cleaned ceramic vessels for millennia without the benefit of petroleum or the resource chemicals required for drinking beverages from paper or polystyrene cups. Other packaging uses of paper and polystyrene however may be more technically unique or beneficial. The choice between the two materials for the enormous variety of other packaging applications may depend on their merits as substitutes as well as their relative densities, and upon other suitable materials, metal, aluminum or solid wood containers, for example.

- The overriding policy implication of this work is that it is not safe to assume that materials should always be recycled. For some materials like polystyrene, recycling makes sense under all conditions, but given some resource bases and package characteristics it may make far more sense to use a paper product once and then burn it to generate electric power. Case by case comparison of materials and disposal methods is required to insure that manufacture, use, disposal and recycling decisions make the wisest use of the available resource bases.

9 SUGGESTIONS FOR FURTHER RESEARCH

The most interesting opportunity to improve on the work and results presented here will be to obtain more accurate information for the energy requirements for paper repulping and reheating polystyrene to its molten state. The assumptions presented are probably higher for each process than actual energy use. Lower assumptions will not change the choices and trade-offs presented since the contrasts are in the orders of 2, 5, and 10. Such information could be obtained through instrumented measurements on actual processing equipment, and may be available in the engineering operating records of some plants.

Another opportunity to improve on this work would be to model the production of the inorganic chemicals that are used as resources for paper production. Inclusion of these energetic costs and environmental loadings will only make paper look less favorable than polystyrene.

Paper has been produced for at least 4000 years, long before the discovery of petroleum, with a variety of technologies. It would be interesting to examine the life-cycle of paper production technologies that utilized only renewable forest resources.

And, as mentioned in the Conclusions above, what is really needed for resource utilization, product, and disposal decisions is the development of "libraries" of process network models for products and technologies so that material flows, energetic costs, and economic variables can be compared with resource bases and constraints. Wise decisions require these more comprehensive and specific analyses.

Personal future research interests of the author, stemming from the work presented in this dissertation, include:

- Further extensions of process network models of physical and biological transformations and exchanges to include the functioning of ecological systems and the interactions between human made and natural systems.

- Investigation of the source-specific net energy efficiency, thermodynamics, and material resource requirements of economic systems at macroeconomic levels of structure and functioning. It is believed that such developments can provide insight into issues surrounding "Sustainable Economics" and "Sustainable Agriculture".

- Investigation of the roles of finance, social and political processes, and public policy in the macroeconomic structure, resource and energy requirements of economies.

- Further investigation of "material-energy balance" problems of complex systems in chemistry and chemical engineering in the context of process network theory.

APPENDIX

APPENDIX

PC Matlab Programs For Process Network Calculations

```
% PROGRAM TO CALCULATE PROCESS NETWORK FOR PAPER
% MANUFACTURING
diary testout1
% Program CALCPAP1.M
clear
echo on
load Klb.txt
load Klo.txt
load Krb.txt
load Kro.txt
load yo.txt
load Xr.txt
load Fb.txt
load Fo.txt
load A.txt
load go.txt
load ce.txt
load gs.txt
load ge.txt
load os.txt
load oe.txt
load pr.txt
load po.txt
load pe.txt
load gba.txt
load goa.txt
%Calculate the K matrices
[m,n]=size(A*Klb)
Kb=inv(eye(n)-A*Klb)*A*Klo
Ks=(Krb*Kb)+Kro
KlbKlo=[Klb Klo]
%Calculate Energies
invIKA=inv(eye(n)-Klb'*A')
% Make Xr conformable for inclusion of steam energy in Fb Fo
```

```
[p,q]=size(Xr)
Xrst=[zeros(p,1) Xr]
Xb=-invIKA*Krb'*Xrst-invIKA*Fb
Xl=-A'*Xb
Fsst=(Kb'*Fb)+Fo
%Convert steam and electric to natural gas and/or fuel oil requirements for Fs
Fs=Fsst
Fs(1,2)=(Fsst(1,1)*gs*go)+(Fsst(1,4)*ge*go*ce)
Fs(1,3)=(Fsst(1,1)*os*(1-go))+(Fsst(1,4)*oe*(1-go)*ce)
Fs(1,4)=(Fsst(1,4)*(1-ce))
Fs(2,2)=(Fsst(2,1)*gs*go)+(Fsst(2,4)*ge*go*ce)
Fs(2,3)=(Fsst(2,1)*os*(1-go))+(Fsst(2,4)*oe*(1-go)*ce)
Fs(2,4)=(Fsst(2,4)*(1-ce))
Fs=Fs(:,2:7)
Xo=-(Ks'*Xr)-Fs
%Include calculated gas and oil in yo vector
e=yo'*Fs
yo(3,1)=e(1,1)
yo(4,1)=e(1,2)
%Calculate y variables
yr=Ks*yo
yb=Kb*yo
ybyo=[yb;yo]
yl=KlbKlo*ybyo
e=yo'*Fs
exo=yo'*Xo
% Calculate cash flow and value added
Cf=(yo'*po)-(yr'*pr)-(e*pe)
Gsa=(Kb'*gba)+goa
Vs=Cf-(yo'*Gsa)
%Output data to file
%Enter diary output file name if desired - then RETURN
diary OUTPAP1A
%keyboard
echo off
KlbKrb=[Klb
        Krb]
KloKro=[Klo
        Kro]
Kb
Ks
A
go
ce
gs
```

```
os
ge
oe
yl
yr
yb
yo
Xb
Xo
Xl
Xr
Xrst
Fb
Fo
Fsst
Fs
e
exo
pr
po
pe
gba
goa
Gsa
Cf
Vs
diary off
echo on
%Enter diary Ks output file name if desired - then RETURN
diary KSPAP1A
%keyboard
echo off
Ks
diary off
echo on
%Enter diary Fs output file name if desired - then RETURN
diary FSPAP1A
%keyboard
echo off
Fs
diary off
echo on
%Enter diary REPORT output file name if desired - then RETURN
diary REPPAP1A
%keyboard
```

```
echo off
yr
yo
Xo
Fsst
Fs
e
exo
Gsa
Cf
Vs
diary off
echo on
%Enter SAVE PAPER1A output file name if desired - then RETURN
save PAPER1a
%keyboard
% End of calculation file
```

```
% PROGRAM TO CALCULATE PROCESS NETWORK FOR PAPER
% MANUFACTURING, USE AND DISPOSAL
diary testout2
% Program CALCAPAP2.M
clear
echo on
load Klb.txt
load Klo.txt
load Krb.txt
load Kro.txt
load yo.txt
load Xr.txt
load Fb.txt
load Fo.txt
load A.txt
%Calculate the K matrices
[m,n]=size(A*Klb)
Kb=inv(eye(n)-A*Klb)*A*Klo
Ks=(Krb*Kb)+Kro
KlbKlo=[Klb Klo]
%Calculate Energies
invIKA=inv(eye(n)-Klb'*A')
% Make Xr conformable for inclusion of steam energy in Fb Fo
[p,q]=size(Xr)
Xrst=[zeros(p,1) Xr]
Xb=-invIKA*Krb'*Xrst-invIKA*Fb
Xl=-A'*Xb
Fsst=(Kb'*Fb)+Fo
Fs=Fsst
Fs=Fs(:,2:7)
Xo=-(Ks'*Xr)-Fs
%Include calculated gas and oil in yo vector
e=yo'*Fs
yo(2,1)=e(1,1)
yo(3,1)=e(1,2)
yo(4,1)=e(1,4)
%Calculate y variables
yr=Ks*yo
yb=Kb*yo
ybyo=[yb;yo]
yl=KlbKlo*ybyo
%Calculate energy
e=yo'*Fs
exo=yo'*Xo
%Output data to file
```

```
%Enter diary output file name if desired - then RETURN
diary OUTPAP2A
%keyboard
echo off
KlbKrb=[Klb
       Krb]
KloKro=[Klo
       Kro]
Kb
Ks
A
yl
yr
yb
yo
Xb
Xo
Xl
Xr
Xrst
Fb
Fo
Fsst
Fs
e
exo
diary off
echo on
%Enter diary REPORT output file name if desired - then RETURN
diary REPPAP2A
%keyboard
echo off
yr
yb
yo
Xo
Fsst
Fs
e
exo'
diary off
echo on
%Enter SAVE PAPER2A output file name if desired - then RETURN
save PAPER2A
%keyboard % End of calculation file
```

```
% PROGRAM TO CALCULATE PROCESS NETWORK FOR POLYSTYRENE
% MANUFACTURE
diary testout1
% Program CALCSTY1.M
clear
echo on
load Klb.txt
load Klo.txt
load Krb.txt
load Kro.txt
load yo.txt
load Xr.txt
load Fb.txt
load Fo.txt
load A.txt
load go.txt
load ce.txt
load gs.txt
load ge.txt
load os.txt
load oe.txt
load pr.txt
load po.txt
load pe.txt
load gba.txt
load goa.txt
%Calculate the K matrices
[m,n]=size(A*Klb)
Kb=inv(eye(n)-A*Klb)*A*Klo
Ks=(Krb*Kb)+Kro
KlbKlo=[Klb Klo]
%Calculate Energies
invIKA=inv(eye(n)-Klb'*A')
% Make Xr conformable for inclusion of steam energy in Fb Fo
[p,q]=size(Xr)
Xrst=[zeros(p,1) Xr]
Xb=-invIKA*Krb'*Xrst-invIKA*Fb
Xl=-A'*Xb
Fsst=(Kb'*Fb)+Fo
%Convert steam and electric to natural gas and/or fuel oil requirements for Fs
Fs=Fsst
Fs(1,2)=Fsst(1,2)+(Fsst(1,1)*gs*go)+(Fsst(1,4)*ge*go*ce)
Fs(1,3)=Fsst(1,3)+(Fsst(1,1)*os*(1-go))+(Fsst(1,4)*oe*(1-go)*ce)
Fs(1,4)=(Fsst(1,4)*(1-ce))
Fs(2,2)=Fsst(2,2)+(Fsst(2,1)*gs*go)+(Fsst(2,4)*ge*go*ce)
```

```
Fs(2,3)=Fsst(2,3)+(Fsst(2,1)*os*(1-go))+(Fsst(2,4)*oe*(1-go)*ce)
Fs(2,4)=(Fsst(2,4)*(1-ce))
Fs=Fs(:,2:7)
Xo=-(Ks'*Xr)-Fs
%Include calculated gas and oil in yo vector
e=yo'*Fs
yo(3,1)=e(1,1)
yo(4,1)=e(1,2)
yo(5,1)=e(1,4)
%Calculate y variables
yr=Ks*yo
yb=Kb*yo
ybyo=[yb;yo]
yl=KlbKlo*ybyo
e=yo'*Fs
exo=yo'*Xo
% Calculate cash flow and value added
Cf=(yo'*po)-(yr'*pr)-(e*pe)
Gsa=(Kb'*gba)+goa
Vs=Cf-(yo'*Gsa)
%Output data to file
%Enter diary output file name if desired - then RETURN
diary OUTSTY1A
%keyboard
echo off
KlbKrb=[Klb
        Krb]
KloKro=[Klo
        Kro]
Kb
Ks
A
go
ce
gs
os
ge
oe
yl
yr
yb
yo
Xb
Xo
Xl
```

```
Xr
Xrst
Fb
Fo
Fsst
Fs
e
exo
pr
po
pe
gba
goa
Gsa
Cf
Vs
diary off
echo on
%Enter diary Ks output file name if desired - then RETURN
diary KSSTY1A
%keyboard
echo off
Ks
diary off
echo on
%Enter diary Fs output file name if desired - then RETURN
diary FSSTY1A
%keyboard
echo off
Fs
diary off
echo on
%Enter diary REPORT output file name if desired - then RETURN
diary REPSTY1A
%keyboard
echo off
yr
yo
Xo
Fsst
Fs
e
exo
Gsa
Cf
```

```
Vs
diary off
echo on
%Enter SAVE PLAST1A output file name if desired - then RETURN
save plast1a
%keyboard
% End of calculation file
```

```
% PROGRAM TO CALCULATE PROCESS NETWORK FOR POLYSTYRENE
% MANUFACTURING, USE AND DISPOSAL
diary testout2
% Program CALCSTY2.M
clear
echo on
load Klb.txt
load Klo.txt
load Krb.txt
load Kro.txt
load yo.txt
load Xr.txt
load Fb.txt
load Fo.txt
load A.txt
%Calculate the K matrices
[m,n]=size(A*Klb)
Kb=inv(eye(n)-A*Klb)*A*Klo
Ks=(Krb*Kb)+Kro
KlbKlo=[Klb Klo]
%Calculate Energies
invIKA=inv(eye(n)-Klb'*A')
% Make Xr conformable for inclusion of steam energy in Fb Fo
[p,q]=size(Xr)
Xrst=[zeros(p,1) Xr]
Xb=-invIKA*Krb'*Xrst-invIKA*Fb
Xl=-A'*Xb
Fsst=(Kb'*Fb)+Fo
Fs=Fsst
Fs=Fs(:,2:7)
Xo=-(Ks'*Xr)-Fs
%Include calculated gas and oil in yo vector
e=yo'*Fs
yo(2,1)=e(1,1)
yo(3,1)=e(1,2)
yo(4,1)=e(1,4)
%Calculate y variables
yr=Ks*yo
yb=Kb*yo
ybyo=[yb;yo]
yl=KlbKlo*ybyo
%Calculate energy
e=yo'*Fs
exo=-yo'*Xo
%Output data to file
```

```
%Enter diary output file name if desired - then RETURN
diary OUTSTY2A
%keyboard
echo off
KlbKrb=[Klb
        Krb]
KloKro=[Klo
        Kro]
Kb
Ks
A
yl
yr
yb
yo
Xb
Xo
Xl
Xr
Xrst
Fb
Fo
Fsst
Fs
e
exo
diary off
echo on
%Enter diary REPORT output file name if desired - then RETURN
diary REPSTY2A
%keyboard
echo off
yr
yb
yo
Xo
Fsst
Fs
e
exo'
diary off
echo on
%Enter SAVE PLAST2A output file name if desired - then RETURN
save PLAST2A
%keyboard  % End of calculation file
```

LIST OF REFERENCES

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[1] H.E. Koenig and R.L. Tummala, "Principles of ecosystem design and management," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-2, No. 4, pp. 449-459, Sept. 1972.

[2] R.L. Tummala and L.J. Connor, "Mass-energy based economic models," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-3, No. 6, pp. 548-555, Nov. 1973.

[3] B.E. Koenig, "Economic systems as cybernetically controlled networks of physical and biological processes," *Proceedings of the 1990 IEEE Conference on Syst. Man Cybernetics.*, Paper No. A0070, Nov. 1990

[4] B.E. Koenig and R.L. Tummala, "Enterprise Models for the Design and Management of Manufacturing Systems", *Joint US/German Conference on New Directions for Operations Research in Manufacturing*, National Institute for Science and Technology / National Science Foundation Conference, July 30 -31, 1991. in press

[5] R.L. Tummala and B.E. Koenig, "Classes of processes models and their characteristics useful for the design of manufacturing systems," *Proceedings of the 1991 IEEE Conference on Syst. Man Cybernetics.*, Oct. 1991

[6] W.W. Leontief, *Essays in Economics; Theories and Theorizing*. New York: Oxford University Press, 1966.

[7] W.W. Leontief, *Essays in Economics; Theories, Facts, and Policies*. White Plains, N.Y. : M. E. Sharpe, 1977.

[8] H.R. Varian, *Microeconomic Analysis*, New York: W.W. Norton and Co., 1978

[9] M.A. El-Hodiri and F. Nourzad, "A note on Leontief technology and input substitution," *Journal of Regional Science*, vol. 28, No. 1, pp. 119-120, 1988.

[10] J.M. Henderson and R.E. Quandt, *Microeconomic Theory: A Mathematical Approach*. New York: McGraw-Hill, 1971

[11] R.S. Kaplan, "Management accounting for advanced technological environments," *Science*, vol. 245, 25 August, 1989, pp. 819-823

[12] A.K. Sethi and S.P. Sethi, "Flexibility in manufacturing: A survey," *The International Journal of Flexible Manufacturing Systems*, vol. 2, 1990, pp. 289-328

[13] R.S. Kaplan, *Advanced Management Accounting*, Englewood Cliffs, N.J.: Prentice Hall, 1982

[14] D.W. Fogarty, J.H. Blackstone, Jr., T.R. Hoffmann, *Production & Inventory Management*, Cincinnati, Ohio: South-Western Publishing Co., 1991

[15] J. Orlicky, *Material Requirements Planning*. McGraw-Hill, 1975

[16] J. Browne, J. Harhen, J. Shivnan, *Production Management Systems, A CIM Perspective*. Addison-Wesley, 1989

[17] H.T. Johnson and R.S. Kaplan, *Relevance Lost: The Rise and Fall of Managment Accounting*. Boston, Mass.: Harvard Business School Press, 1987

[18] F.R. Bacon Jr. and T.W. Butler Jr., *Planned Innovation; A dynamic approach to strategic planning and successful development of new products*, 2nd ed., Ann Arbor, Michigan : Industrial Development Division, Institute of Science and Technology, 1988.

[19] J. Kornai and B. Martros, *Non-Price Control*. New York: Elsevier North-Holland, 1981.

[20] E.C. Alocilja, "The application of process network theory in agroecosystems," *American Society of Agricultural Engineers*. 1990 International Winter Meeeting, Paper No. 907578, Dec. 1990

[21] F.A. Dadoun and E.C. Alocilja, "Process network theory in nitrate leaching analysis," *American Society of Agricultural Engineers*. 1990 International Winter Meeeting, Paper No. 907576, Dec. 1990

[22] P.M. Saama, M.A. Schipull and E.C. Alocilja, "Utilization of the process network theory in the analysis of a beef feedlot system," *American Society of Agricultural Engineers*. 1990 International Winter Meeeting, Paper No. 907575, Dec. 1990

[23] B. Barry, J.C. Schäper and E.C. Alocilja, "Process network theory applied to the analysis of irrigation perimeters in Senegal," *American Society of Agricultural Engineers*. 1990 International Winter Meeeting, Paper No. 907580, Dec. 1990

[24] A.R. Tilma, C.B. Tilma and E.C. Alocilja, "Process network theory (PNT) analysis of a swine/crop system," *American Society of Agricultural Engineers*. 1990 International Winter Meeeting, Paper No. 907577, Dec. 1990

[25] E.C. Alocilja, "Process network theory," *Proceedings of the 1990 IEEE Conference on Syst. Man Cybernetics.*, Paper No. A0071, Nov. 1990

[26] Society of Environmental Toxicology and Chemistry, *A Technical Framework for Life-Cycle Assessments.* Workshop Report, Washington, D.C.: Society of Environmental Toxicology and Chemistry, and SETAC Foundation for Environmental Education, Inc., January 1991.

[27] S.W. Biggs, *Material and Energy Balances.* Lafayette, Ind.: Purdue University, 1963

[28] R. Raman, *Chemical Process Computations*, London: Elsevier Science Publishing, 1985

[29] D. Milbank, "Aluminum's envious rivals turn green, rush to show they, too, are recyclable," *The Wall Street Journal*, September 18, 1991, pp. B1

[30] F.E. Allen, "Governors group to urge 200 firms to cut waste by using less packaging," *The Wall Street Journal*, March 15, 1991

[31] F.E. Allen, "McDonald's to reduce waste in plan developed with environmental group," *The Wall Street Journal*, April 17, 1991, pp. B1

[32] The Council For Solid Waste Solutions, "Blueprint for plastics recycling reaches 75 million Americans," *Council News*, June 1991, pp. 1

[33] F.E. Allen, "As recycling surges, market for materials is slow to develop," *The Wall Street Journal*, vol. LXXIII, No. 67, Janurary 17, 1992, pp. A1, A4

[34] P. Sebastian, "Paper chased," *The Wall Street Journal*, April 9, 1992, pp. A1

[35] M.B. Hocking, "Paper versus polystyrene: a complex choice," *Science*, vol. 251, 1 Feb., 1991, pp. 504-505

[36] H.A. Wells, Jr., "Letters; Paper versus polystyrene: Environmental impact," *Science*, vol. 252, 7 June 1991, pp. 1361

[37] N. McCubbin, "Letters; Paper versus polystyrene: Environmental impact," *Science*, vol. 252, 7 June 1991, pp. 1361

[38] R. Cavaney, "Letters; Paper versus polystyrene: Environmental impact," *Science*, vol. 252, 7 June 1991, pp. 1362

[39] B. Camo, "Letters; Paper versus polystyrene: Environmental impact," *Science*, vol. 252, 7 June 1991, pp. 1362

[40] M.B. Hocking, "Letters; Paper versus polystyrene: Environmental impact," *Science*, vol. 252, 7 June 1991, pp. 1362

[41] M.B. Hocking, "Relative merits of polystyrene foam and paper in hot drink cups: Implications for packaging," *Environmental Management*, vol. 251, No. 6, pp. 731-747

[42] G.T. Austin, *Shreve's Chemical Process Industries*, New York: McGraw-Hill, 1984

[43] M.G. Erskine, *Chemical Conversion Factors and Yeilds, Commercial and Theoretical*, Melno Park, California: Chemical Information Services, Stanford Research Institute, 1969

[44] D.M. Himmelblau, *Basic Principles and Calculations in Chemical Engineering*, Englewood Cliffs, New Jersey: Prentice-Hall, 1982

[45] M.B. Hocking, *Modern Chemical Technology and Emission Control*, Berlin, Heidelberg: Springer-Verlag, 1985

[46] R. Greene ed., *Process Energy Conservation*, New York, N.Y.: McGraw-Hill Publications Co., 1982

[47] Jacques Girouard, Engineering Representative, B.F. Goodrich, Geon Vinyl Division, Kitchner, Ontario. Personal communication, Jan. 1992

[48] Based on the author's 5 years of experience in recycled paper insulation manufacturing and highway trucking business.

[49] Paul Purleski, Sales Representive, Gordon Food Services, Grand Rapids, Mich., Personal communication, Feb. 1992

[50] Motor Vehicle Nitrogen Oxides Standard Committee, Assembly of Engineering, National Research Council, *NO_x Emission Controls for Heavy-Duty Vehicles: Toward Meeting a 1986 Standard,*" Washington, D.C.: National Academy Press, 1981

[51] *Encyclopedia of Polymer Science and Engineering*. New York: Wiley Interscience, vol. 8, pp. 26, 1985

[52] *Encyclopedia of Polymer Science and Engineering*. New York: Wiley Interscience, vol. 16, pp. 767, 1985

[53] R. Cavaney, "Trees we can replace, fossil fuels we can't", *The Wall Street Journal*, September 12, 1991