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THE REFERENCE MATERIALS SYSTEM--MATERIALS POLICY INFORMATION SYSTEM

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ABSTRACT

The social and economic development of a nation is dependent on a reliable supply of materials and energy and on the efficient utilization of these resources. Decision-making in industry and the formulation of government policies require a comprehensive information base encompassing the technical, economic, and environmental factors involved in the flow of materials through production processes and the overall economy.

The Reference Materials System (RMS) is a network description of the flow of materials from resource extraction through refinement, production, and transportation processes to the utilization, maintenance, and recycling operations. The system has been employed for the assessment of material production technologies and for the evaluation of substitution possibilities.

The RMS provides a framework for integrating engineering and economic information into a comprehensive systems framework. The network flow diagram is quantified in terms of the mass flow of all renewable and nonrenewable materials on an annual basis through each step of the system. A variety of data elements including capital and labor requirements may be organized in this framework to provide a Materials Policy Data Base. This process description of the materials system may also be coupled with economic policy models of the input-output or econometric variety to ensure proper analysis of the role of materials in the overall economy.

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DISCLAIMER

INTRODUCTION

It is traditional to view the economy of a nation from the perspective of financial institutions with production, trade, and consumption expressed in monetary units. Many of the policy levers available to governments are of a monetary or fiscal nature, so it is quite understandable that most information systems dealing with major sectors of the economy stress this type of economic data. As resource problems arise in specific sectors of the economy, attention must be focused on the physical aspects of production, trade, and consumption. In addition, the recognition of the need for long term research and development to solve resource supply, substitution, and conservation problems leads to an increased need for a comprehensive information base that stresses the physical and technological aspects of the physical flow of energy and materials through the economy.

Information on the physical aspects of resource supply, conversion, and utilization does not, of course, replace financial and economic data, but is complementary to such data in providing a complete picture of the structure of the economy of a nation. This paper outlines a framework that may be employed to organize information on the physical flow of materials from their harvesting, or extraction, through the conversion steps required to produce useful materials, to their utilization, maintenance, and recycling in specific sectors. The incorporation of the utilization steps is of special importance since it is this portion of the materials systems that governs the conservation of materials and the substitution of abundant materials for scarce ones. While the information system is organized about the physical flow of materials through the economy, other factors of production in the economy such as energy, labor, and capital, may be incorporated along with environmental effects.

The materials information system outlined here is compatible with a large variety of data systems and analytical models. Coupling of the information system to simulation models and economic models has been demonstrated in a conceptual way.

The availability of materials for housing, durable goods, industrial construction, transportation systems, and energy is central to the life-style and prosperity of a nation. The materials system is quite complex in view of the existence of a large number of natural sources of renewable and nonrenewable character, and the multitude of technical activities operating within a complex institutional framework. The technical activities include the exploration for a wide range of material resources, conversion of these resources into useful products, operation and maintenance of these products over their life span, and, finally, recovery or recycling of these products back into the resource stream. Although the materials system itself is a vital element of the nation's economy, this system has close relationships with other sectors including its effect on employment, energy needs, capital requirements and the environment. Technical and policy options designed to deal with specific issues may alter the trade-offs among these sectors.

While energy problems occupy much of the nation's attention and are dealt with by a cabinet-level agency, the Department of Energy, there is no focal point for the formulation and coordination of materials policies. Supply, demand, and allocations within the U.S. materials system are largely determined by independent forces working through the market in the private sector. However, the problems arising from growing environmental concern and changing patterns in the international supply and demand of resources generally induce changes in resource markets that are outside the scope of the decision-making capacity of the private sector. Government support for research and development in the materials system is increasing but is still quite fragmented. Government policies as well as private sector decisions must be based on improved up-to-date knowledge of the technical, economic, and environmental parameters of the materials system. This kind of information is also sought by scientists and engineers who need technical data on materials properties and processes, and by industrial managers who seek information on materials supply, demand, and potential markets.

A large number of formal and informal materials information systems have been devised, both in private and public sectors. Unfortunately these systems, in addition to being quite disparate and incompatible, are generally deficient in that they consider only isolated aspects of the materials system. The need to address the broad technical and policy questions in both the public and private sectors points toward the requirement for a framework within which economic, environmental, and technical factors involved in the supply and utilization of all alternative materials may be simultaneously considered for analysis of the materials system. The objective of this paper is to outline a comprehensive framework, the Reference Materials System (RMS), that may be used to organize relevant information. In addition, the framework is compatible with a wide variety of analytical methods that may be employed to assess the broad impacts of materials policies. The RMS represents the supply and demand balance in the materials system and the technologies employed to produce and utilize materials. An important feature of this framework is the incorporation of the utilization, maintenance, and recycling portion of the system at the same level of detail as the supply side. These portions of the material system are often ignored in policy analysis.

REFERENCE MATERIALS SYSTEM

Many studies have been performed on the energy and environmental aspects of materials production. Berry[1] and Midwest Research Institute[2] have published information on the energy inputs to the production of glass, aluminum, and plastic container materials, and Ayres[3] has analyzed environmental impacts associated with materials production. Hannon[4] has considered the direct and indirect energy inputs to materials using input/output modeling in the analysis of recycling policies. The Reference Materials System format provides a comprehensive and standard format in which the results of such process analysis of specific materials and production steps may be displayed. The methodology is similar to the Reference Energy System which has been coupled to interindustry models of the economy[5] and can be used in a similar manner to provide a generalized coupled process and economic model for use in technology and policy analysis. The Reference Materials System concept has been employed as the central systems analysis approach by the Committee on Renewable Resources for Industrial Materials of the National Research Council (NRC). The thrust of the NRC study was to identify the most promising areas for substituting nonrenewables by renewables which in turn would highlight the Research and Development (R&D) programs needed to overcome the barriers to production and use of renewable resources. The RMS approach has also been adopted for a study[6] in Ireland concerned with the use of biomass as a source of energy. Although the specific emphasis on the various policy objectives will vary from country to country depending upon its stage of development, mineral base, etc., the RMS, because of its general nature, can be adapted as a policy and planning tool to any national situation.

For example, trade-offs between the labor requirements and capital expenditures as influenced by a particular technology will be somewhat different in an industrialized country as compared with a developing country where the policy objectives may differ. Such policy objectives are exogenous to the RMS and may be formulated independently.

The nation's materials system can be thought of as consisting of an integrated set of technical activities such as exploration, refinement, conversion, transportation, fabrication of material resources into useful products, and finally, the maintenance and recycling of these products. The RMS is a network representation of the physical flow of materials through all of the production and utilization steps that a resource must go through to be used for a specific purpose in the economy. The scope of the RMS is outlined in Fig. 1. At the left-hand side is a listing of resources both renewable and nonrenewable, while the products and end uses, defined at the functional level, are listed on the right side. The definition of the use of materials for specific functions and purposes is central to the RMS concept. Only at this level can conservation and substitution opportunities be analyzed with any technical reliability. Engineering properties such as strength-to-weight ratios, corrosion resistance, and durability must be considered.

The completed RMS, involving a network representation of the flow of materials from the resource side through all of the "activities" listed along the top to a specific end use such as building and construction, and the year 1977 is shown in Fig. 2. This figure is quantified in terms of the mass of material flowing annually through each activity. While the material flows on the supply side were obtained from the Statistical Abstract,[7] and the annual statistical reports,[8, 9] put out by various trade associations, the data on the demand side were mostly estimated using the product mixes and conversion ratios, as they existed in the year 1974, from the Materials Source Book.[10] The network can also be quantified in terms of energy use, cost, labor, and environmental effects associated with each activity. A path from a specific resource to a specific end use is called a "trajectory." Each "activity" in the trajectory represents a technical process or production step that is characterized by both a material flow element (and material losses) and the data elements listed, e.g., energy requirements, other material inputs, labor and capital needs, and environmental effects. The activity category involving "installation, erection, and maintenance," not relevant in the energy system, is of special importance in the case of a materials system for evaluating life-cycle usage characteristics of materials. Opportunities for recycling of materials are identified in terms of activities characterized by material flows and data elements. Imports and exports of resources and products can be indicated by flow vectors from and into the appropriate nodes.

The RMS illustrated in Fig. 2 is simplified and aggregated for presentation purposes only. Additional detail is provided in versions of this system that have been developed for policy studies. An example of additional information that is needed is alloying materials such as chromium, molybdenum, and cobalt that provide desired strength and corrosion resistant properties for certain applications.

It is feared by many that resource scarcity will limit future economic and social development. Analysis of the role of materials in our society requires the extension of the Reference Materials System to a general economic framework. The conventional Input/Output framework provides a detailed picture of the structure of the economy and of interindustry flows. While normally quantified in monetary units, Input/Output Tables have also been quantified in physical terms (mass flows, energy flows, etc.). The Reference Materials System provides the basis for estimating the technological coefficients and material substitutions represented in the Input/Output Tables. Figure 3 shows the format of a modified Input/Output Table. The flow of materials resources through the materials conversion processes into the other non-material industry sectors and the final demand sectors is represented by coefficients representing the mass of specific materials required per dollar or physical unit of output in the industry sectors. The summation of total outputs in dollar terms represents the Gross National Product (GNP) of the nation. This framework then provides the analytical link between GNP (which when exhibited in terms of individual sector elements is representative of a life-style pattern) and the requirement for specific materials. When presented at this level of detail, the results of engineering analysis may be represented in a policy framework. This step of introducing the physical representation of a technical system in an economic framework has been accomplished for the energy system but not as yet for the materials system.

The logic of incorporating a physical representation of a technical system in an economic framework along with consideration of resource, labor, capital, and environmental factors is illustrated in Fig. 4. This figure illustrates the way in which resources and technology underlie the economy of a nation and affect its environment. Starting at the bottom, resources are employed in technological systems to produce goods and services in the economy. Environmental effects are also produced that must be balanced against benefits of production. Policy actions or decisions taken at any level can affect the need for and use of the materials and technology employed in the nation's economy.

RMS projections of the material flows, compatible with the economic forecasts for the future years, say 1985 and 2000, can be prepared assuming a natural evolution of technologies and no new federal policy initiatives. This projected system can then be used as a base case for the substitution analysis and technology assessment as discussed in the following sections. The RMS can be prepared to represent the flow of materials through an industry, regions of the country, or the entire country.

ANALYSIS OF MATERIAL UTILIZATION AND SUBSTITUTION

The RMS and the associated data can be used for the analysis of materials utilization and substitution. This is done by using the perturbation technique in which incremental effects of the substitution are analyzed with respect to the material flows and attendant energy, economic, and environmental implications indicated on the RMS diagram and backup data sheets.

The technique of perturbation analysis involves the following steps following the definition of a base, or most likely case, in the RMS format

1. Analysis of the specific end use involved in a utilization or substitution problem.
2. Definition of any new processes to be used in the affected trajectory from the resource to the specific end use (definition of losses, energy, labor and capital requirements, and environmental effects).
3. Revision of flows through the affected trajectories in the RMS to reflect the revised utilization or substitution of materials and/or new processes.
4. Accumulation and tabulation of resource, energy, labor, capital, and environmental consequences of the utilization or substitution.

In analyzing the specific nature of the substitution, it is necessary to address the specific application. The mass ratio of substitution, e.g., kg of paper that would replace a kg of plastic, depends on the specific application and the nature of the material. Thus, one would have to focus, for example, on paper bags as a substitute for polyethylene bags. The determination of these substitution ratios must be done exogenously to the RMS and the results reflected in the revised or perturbed RMS. In certain instances, material preferences and substitution may be constrained or influenced by such factors as esthetics and codes or standards.

The parameters of the technical characteristics of new processes must also be obtained exogenously to the RMS by people with a process background. The intent of the RMS format is to capture those characteristics of the technology that are important to materials policy formulation because it is not available in a consistent and comprehensive format.

Following these steps, the perturbation of the appropriate trajectories and the accumulation of information on detailed consequences is straightforward using the RMS. In the case of an analysis of the substitution of paper bags for polyethylene bags for example, the flows through the wood to paper trajectory would increase by the appropriate amount while the flow of crude oil and natural gas through the petrochemical trajectory would be decreased. The full materials system implications may then be traced all the way back to the forest and the source of the oil, imported or domestic. The results of the analysis may then be used as a basis of support or revision of the original utilization or substitution measure.

When used in this fashion, the RMS can be a useful technique for the analysis of materials policy. It must be recognized that the technique focuses on the physical structure of the system and its requirements. Thus, although substitution analysis may be performed in a rather direct manner, in cases of more general policy analysis the effects of a policy action on the supply or demand for materials use and on the physical structure of the system must be developed or estimated prior to use of the RMS.

A case study to evaluate the energy implications of substitution of plastics by paper products for certain kinds of packaging and containers has been included in the Appendix.

EVALUATION OF NEW MATERIAL TECHNOLOGIES

The research and development policy area is of great importance to the future development of the nation's materials system. Only through the development of new technologies can the diversity and flexibility be realized to allow the materials system to adapt to the changes in the resource availability and environmental concerns that will occur over time.

The major thrust of the problem in this case lies in estimating the parameters of the new and as yet undeveloped technology. Having done this, the perturbation technique, as in the case of substitution analysis, can be used to compute the incremental effects with respect to resource consumption and attendant energy, economic, and environmental effects. The uncertainties in estimating the parameters of new technology are recognized but, by using the perturbation technique, the sensitivity of policy comparisons to errors in the forecast is reduced.

Following is the list of pertinent data on the technology under consideration that should be assembled prior to the actual technology assessment.

1. Date or dates of implementation
2. Degree of implementation at the date, e.g., fraction of the total end use demand met by the use of this technology
3. Primary material input
4. Economic data: capital cost, plant life, operating and maintenance cost, etc.
5. Enviromental effects

The place of the technology should now be appropriately noted on the RMS for the time frame of interest. The technological area being replaced should also be noted and the resource allocations should be checked for consistency. Knowing the level of implementation, the technology is inserted in the RMS. The next step is to sum up the resource, energy, capital, and environmental consequences of the perturbed system and compare them with the base case to arrive at the incremental benefits (or losses).

It is clear that the system under discussion is static in time and that the replacement does not occur instantaneously. If the purpose of the assessments is just to ascertain the technological effect of the future system change, the lack of dynamic response is not critical. However, if the assessment is to be used for research and development planning, it is important that the cost of the research and development program be compared with the discounted present worth of the ultimate benefits of implementing the technology over the entire planning horizon. These benefits may be estimated with the static system by applying it at several points and calculating the present worth of that stream of annual benefits. With this information, a cost-benefit ratio can be computed for technologies under consideration and the corresponding research and development areas can be ranked accordingly. Due account must also be taken of several other factors, e.g., uncertainties involved in any critical research areas, safety aspects, international questions, institutional factors, etc. before developing final research and development strategies. Finally, increased sophistication in the treatment of environmental impacts may be incorporated as an improvement in the above analysis. Regional definition of the materials system is important in some applications but is of extreme importance with respect to environmental effects as they cannot be addressed adequately in systems representing a national average situation.

CONCLUSIONS

The framework for a Materials Management Information System outlined in this paper has been demonstrated to be feasible. It can provide a valuable and essential tool to ensure a proper base of information for materials policy. In addition to providing a documented information base, the framework can be used in support of modeling and policy analysis. At the Federal level, the Reference Materials System is compatible with techniques used for policy analysis, such as input-output analysis, macroeconomic modeling, and energy systems analysis. Additional detail can be incorporated in specific sectors of the materials system or of the economy. An essential feature of the method is the concentration on the utilization of materials and the possibilities for substitution in specific end use applications.

In view of the need to assure adequate supplies of nonrenewable and renewable materials, to encourage the effective substitution of renewable resources, and to ensure proper coordination of materials policy with national policy, a comprehensive materials information system is needed. The materials information system will assist in the formulation of federal research and development policy in the materials sector, and in the formulation of policies that encourage the substitution of abundant and renewable resources for scarce ones.

A comprehensive materials information system must deal with both physical and economic data including energy, labor, capital, and environmental factors. Further it must be designed to be compatible with analytical methods used by other agencies at the Federal level including the Departments of Agriculture, Commerce, Energy, and The Interior.

APPENDIX

Case Study of Material Substitution in Containers and Packaging Sector

Packaging is used for three major classes of goods: durable, nondurables, and foodstuffs. The overwhelming fraction of durable goods is packaged in corrugated cardboard. Corrugated cardboard is also most commonly used as a packing material in case of durables. Nondurables consists of clothing, textiles, and chemicals and require a variety of packaging characteristics. Foodstuffs, the third major area for packaging, represent about 15% of the production activity of the U.S. economy and account for 60% of the total shipment value of the entire range of goods that are packaged. This sector involves the widest variety and largest amount of packaging materials, apart from corrugated cardboard, produced from renewable resources. In the following discussion, specific examples have been chosen for which both nonrenewables and renewables can be interchangeably used to meet certain packaging requirements. Such examples are: sanitary food containers used for milk, butter, margarine, frozen foods, ice cream, shortening, etc; trays for packaging meats, eggs, and produce; and flexible containers, e.g., bags and sacks.

Although labor requirements and capital costs are also important considerations in the comparison of alternative materials, attention is focused exclusively on energy implications in this case sutdy of materials for containers and packaging.

In connection with sanitary food containers, two RMS trajectories are shown in Fig. 5. These correspond to the special case of half-gallon containers made of plastic and of paper. Mass flows and energy values shown in the figure under each activity link refer to requirements for manufacture of one container of each type. Energy data are in terms of the "gross" value of energy requirement. Summing all the energy components along the two trajectories, one can see that a plastic bottle weighing 54 grams needs about 8.4×10^6 joules, whereas an equivalent paper carton weighing 64 grams needs 6.4×10^6 joules. Also, the plastic bottle requires 22 grams and 55 grams of natural gas and crude oil, respectively, as chemical feedstock, while an equivalent paper carton needs 130 grams of groundwood. Adding the energy content of raw materials, the total energy inputs to a plastic bottle and an equivalent paper carton work out to 11.9×10^6 and 7.9×10^6 joules, respectively. In Fig. 6 two trajectories for the manufacture of size 6 meat trays from styrofoam and from molded wood pulp are shown. The energy requirements in the two cases add up to about the same value, 0.9×10^6 joules each. Here again, taking into account that 2.3 grams of natural gas and 7.2 grams of crude oil are needed as chemical feedstocks in the case of the polystyrene tray and 30 grams of groundwood is needed as raw material for one pulp tray, the total energy values increase to 1.3×10^6 joules, remaining same in both cases. In the case of flexible containers, polyethylene is used for plastic bags and Kraft paper for paper bags. The energy cost of Kraft paper[1] is $\simeq 48 \times 10^6$ joules/kg, and that of polyethylene, $\simeq 160 \times 10^6$ joules/kg or 3.3 times as much. But, because medium-weight polyethylene bags weigh only half as much as an equivalent paper bag, the ratio of energy consumption of plastic and paper bags is $\simeq$ 1.65:1.

The above comparison is not entirely fair to plastics if there is the possibility of reusing the plastic containers. As an example, to make and fill a half-gallon plastic milk container a single time requires about 8.4×10^6 joules of energy. If it were reused, and the washing and filling costs remained the same with each use ($\simeq 3.2 \times 10^6$ joules), then the cost would drop to 5.8×10^6 joules with one reuse, to 4.9×10^6 joules with two reuses, and to 4.5×10^6 joules with three reuses. Similarly, although a single use of plastic bags requires more energy than paper bags, the two become comparable if more durable polyethylene bags are reused once. These results are summarized in Table I. Using this information in conjunction with RMS with sufficient disaggregation in the Containers and Packaging Sector, the perturbation technique can be applied in rather straightforward manner to assess the full materials system implications in terms of energy and resource requirements arising from the substitution measures considered here.

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TABLE I

ENERGY REQUIREMENT FOR TYPICAL CONTAINERS AND PACKAGING

Container/packaging (product) type	Raw material requirements Per unit product: Unit weight (grams)	Natural gas (grams)	Crude oil (grams)	Wood (grams)	Energy of manufacture: per unit product (10^6 Joules)	10^6 Joules/ Kg. of Product	Energy content of raw materials: per unit product (10^6 Joules)	Total Energy: per unit product (10^6 Joules)
Half-gallon Milk Container								
Polyethylene plastic	54	22	55	----	8.4 5.2*	155.0 96.0*	3.5	11.9
Paper	64	----	----	130	6.4 3.0*	100.0 47.0*	1.5	7.9
Size 6 Meat Tray								
Polystryrene plastic	6.7	2.3	7.2	----	0.9	127.0	0.4	1.30
Wood pulp	20	----	----	30	0.94	47.0	0.36	1.30
Flexible Container (bag or sack)								
Polyethylene	18	6	16	----	2.9	160.0	1.0	3.9
Kraft paper	36	----	----	70	1.7	48.0	0.8	2.5

* These values exclude the energy required for filling the containers.

Scope of Reference Material System and Associated Data Elements

Resource base	Production (growing)	Harvesting or extraction	Processing	Transportation (aggregate)	Fabrication and recycling	Product Identification	Additional Fabrication (e.g., Erection) & Maintenance	End use and recycling

Resource base

Renewables

Forest resources
Grazing and rearing land resources
- -birds
- -cattle
- -sheep

Crop land resources
- -cotton
- -cereal and sugar cane
- -others

Other forest resources
- -coconuts
- -citrus peel
- -gum

Marine resources including agricultural types
- -algae
- -menhaden etc.

Nonrenewables

Aluminum
Iron and steel
Cement and concrete
Oil and gas
Coal

Harvesting or extraction

Land use
Energy
Fertilizer and chemicals
Labor
Environmental
- -solid waste

Capital Cost
Operating Cost
Institutional and organization problems

Data Elements to be identified for each resource/activity combination

Product Identification

Lumber
Plywood
Paper
Particle board and fiberboard
Chemicals
Fibers and woven fabrics
Nonwoven fabrics
Elastomers
Fuels
Plastics
Aluminum mill products
Steel mill products
Concrete

End use and recycling

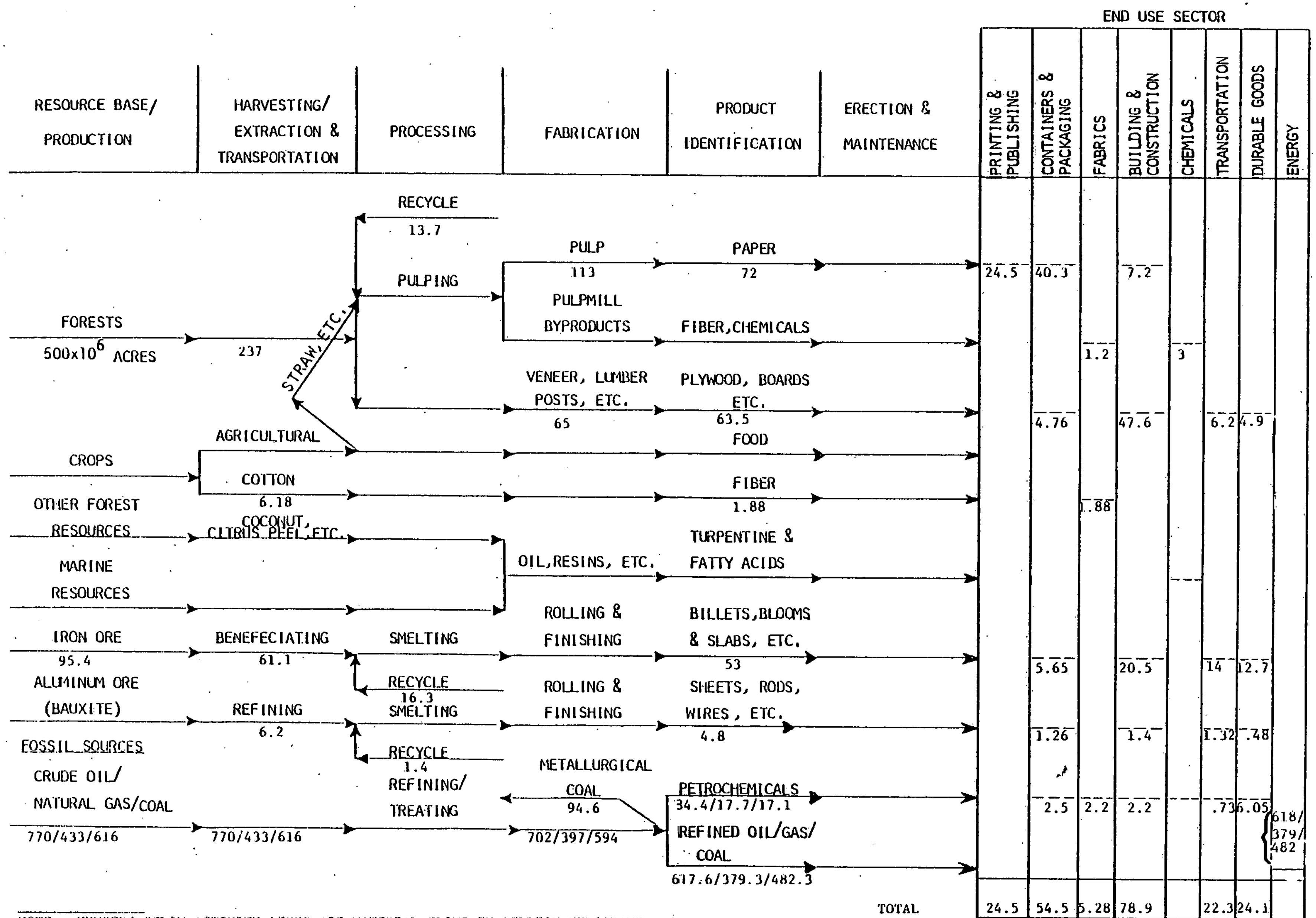
Commercial and industrial structures
Housing
Transportation
Furniture and upholstry
Energy
- -fuel
- -power

Books and publications
Producer goods
Textiles
- -clothing
- -soft goods (footware)
- -packaging

Communication
Disposable products
- -packaging
- -other

Recreation (competes for use of land)

Figure 1



NOTE: NUMBERS BELOW ACTIVITY LINKS ARE MATERIAL FLOWS IN BILLION KILOGRAMS

Fig. 2. Reference materials systems (year 1977)

MATERIAL UTILIZATION IN THE ECONOMY: DATA FORMAT

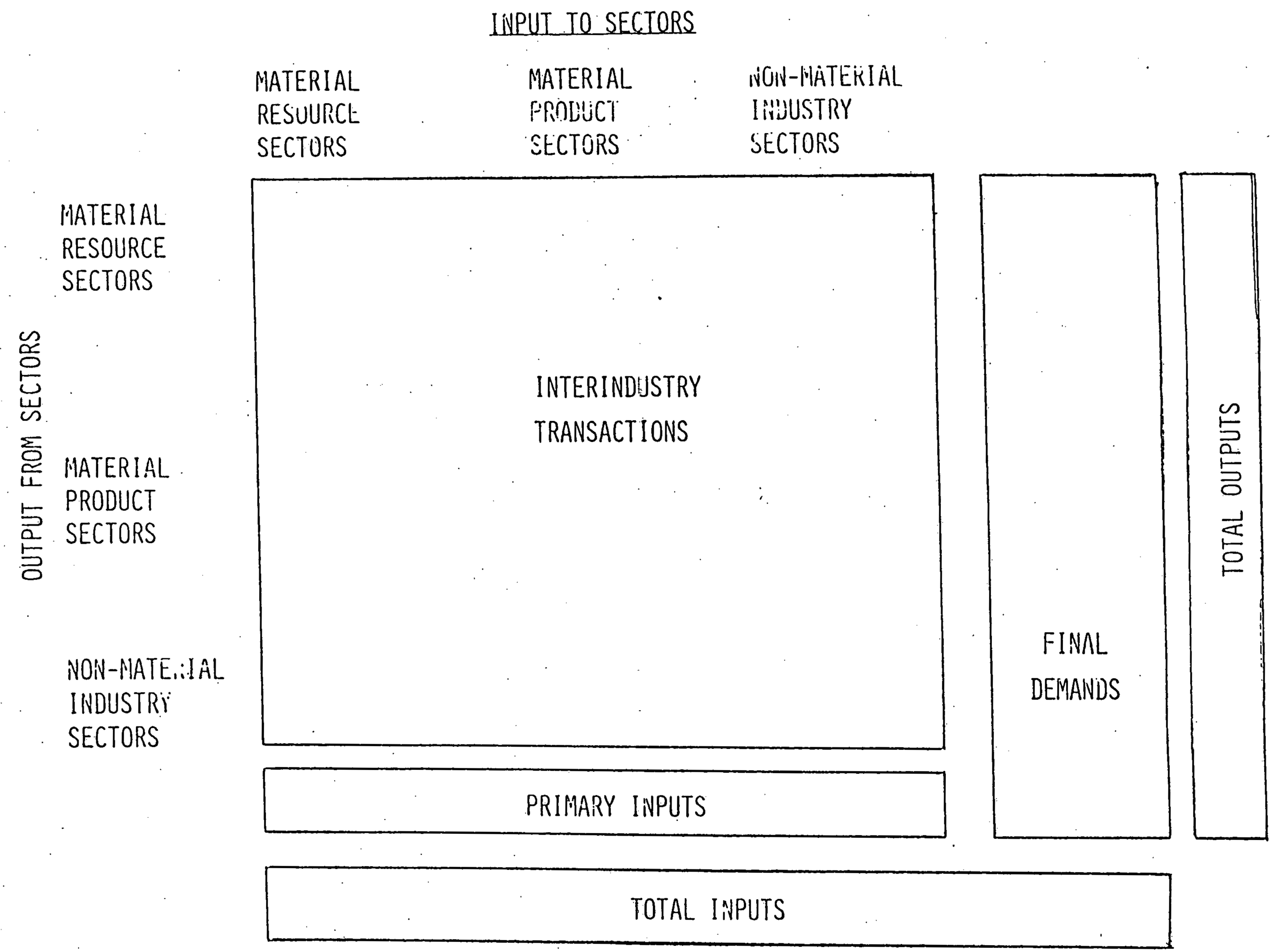
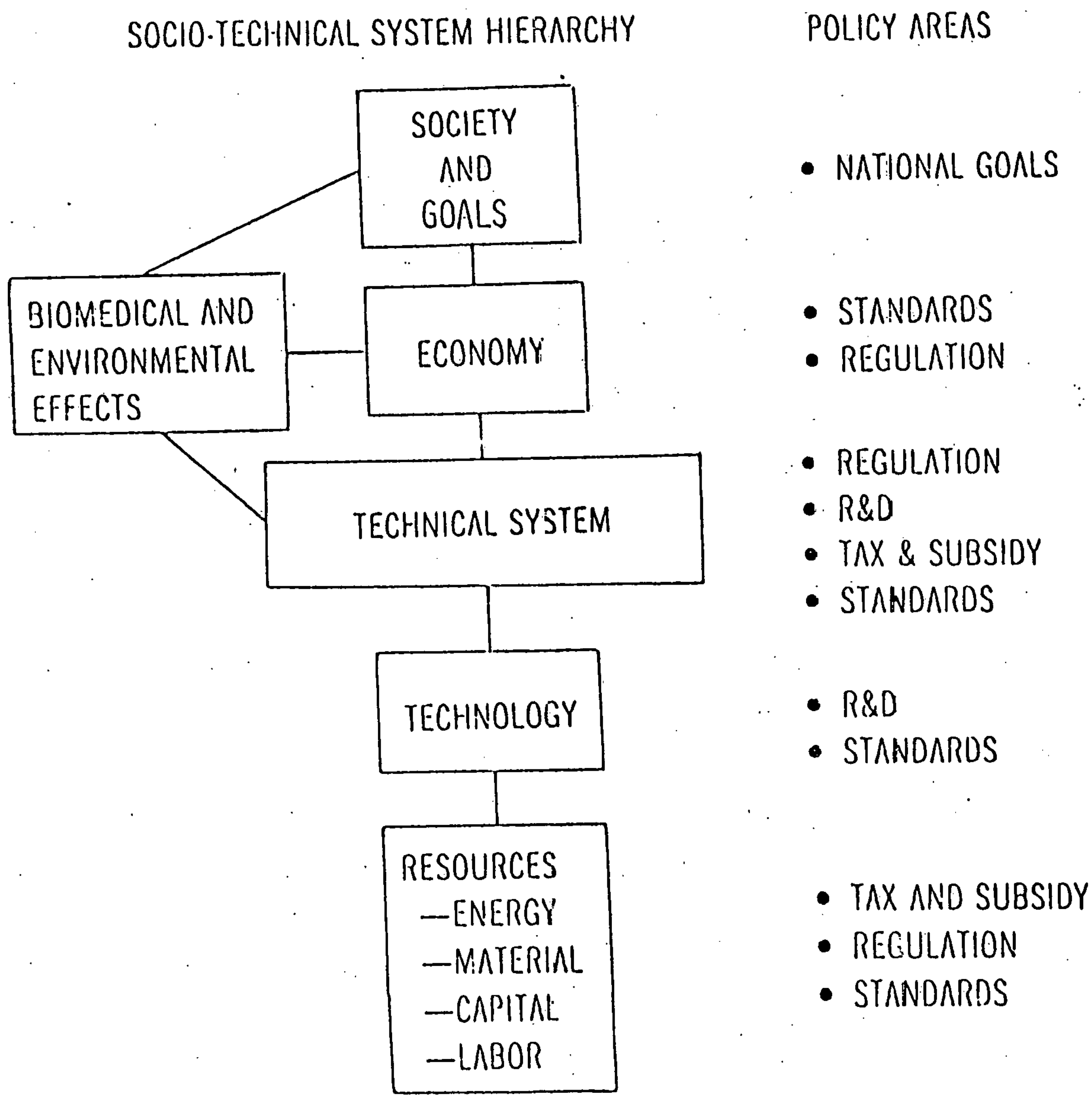


Figure 3

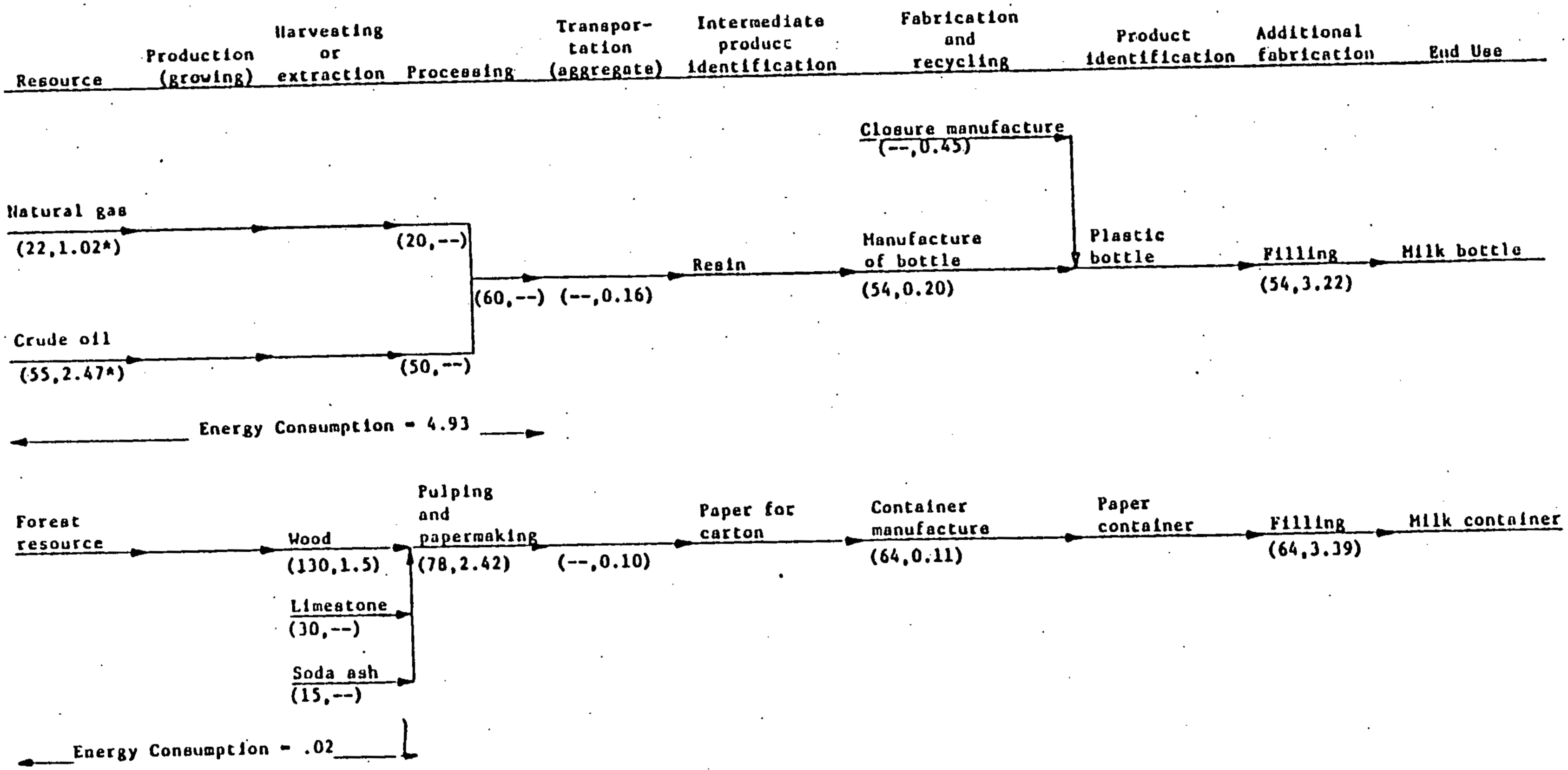


SOCIO-TECHNICAL SYSTEM HIERARCHY

Figure 4

REFERENCE MATERIALS TRAJECTORIES

Half Gallon Milk Container (Plastic Bottle vs. Paper Carton)



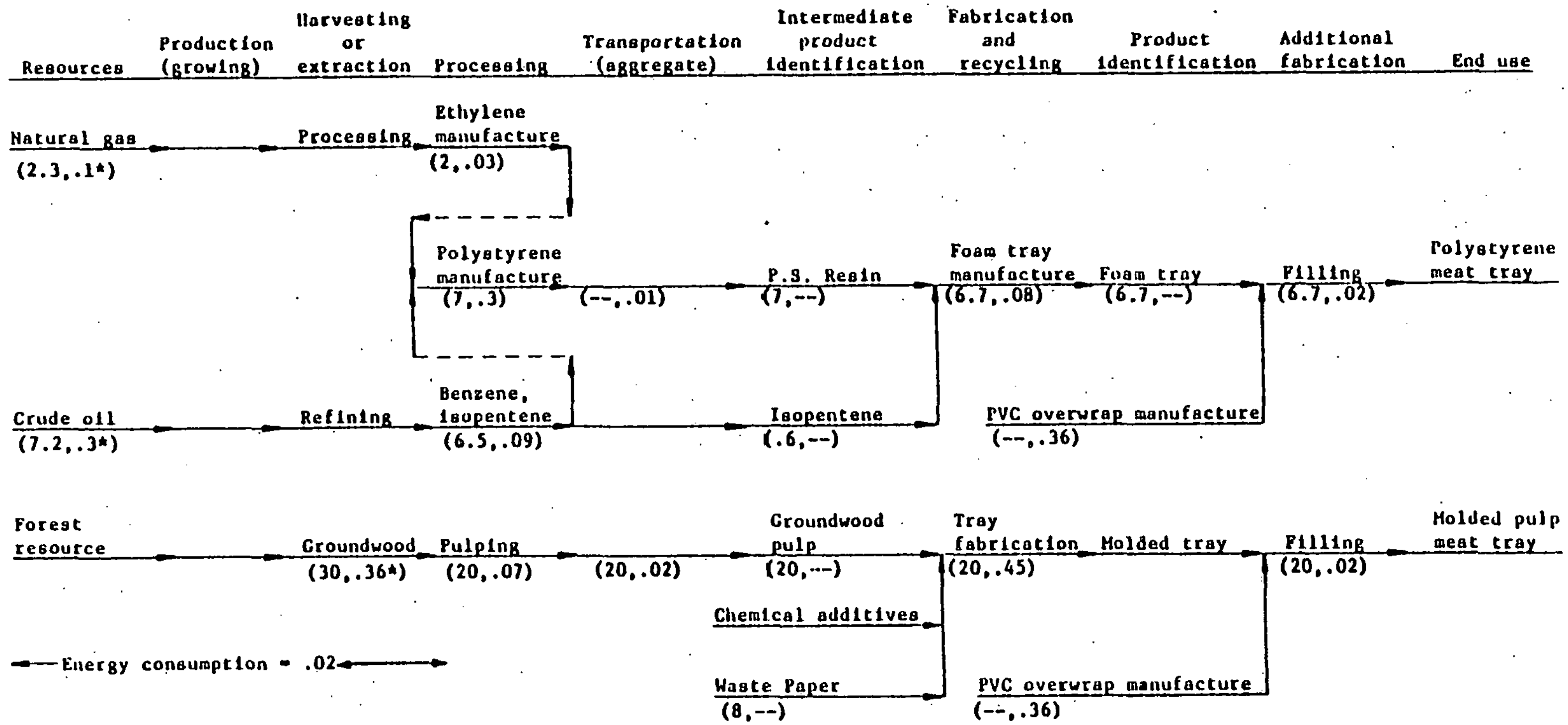
Note: Numbers in the parentheses below the activity links refer to mass flow in grams and energy requirement in million joules, respectively, for the corresponding steps in the manufacture of one-half gallon milk containers.

* Energy content of resource.

Figure 5

REFERENCE MATERIALS TRAJECTORY

Size 6 Meat Tray (Polystyrene vs. Molded Pulp)



Note: Numbers in the parentheses below the activity links refer to mass flow in grams and energy requirement in million joules, respectively, for the corresponding steps in the manufacture of one Size 6 meat tray.

* Energy content of resource.

Figure 6