Analytical Tools for Material and Energy Balance, Cash Flow, and Environmental Loads in a Dairy Cattle Enterprise

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ABSTRACT

Analytical tools for the preconstruction technical design and postconstruction management of a dairy enterprise are presented. The enterprise is represented as a network of production processes with alternative operating technologies and scale of operation as technical parameters of environmental loads and cash flow. The operating technologies of the network are represented by material conversion coefficients and energetic cost functions. Generalized laws of material and energy balance are used to define an on-line management accounting system for recording resource and product flows, physical energy, and human time involved in the production process. Cash flow and value added are computed from the technologies of the network, prices of material and energetic resources, and costs of operating facilities. A microcomputer application was developed to evaluate the environmental loads and the economic consequences of alternative technologies, product prices, and amortization schedules for facility and equipment costs. The concepts and analytical tools presented for the design and management of dairy enterprises provide a framework through which scientists across disciplines and producers across product lines can work together to increase overall farm profitability and to reduce environmental loads.

INTRODUCTION

Dairy production systems have many interrelated subsystems and component processes. Parameters that affect the entire system or any of its processes have been traditionally considered separately by specialists in areas such as nutrition, physiology, genetics, agronomy, and engineering. In evaluating the performance of the entire system, the specialists have not been able to take all of these parameters into consideration.

Recent studies indicate that the use of computers (5, 13, 14) and linear programming to formulate least cost rations (31) has had a significant impact on the dairy and feed industries. Biometrical (22) and computer simulation modeling techniques (6, 23, 27, 29) have been used to address production phenomena. Operations research techniques have been applied to farm planning and management problems (11, 12, 28). Systems analysis techniques have been applied to modeling animal production hierarchically from the cell to organ tissue, whole animal, herd, and region or country (18, 20, 25, 33). Input and output models have been used to analyze resource flows in a system (19, 24). Heuristic expert systems have been utilized to formulate decision-making strategies (15). The approaches and models in these studies are based on theories and practices that do not explicitly represent the underlying science and technology. Monetary prices, for example, although useful in allocating resources, have no physical or biological causal consequences, obey no natural laws, and carry no information regarding the technical structure of the economic enterprise. Production technologies, the fundamental parameters of modern agricultural economics, remain quantitatively undefined in.
A new set of analytical tools demonstrates how the laws of material and energy balance serve as a scientific link between the technical and economic aspects of a given processing network. Applications of processing networks in agriculture (1, 2, 3, 9, 26, 30), ecology (17), manufacturing, and life cycle assessment (16) have been explored. This paper presents the dairy enterprise as a network of quantitatively defined processing technologies. Analytical tools to evaluate the technical and economic performance of the enterprise are discussed.

**MATERIALS AND METHODS**

**Networks of Processes**

A working diagram such as that illustrated in Figure 1 is used to characterize an enterprise as a network of processes. Each small closed box represents a primary process. The larger closed box represents a closed spatial boundary, called the enterprise boundary, circumscribing the network of primary processes. Each primary process can be partitioned into secondary processes (Figure 2). The size and number of primary and secondary boundary partitions identified in the network diagram depend on the degree of structural detail to be considered and may be selected on the basis of practical design, operating considerations, areas of scientific research, specialization, and innovation.

The directed line segments and associated end points represent the flow rates of biologically specific or structurally specific materials into and out of the boundaries of the respective processes. The boldfaced line segments identify the flow rates selected as independent variables in the generalized material balance equations characterizing the process; they are called the material products of the respective process. The dependent variables in the material balance equations for each of the process are always represented by normal line segments with end points; they are referred to as the material resources of the processes.

If the product of one process is linked as a resource to another process, it is so indicated by connecting the end points of the corresponding line segments. The point of connection is called a node. One and only one independent variable is associated with each node. If the product of a process crosses the boundary of the enterprise, it constitutes a product of the enterprise. Likewise, if a resource for a process crosses the boundary of the enterprise, it constitutes a resource for the enterprise. All other processes, products, and resources are internal to the boundary of the enterprise.

Physical energy, management time, labor, and land are required to carry out the respective processes. As a class, these resources are called functionally specific energetic resources; they are required to convert materials from one technical or biological form to another.

**Mathematical Representation of Processing Networks**

Material balance is maintained at the boundary of each process only if the flow rate of each resource is proportional to the flow rate of the material product of the process and is denoted by

\[ \dot{y}_{rs} = k_{rs} \dot{y}_{0s} \]

where \( r \) denotes resources crossing the boundary, \( s \) denotes a process in the network, \( o \) denotes product crossing the boundary, \( \dot{y}_{rs} \) is a column vector of material resource flow rates per unit of time, \( k_{rs} \) contains constants of proportionality called the material conversion coefficients, and \( \dot{y}_{0s} \) is the product flow rate. Herein, the dot notation refers to state variables that vary with time. Each element of \( k_{rs} \) has dimensions as required to convert from one material, unit of measure, or time scale to another. The energetic cost \( x_{os} \) of \( \dot{y}_{0s} \) at the boundary is given by

\[ x_{os} = -k_{rs}^{T}X_{rs} - f_{e}(\dot{y}_{0s}) \]

where \( k_{rs}^{T} \) is the transpose of \( k_{rs} \), \( X_{rs} \) is a matrix of the energetic cost of \( \dot{y}_{rs} \), and \( f_{e}(\dot{y}_{0s}) \) is
a row vector of the marginal energetic costs per unit of $y_{os}$. Values of $X_{rs}$ and $f_s(y_{os})$ are positive if energy is generated and negative if energy is dissipated.

Energetic balance is maintained at the boundary of each process only if the energetic resource rate, $e_s$, within the boundary is allocated to the material products of the process

$$e_s = - f_s(y_{os})y_{os} - e_s(0)$$

where $e_s(0)$ is a fixed component and represents the intrinsic losses of the process, such as those attributable to setup, cleaning, and down time of machines; $f_s(y_{os})$ is a variable component. The units of measure and time scales for the respective energetic factors are arbitrary, provided only that they are used consistently for all processes in the enterprise network. Intrinsic losses form a basis for the technical economies or diseconomies of scale.

Figure 1. Schematic representation of a dairy enterprise. NPK = N, P, and K fertilizer.
Figure 2. Schematic representation of the dairy herd.
and are specifically included in the mathematical representation of the technologies of processes. The intrinsic losses for the entire network are independent of the production rates and are given simply as the sum of intrinsic losses for the network of processes.

If each process has but one product, $k_{rs}$, $f_s(y_{os})$, and $e_s(o)$ can be evaluated from on-line operating data; they are called the technical parameters of the processes. Material losses, such as atmospheric emissions and soil nutrient losses, may be inferred from the differences between the chemical composition of the material resource inputs and the composition of the product. Labor and fuel use can be determined from the operating time of machines and associated operating requirements.

When placed side by side, the column vectors of technical parameters for each of the processes form a matrix of technical parameters called the network technologies. The columns correspond to products of the processes. As a standard format, the columns are ordered such that the processes for which the products cross the boundary appear as a set of right-hand columns, and the products for the intermediate processes appear as a set of the left-hand columns of the matrix. The rows in the matrix correspond to the material resources and energetic costs. The rows are ordered such that the internal material resources appear as the top set of rows, material resources crossing the boundary as the second set of rows, and marginal energetic costs as the last set of rows in the coefficient matrix for the network equations

\[
\begin{bmatrix}
  y_1 \\
  \vdots \\
  y_r \\
  \vdots \\
  e_s
\end{bmatrix}
= 
\begin{bmatrix}
  K_{ib} & K_{io} \\
  \vdots & \vdots \\
  K_{rb} & K_{ro} \\
  F_b & F_o
\end{bmatrix}
\begin{bmatrix}
  y_b \\
  \vdots \\
  y_o
\end{bmatrix}
\]

where $I$ denotes resources internal to the boundary, $b$ denotes products internal to the boundary, $K_{ib}$ with $I$ rows and $b$ columns is the ratio of internal resources to boundary products of the enterprise, $K_{ib}$ is the ratio of internal resources to internal products, $K_{ib}$ is the ratio of boundary resources to internal products, $K_{ro}$ is the ratio of boundary resources to boundary products, $F_b$ is the marginal energetic cost coefficients for the boundary products, and $F_b$ is the marginal energetic cost coefficients for the internal products.

### Technical Measures of Enterprise Performance

The linkages between the network technologies are derived from the continuity of internal products and resources as specified by the nodes of the working diagrams of Figures 1 and 2.

\[
y_b = A_{b}y_1
\]

where $A_{b}$ is a matrix of binary coefficients, $\pm 1$, or $0$, depending on the incidence and relative orientation of line segments representing the products and resources at nodes of the network. This incidence matrix is necessary and sufficient to eliminate all internal variables from the network equations and to compute the technology of the entire enterprise from the network technologies (16, 17). The computation involves two steps. First, the ratios of internal to boundary products of the network is computed as

\[
K_b = (I - A_{b}K_{ib})^{-1} A_{b}K_{io}
\]

where $I$ is the identity matrix. Second, the material conversion and marginal energetic cost coefficients for the entire network, $S$, are computed, respectively, as

\[
K_s = K_{ib}K_b + K_{ro}
\]

\[
F_s' = F_b'K_b + F_o'
\]

The network technologies and incidence matrix represent the technical design parameters of the network. For any proposed level of production, the flow rates of material resources across the boundary of the enterprise are obtained by multiplying the respective conversion coefficients in the technology of the enterprise by the proposed product rates. The marginal energetic resource rates are obtained in the same manner. The intrinsic losses are added to the marginal energetic rates to obtain the total energetic rates. The resources per unit
time for the enterprise are given by the material and energy balance equations

\[ y_s = K_s y_0 \]

\[ e_s = - F_s y_0 - e_s(0). \]

### Economic Measures of Enterprise Performance

The products of a given enterprise are physically exchanged with other enterprises as resources. Products and resources are also exchanged with the natural environment. The enterprises engage in similar exchanges with regard to the energetic resources.

Cash flow rate for the enterprise is a function of the material flow rates, the energetic rates, and exchange prices,

\[ v_s = y_s p_o - y_s p_r - e_s p_e, \]

where \( v_s \) is the cash flow, \( p_o, p_r, \) and \( p_e \) are prices for product, material resources, and energetic resources. If prices for resources exchanged with the natural environment are taken as zero, the natural environment is excluded from the cash flow.

Value added for the enterprise is obtained by summing cash flow over a given period, such as a year, and subtracting an amortized monetary cost of developing and maintaining the operating environment of the production network. The operating environment of dairy enterprises have both a natural component and an engineered component. The cost of the engineered component is amortized according to management and economic policies, however established. If no amortization is associated with the natural component, contributions of the natural environment to the production processes are not recognized in value added.

### Technology-Based Management Accounting Systems

The network technologies can be routinely updated to establish means and variances of \( K_s, F_s, \) and \( e_s(0) \) as performance criteria for the production network. Deviations from these criteria become a basis for corrective action in management. The management accounting system itself becomes the basis for budgeting, risk assessment, strategic planning, evaluation of alternative technologies, and other elements of management. A record system based on the network of processes is appropriately referred to as a technology-based management accounting system.

### RESULTS AND DISCUSSION

#### Description of the Computer Program

Based on the principles outlined, DairyNet™ was developed (10). DairyNet™ is an interactive and user oriented on-line information system that utilizes visually appealing dialogue boxes and input fields to request user input. An easy to use and easy to learn hierarchical menu structure provides access to information. Details of data storage, file structures, and analytical routines are discussed elsewhere (10). The computational algorithm of DairyNet™ is illustrated in Figure 3. Flow rates, utilization, and price data are required for 1) products, material resources, and by-products; 2) land; 3) human time; and 4) fuel and electricity. Monetary cost data are required for 1) equipment, 2) farm structures, and 3) repairs and maintenance. From these data, the requisite structural matrices are formed, and the technologies of the entire enterprise are computed. Cash flow and value added are then computed for a given set of enterprise technologies, exchange prices, and amortization functions. Sample computations are demonstrated for data taken from the Michigan State University Kellogg Biological Station, Hickory Corners, MI, with supplementary data obtained from the literature (8, 21). These data can be taken as baseline data and modified as needed for other assessments. A graphical interface to assist in the analyses is included. Supplemental computer software is suggested for management of individual animal information, such as BW, DMI, daily milk yield, calving dates, and breeding dates.

For a given dairy enterprise, capabilities of DairyNet™ include 1) computation of the requisite matrices, 2) evaluation of current and alternative technologies for management purposes, 3) short-term projections to aid in tactical decision-making, and 4) long-term projections to aid in strategic decision making.

On a broader perspective, capabilities of DairyNet™ include 1) data recording formats
for the dairy industry, 2) procedures for measuring economic performance of dairy enterprises, 3) increased effectiveness in the utilization of existing information in the identification of research priorities, and 4) definition and quantification of alternative technologies.

A copy of DairyNet™ can be obtained from Michigan State University, Department of Animal Science, East Lansing, MI. Compatible
microcomputers must meet the following requirements: 1) IBM AT, PS/2 or fully compatible central processing unit (80286 and higher), 2) Microsoft DOS operating system version 3.1 or higher (© 1984–1993, Microsoft Corp., Bothell, WA), 3) 4 megabytes of RAM, 4) support for a graphics display adapter, and 5) 5 megabytes of free disk space.

CONCLUSIONS

As fundamental propositions, the laws of material and energy balance can be mapped into economic variables. For a given enterprise, monetary prices are assigned to the product and resources. However, environmental loading and resource utilization efficiencies cannot be derived from monetary prices. Such information can come only from the generalized laws of material and energy balance, correctly formulated and applied to the dairy enterprise as a network of processing technologies.

This paper demonstrates how the laws of material and energy balance serve as the computational link between the technical and economic aspects of a dairy enterprise. In principle, environmental loads, resource utilization efficiencies, cash flow, value added, and all other technical and economic measures of enterprise performance can be evaluated quantitatively as an explicit function of the network of processing technologies, the rate of production, resource use, product and resource prices, and amortization policies. These parameters and variables condition the choice of processing technologies and scale of operation selected by the dairy enterprise. A new generation of analytical and computational tools is now available for 1) the management of environmental loading and efficient resource utilization and 2) integration of areas of scientific and technological specialization for improved technical design and operation of the dairy enterprise as a whole.

ACKNOWLEDGMENTS

The authors acknowledge the full support of the staff of the Kellogg Biological Station. Special recognition is given to B. Knezek, H. Webster, J. Bronson, R. Ashley, P. Foldesi, and L. Langshaw.

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