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EVALUATION OF RECYCLING AND REUSE OF BUILDING MATERIALS USING THE EMERGY ANALYSIS METHOD

By

VORASUN BURANAKARN

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1998

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December, 1998

Dean, College of Architecture

Dean, Graduate School

For my lovely father, mother, grandmothers, and my families.

ACKNOWLEDGMENTS

I would like to thank Professor R. Wayne Drummond, Dean and the committee chairperson, who give me philosophical advice and an opportunity to pursue my advanced study at University of Florida, Dr. Mark T. Brown, the committee cochair, for his academic support, advice, and constructive ideas. I would also like to thank the rest of the supervisory committee, Professor Ira H. Winarsky, Dr. Charles J. Kibert, Dr. Clay L. Montague, and Professor Larry L. Peterson, for recycling, environmental, and architectural ideas, data sources, beneficial comments, and constructive advice.

My personal appreciation is extended to Dr. S. Abdol Chini for concrete recycling data, Dr. Robert F. Cox for building maintenance and repair information, Mr. Semmy Ju for data concerning building construction and demolition processes, Mr. James L. Womack for building demolition information, and Mr. Al Dampe for building construction information.

For data collection section, my sincere appreciation is extended to companies and manufacturers who provided all appropriate and proprietary information. Since in-house data are extremely sensitive if released to other competitors, all data sources are kept confidential.

I am truly indebted to the Royal Thai Government for primary financial support through the study.

This dissertation is a present for my parents, Professor Dr. Vira and Mrs. Sunee Buranakarn, who have provided energetic support through my studies. Finally, the ultimate appreciation is given to all my families' members, especially both grandmothers, for their utterly moral inspirations.

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EVALUATION OF RECYCLING AND REUSE OF BUILDING MATERIALS USING THE EMERGY ANALYSIS METHOD

By

Vorasun Buranakarn

December, 1998

Chairman: R. Wayne Drummond
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Major Department: Architecture

In this dissertation, regarding the costs and benefits of recycling building materials, the main question was: what are appropriate measures or indices to judge recycle benefits? To answer this question, techniques of emergy analysis were used to evaluate inputs to the production processes of six major building materials and several other secondary materials as well as the inputs to recycle systems for these products in three different recycle trajectories. Emergy is the amount of energy required to make something expressed in units of the same form of energy. The emergy in building materials and recycle systems was expressed as solar emergy.

The emergy per mass for building materials varied from a low of 0.88 E9 sej/g for wood to a high of 1.27 E10 sej/g for aluminum. Generally, emergy per mass is a good indicator of recycle-ability, where materials with high emergy per mass are more recyclable. Recycling added between 1% (concrete) and 568% (wood) to the emergy inputs per gram of building materials. The analysis of materials suggested that recycle of wood may not be advantageous on a large scale, but metals, plastic, and glass have very positive benefits.

Two types of solid waste disposal systems were evaluated: municipal solid wastes (MSW), and construction and demolition (C&D) wastes. Expressed as emergy, the costs of collecting and landfilling (for 50 years) MSW were 264.4 E6 sej/g while sorting recycled materials was evaluated as 8.2 E6 sej/g. The costs of demolition, collection and landfilling C&D wastes were 83.4 E6 sej/g and sorting costs were 6.7 E6 sej/g.

Several different recycle trajectories were identified and analyzed: 1) material recycle, 2) byproduct use, and 3) adaptive reuse. Four recycle indices measuring the benefits of various recycle systems suggested that materials that have large refining costs have greatest potential for high recycle benefits. Aluminum had the highest benefit of about 49.9 where expression as emergy required for emergy cost of recycle. Highest benefits appear to accrue from material recycle systems (ranging from 0.05 to 49.9), followed by adaptive reuse systems (3.3 to 32) and then by byproduct reuse systems (2.4 to 9.2).

CHAPTER 1
INTRODUCTION

Statement of Problem

As limits to the unrestricted exploitation of resources have been felt in the last two decades, increased attention has been given to their wise use. Recently the concept of sustainability has been applied to, among other things, conservation of resources. Development is said to be sustainable if it meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). As a result, there has been a strong movement in the last several years to increase efficiency in the use of resources and increase potential for recycle and reuse of resources at all levels of society.

In many cultures, building materials have been used for centuries in a linear fashion. Structures were built, served their useful life and were replaced. In the process, materials were extracted from the environment, sequestered in the building and then discarded. The built environment (buildings and infrastructure of cities) accounts for approximately 40% of all materials extracted and used by the world's cultures (Roodman and Lenssen, 1995). Therefore tremendous impact on the rate of use efficiency of resource exploitation can be achieved if recycle and reuse of materials are incorporated into the design and construction of the world's infrastructure. However, some materials are easily recycled and reused while others are far more difficult requiring more energy and materials in their recycle than is expended in their initial extraction and transformation. Understanding the costs of recycle and reuse compared to initial extraction and transformation costs is an important component in evaluating the net effects of recycle of building materials and byproduct wastes.

Since all processes of resource extraction require energy, and recycling also requires energy, the comparative analysis of the relative amounts of energy required for both processes may provide much needed insight into the costs and benefits of recycling and reuse of resources. This leads to the overall question of this study: what are appropriate measures or indices to judge recycle benefits? Other important research questions include: are there general characteristics of resources (quality, concentration, rarity, and so on) that are more easily recycled than others? In other words are their classes of resources where recycle does not pay, and classes where the net benefits of recycle are large? Can recycle potential be predicted from some attribute of resources such as their useful life, or initial costs of production?

Background

Building Materials

During buildings' lives, their operations and maintenance have played a major role in the United States consuming 35 to 60 percent of the total national energy budget (Stein, 1977; Lowe, 1991; Roodman and Lenssen, 1995). Average annual energy used during building construction is about two times that of the building operation and maintenance period (Stein, 1977). Buildings use 40 percent of the national virgin (raw) materials (Roodman and Lenssen, 1995).

Building materials have a relatively long life span, a large portion of resource and energy consumption, and a high investment value compared to the other consumer products. Roodman and Lenssen (1995) found that some building materials such as concrete require the same amount of energy in both productions from virgin materials and from recycled materials. Other building materials such as glass and aluminum save more energy when recycled than when they are not. These savings range from 20 to 90 percent (Roodman and Lenssen, 1995).

Recycling Patterns

Recycling is an important concept in completing the ecological life cycle of materials, where waste or production output from one system is an input source to another system. Recycling serves to amplify and reinforce production processes, and provides a multiplier to the input resources. Systems that do not develop a complete cycle of materials will not be long continued (Odum, 1996).

In this dissertation, three different patterns of recycling were evaluated as follows:

1. Material recycle: the most common form of recycling. Materials from a product are replaced as part of raw material inputs to produce the same product such as aluminum cans, paper, glass bottles, and steel.
2. Byproduct use: In byproduct use, a byproduct or waste from one process is used as part of raw material inputs to produce another product such as fly ash added to cement or concrete, wood chips and sawdust used to make particle board.

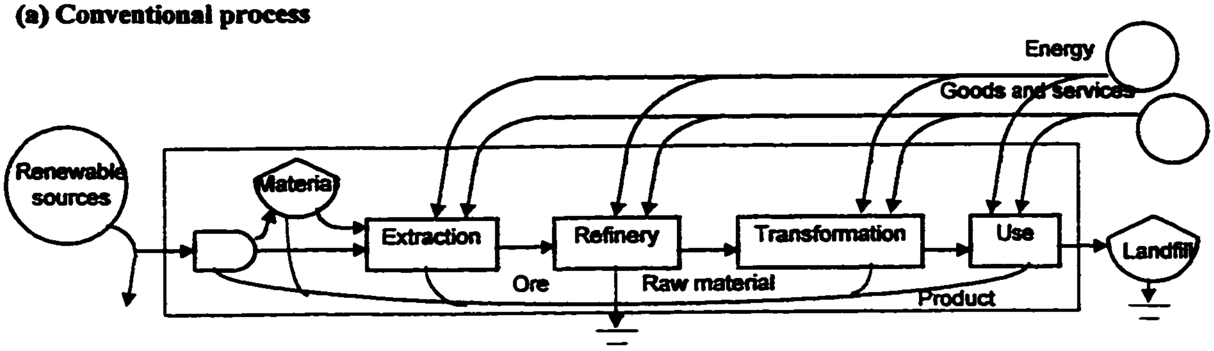
3. Adaptive reuse: In adaptive reuse, pre-consumer or post-consumer products are used as part of raw material inputs to produce a product is different from the previous product such as ceramic tile with post-consumer glass, vinyl floor with post-consumer plastics.

Figure 1-1 shows process diagrams of recycling patterns. The conventional process (a) is a primary production process that transforms extracted and refined energy and raw material inputs to a product output which eventually finds its way into a landfill.

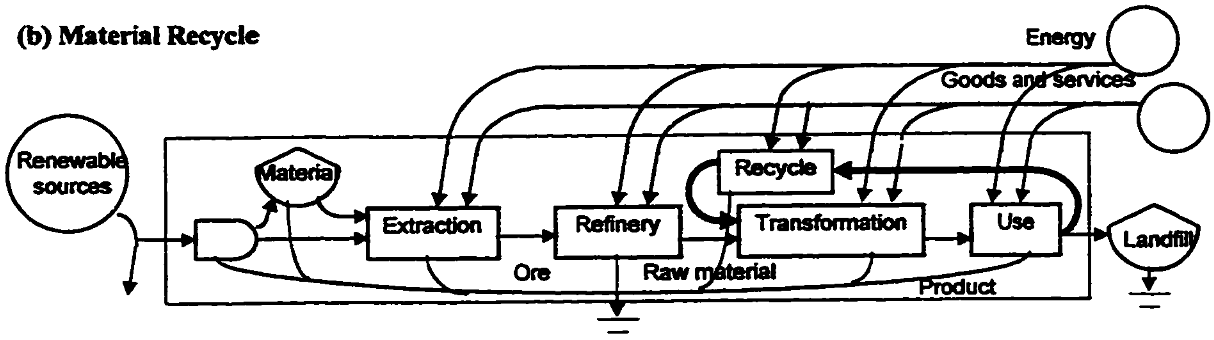
Emergy Analysis of Systems, Products, and Processes

Emergy analysis is a technique of analysis that evaluates inputs to processes in common units of energy of one form, usually solar energy. Increasingly, it is being recognized that not all energy is equivalent in its ability to do work, therefore quality correction is necessary (Odum, 1996; Brown and Ulgiati, 1997). In emergy analysis, all energies are expressed in the same form, thus avoiding the problem of comparing energies of different qualities. In addition, all energy used, both in the present and in the past, to produce a good or services is evaluated. In this way emergy analysis evaluates all required inputs (materials, services, and energy) to a process in common units of emergy, whether they were used in the past or are being used in the present. When a material, energy or service is expressed in common units of the energy required to make it, the quantity is called emergy and its units of measure are emjoules. If expressed as solar emergy the units are solar emjoules (abbreviated sej). A more complete definition of emergy, other terms used and indices calculated to aid policy and management decisions are given in the methods section of this dissertation. In the following paragraphs, an

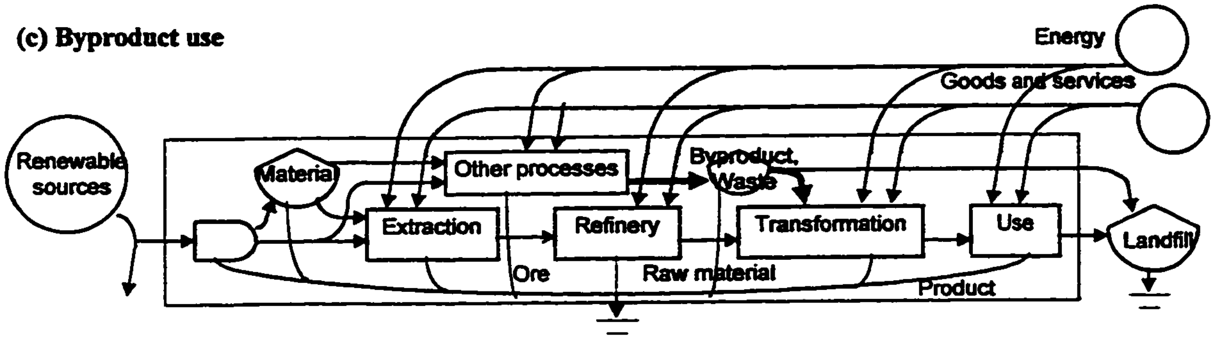
(a) Conventional process



(b) Material Recycle



(c) Byproduct use



(d) Adaptive Reuse

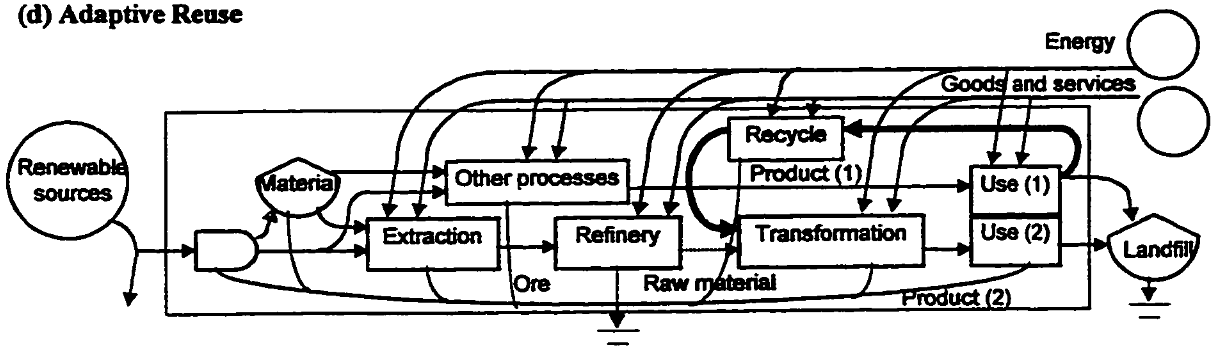


Figure 1-1. Material flows and recycling patterns. (a) conventional material flow, where material is discarded after use, (b) material recycle where material is recycle back to a stage in the transformation process and re-transformed, (c) the use of a byproduct waste from another production process in place of some material, and (d) the reuse of a material for some other purpose.

overview of the systems, products and processes that have been analyzed using emergy analysis is given.

Odum et al. (1983) evaluated numerous materials including aluminum ingot, bauxite, iron ore, steel, and machinery. Odum (1996) evaluates many products and processes relating to building materials. Iron ore and bauxite are part of a major flow of material in the sedimentary cycle where scare resources, concentrated into deposits, have been concentrated from natural processes over a long period of time. Therefore, scare resources have high emergy contents.

Roudebush (1992) combined "value engineering method" with emergy analysis to develop an "environmental value engineering system" which includes environmental impacts from built environments. The environmental value engineering analysis system evaluated 10 phases of building materials life cycle from natural extraction to disposal. The case study between concrete masonry unit (CMU) and concrete tilt-up wall panel alternatives illustrated that the CMU wall panel had about 11% higher environmental impact than the concrete tilt-up panel. However, recycling was not evaluated in the case study alternatives. Emergy analysis was used by Haukoos (1995) to evaluate conventional building systems and several primary building materials. The emergy costs of some building materials were first calculated. Then, three residential design alternative case studies (wood frame, concrete block, and steel frame) were evaluated. Dollar costs of three alternative case studies were similar. The emergy costs of wood and concrete block alternatives were similar while the steel alternative was higher. Haukoos (1995) suggested that a ratio of renewable to non-renewable emergy, and total non-renewable emergy per building life should be considered for an analysis of sustainability.

Review of Other Methods of Analysis

There are numerous methods of analysis that can be used to evaluate the material and energy requirements of production processes. Among these are embodied energy analysis, exergy analysis, and life cycle analysis. Each emphasizes significantly different spatial and temporal scales, or boundary conditions. Table 1-1 and Figure 1-2 summarize the various methods and in the following paragraphs each are reviewed.

Exergy Analysis

Exergy is available energy to do work in a process or system and work is an interaction between a system and its surroundings (Jones and Hawkins, 1986; Bejan, 1988). Exergy can be defined as physical or chemical energy. Available exergy is limited to physical or chemical exergy within production process. An exergy analysis relates the concentration of energy and material inputs to a production process to their surrounding environment and calculates the exergy based on their chemical energy (Gibb free energy) or enthalpy (Bejan, 1988). Exergy excludes services and support facilities, such as machinery, since they are not part of the material and energy inputs to the production process.

Morris and Szargut (1986) evaluated chemical exergy of some elements and compounds and provided possibilities for improvement of thermal and chemical processes. The external exergy losses depend on the reference species and the internal exergy losses in a process does not influence the calculation.

Exergy analysis is appropriate to develop and improve manufacturing process and product efficiency. Exergy analysis based on thermodynamic theory has been used for detailed evaluation. Materials and energy inputs as mass balance are completely evaluated. Human service (labor), supporting facilities, and environments are excluded.

Embodied Energy (Input-Output Analysis)

Embodied energy analysis (sometimes referred to as Input-Output energy analysis) was developed by The Center for Advanced Computation at the University of Illinois (CAC), today named The Energy Research Group of the University of Illinois. The analysis technique was to be used as a tool for economic planning. Embodied energy analysis uses an input-output matrix of dollar flows through the United States economy and matrix inversion technique to calculate energy intensities for sectors of the economy. Only primary energy is used in the analysis, and energy is assigned to each sector based on dollar flows between sectors (Hanon et al., 1977b). Energy intensities (BTUs per dollar) are calculated for 399 industrial sectors based on the Standard Industrial Classification (SIC). In this way the primary energy (fuel, nuclear, and hydroelectric ...all expressed in equivalent coal energy) requirements for any production process are evaluated by multiplying the dollar expenditures for fuels, materials, and goods by an energy intensity factor for the particular sector from which the good or material is purchased. Labor is not included, nor is the work of the environment in producing "natural capital" as inputs or for environmental services in processing waste byproducts. In addition the embodied energy analysis excludes energy used in administration such as electricity used in administrative offices and fuels for space heating and cooling (Hanon et al., 1977b; Stein et al., 1981).

The total embodied energy of a building includes the energy consumed in all phases of the industry from provision of raw materials to finished construction. It sums direct energy consumed for individual components, the direct energy used in assembly or manufacturing process, and direct energy used for transport to the jobsite. In practice, embodied energy analysis of building systems does not include indirect energy required in the past to produce energy or machinery. Imported products are considered to have the same energy value as domestic products. Labor is evaluated in all stages. Labor intensity data has been developed by using full time employment (FTE) per dollar which was converted into man hour per unit such as square foot of building component (Hanon et al., 1977b; Stein et al., 1981). Labor of each alternative is compared directly using man hour not labor energy. Energy consumed during building operation, such as electricity for heat or cooling space was evaluated by Hanon et al. (1977b). Maintenance inputs and energy were excluded. To decide which material alternatives are appropriate among the others, both energy embodied (BTUs per unit) and labor intensity (man hours) are considered, but evaluated separately (Hanon et al., 1977b).

The CAC embodied energy technique was used to evaluate the energy embodied in building from construction and manufacture processes and the energy used during building life or operation (Hanon et al., 1976; 1977b). The CAC analysis (Stein et al., 1981) was presented in three ways as follows:

1. The energy of 399 industrial-sectors (SIC).

2. Total BTU energy per square foot of structural component such as standard steel system, reinforced concrete system, and wood frame wall.

3. The BTU per square foot of 23 building types such as residential one-family, hotel or motel, office buildings, and warehouses.

Money as a measurement of inputs in the system has been argued, and can not provide accurate results since it has many variations such as transaction, interest, devalue, exchange, value added, and so on (Daly and Townsend, 1993; Odum, 1996). Price or market price does not cover all costs. It excludes the work of nature such as natural costs as rain, winds, and other environment sources. Daly and Townsend (1993) argued that the economic system should be considered based on the energy limitations from natural systems or ecological support.

Life-Cycle Assessment Analysis

The analysis of life cycle has been used since 1960s to evaluate energy efficiency, recycling, and solid waste disposal costs of alternative products (Johnson, 1997a). Currently, Life-Cycle Assessment (LCA) has been required by The Society of Environmental Toxicology and Chemistry (SETAC). LCA has three approaches: (1) life-cycle inventory, (2) life-cycle impact analysis, and (3) life-cycle improvement analysis. The objective of life-cycle inventory is to develop a data base of energy and raw material requirements, air emission, water effluents, solid waste generation, and other environmental releases throughout the life cycle of a product, process, or activity. Life-cycle impact analysis includes both quantitative and qualitative processes that characterize the effects of environmental impacts on the ecological system and on human health. Life-cycle improvement analysis is a systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and materials throughout the life cycle of a product, representing both quantitative and qualitative measures such as changes of product or process, material use, consumer use, and waste management (Fava et al., 1991; Vigon et al., 1994). LCA is used to provide alternatives concerning energy and material conservation, and reducing wastes as health consideration for decision making. The LCA method has been proposed as a standard methodology in The International Organization for Standardization (ISO) as ISO 14040 to 14043 (Sayre, 1996).

The life-cycle inventory focuses on the entire life cycle of the product, process, or activity. The life cycle of any product is composed of five processes: (1) extraction and processing of raw materials; (2) manufacturing, transportation, and distribution; (3) use, re-use, and maintenance; (4) recycling; and (5) final disposal. A raw material is defined as a primary or secondary material input at the first stage in a process. Secondary material includes materials from pre-consumer and post-consumer recycling processes. Mass balance and weight proportion of input requirements to produce the outputs (product and co-products) are used in the calculation (Curran, 1996). A recycled input can be characterized as closed-loop or open-loop. For closed-loop recycling, 100% of materials are recycled back to the manufacturing process after use. On the other hand, for open-loop recycling, all materials are discarded at the end use stage (Fava et al., 1991; Vigon et al., 1994; Curran, 1996).

A byproduct is defined as a useful product which is not a primary product. A co-product is a marketable byproduct from a process including any waste materials that can be used as raw material in a different manufacturing process (Vigon et al., 1994). Waste is defined as any output that does not have a market or usable value and which is discarded to the environment. In LCA calculation, waste does not have embodied energy content but may contain energy which, if released to the environment, requires clean up or requires treatment before being discarded to avoid environmental impacts. For maintenance and using period, LCA includes energy, materials, and waste produced in the life cycle calculations. Waste is determined by weight per unit product or by volume in solid waste.

LCA is used as a guide to evaluate and choose materials during industrial process (Johnson, 1997b). Some manufacturers have used the LCA method to report and improve processes reducing input materials, emissions, wastes, energy consumption, and using more renewable energy (Curran, 1996).

The Life Cycle Analysis uses material balance calculation and thermodynamics concepts to evaluate the systems and processes. The analysis requires detailed data. Life-cycle analysis is time consuming and many times it uses technical terms which are difficult for individuals from different sectors of the economy to understand and study results are often difficult to compare (Fava et al., 1991). Another question is how to use the evaluation results for decision making, process improvement, resource and energy conservation, toxic reduction, and so on. Since LCA has been evaluated by engineers, other knowledge such as health and ecology are necessary but often not included (Johnson, 1997a).

Given in Table 1-1 and Figure 1-2 is a summary of the main points related to each of analysis techniques.

Table 1-1. Summary of the main methods used to evaluate energy and material requirements of manufactured materials.

Methods	Scope of Study	Coefficients	Data Requirements	Units	Additional comments
Exergy	Production processes		Actual data	Thermodynamic units	No energy quality correction. Only includes direct energy. No labor and environmental inputs.
Embodied energy (Input-output analysis)	1. 18 new building construction sector. 2. 399 sectors of Standard Industrial Classification (SIC).	Margin factor (using present value of current $)	1. Current dollar 2. BTU of energy intensity	British Thermal Units (BTU)	No energy quality correction. Labor is not included. No environmental inputs.
Life Cycle Analysis	1. Time and scale of interest excluding natural processes. 2. Quantitative data less than 5%, 10%, or 20% are excluded.		Actual, average, or statistical data	Thermodynamic units and Mass balance (SI units; Joules, kilogram, kilometer, etc.)	No energy quality correction. Labor is not included. Only direct environmental inputs included.
Emergy Analysis	1. Time and scale of interest based on ecological boundary. 2. Quantitative data less than 5% are excluded.	Transformity	Statistical or actual data	Solar emjoules	Labor is included. Environments and services are included. Correction for energy quality.

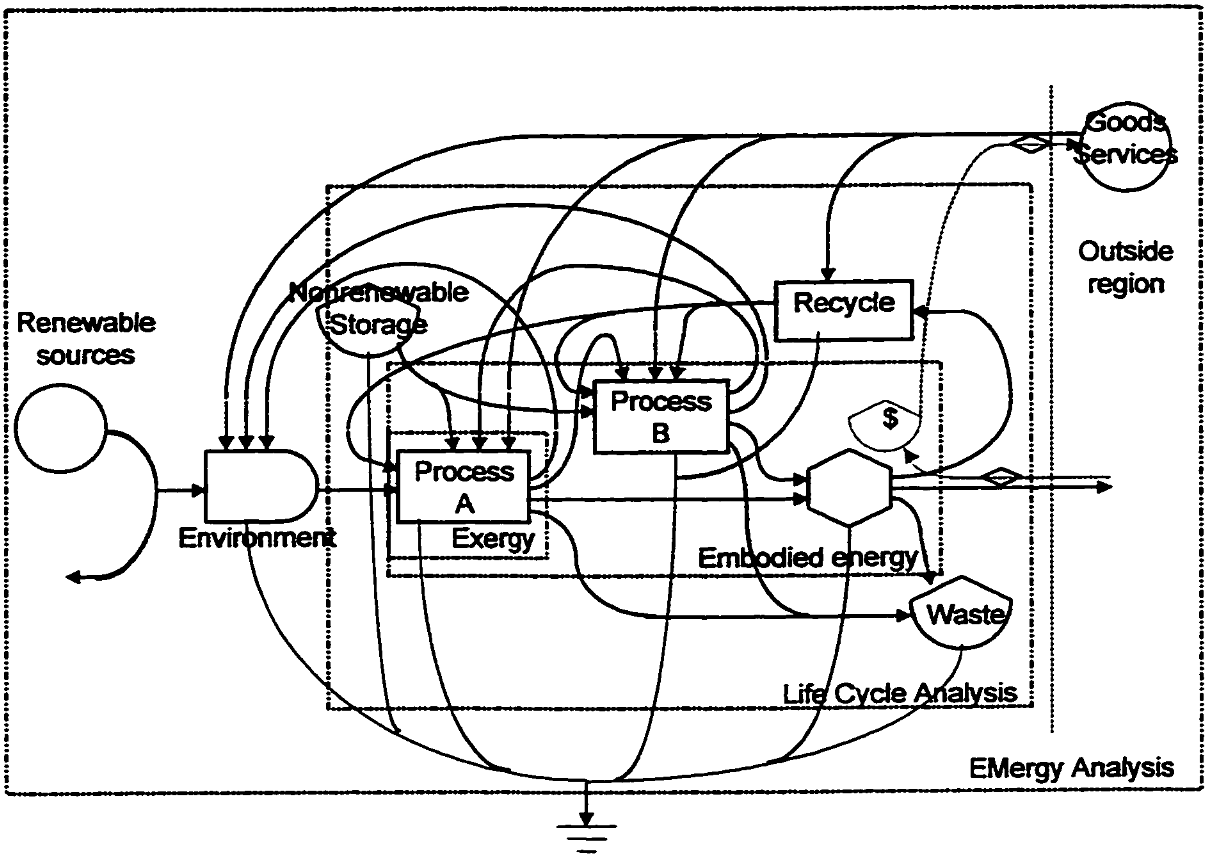


Figure 1-2. Scale and scope of the various methods of evaluating material and energy requirements of processes. Each dashed line encloses the portions of systems that an evaluated with each method.

Scope of Study

This dissertation focuses on recycling patterns of major building materials defined by the American Institute of Architects (AIA) Masterformat. It uses a standard measurement unit of solar emergy and includes all energy necessary for production processes (i.e. fossil fuel, renewable energy, and human services). For each major material their different patterns of building material cycles were evaluated: 1) cost of manufacture from "raw resource," 2) demolition, and 3) costs of recycle. For comparison, the emergy costs of "landfilling" of materials were also evaluated.

Overall, the steps in the emergy evaluation of building material and recycling were as follows:

1. A complex systems diagram of each material process was drawn to gain understanding and as an inventory of energy and material flows necessary for each step in the material cycle.

2. A simplified diagram was aggregated from the complex diagram to aid in overviewing processes and to aid in comparisons between materials.

3. Energy and material input and output data for each building material were obtained from the literature and collected from current data provided by manufacturers.

4. Emergy evaluation tables were constructed and each energy source in the aggregated diagram was an evaluated row in the table. Transformities, Emergy, and Emdollar values for each material and process were calculated.

5. Emergy indices were calculated for each material and process to aid in comparison. Comparisons were made between recycle, reuse, and byproduct use.

CHAPTER 2
METHODOLOGY

This chapter presents methods to develop recycling indices and evaluations. First, material selection criteria and definition of temporal boundary are given. Second, a description of main features of emergy analysis is given. Third, the emergy evaluation methodology is given as a step by step procedure, and finally indices for comparison of materials and recycling alternatives are described and defined.

Material Selection Criteria

To define research boundary, the dissertation mainly focused on major building materials which have been used in the construction industry. Selected major building materials were based on the following criteria:

1. One or two materials of each major building material in American Institute of Architects (AIA) Masterformat were chosen. Concrete, masonry, metals (ferrous and non-ferrous), wood, plastics, and glass were selected.
2. For each major building material, one product was chosen that had a long useful life as "structure," and another product was chosen that had a short useful life as "finish."
3. Material must be recyclable in some manner (material recycle, byproduct use, or adaptive reuse).
4. Material has a relatively large portion of the market.
5. Data were available from a real operating process.

6. Most data and products were in the United States or Canada. If available data could not be found, data from another country were used.

7. In case of post-consumer materials, only the use of recycling materials as main inputs was evaluated.

8. If a composite product was evaluated, the product should contain a large portion of major material from recycling, for example, wood with plywood as I-beam. Composite products which were not recyclable were not considered.

Given in Table 2-1 is a list of materials that were evaluated in this dissertation.

Application Life and Useful Life

In this dissertation, two life cycle times were used to compare materials. The first, useful life, is the usable period of time that a material will serve its functions. It is the time interval that a particular material or configuration of material will last under normal use. The second life cycle considered in this dissertation is application life. As shown in Figure 2-1, the application life of a particular material or configuration of materials is the life required of the material. The application life may be longer or shorter than the useful life. Given in Table 2-2 is a summary from the literature of useful and application life of building materials.

Emergy Analysis

The techniques of emergy analysis are used to evaluate energy and materials requirements in common units of solar emergy required to produce them. Emergy is a measure of the available energy that has already been used directly and indirectly during

Table 2-1. The final list of selected materials.

Building Materials	**Use as Finish**	**Use as Structure**
Cement	mortar	
Concrete	pavement	column or beam
Masonry	clay tile	clay brick
Ferrous metal	wall panel	column or beam
Non-ferrous metal	aluminum sheet	column or beam
Wood	plywood	post or beam
Plastics	vinyl floor	plastic lumber
Glass	ceramic tile	

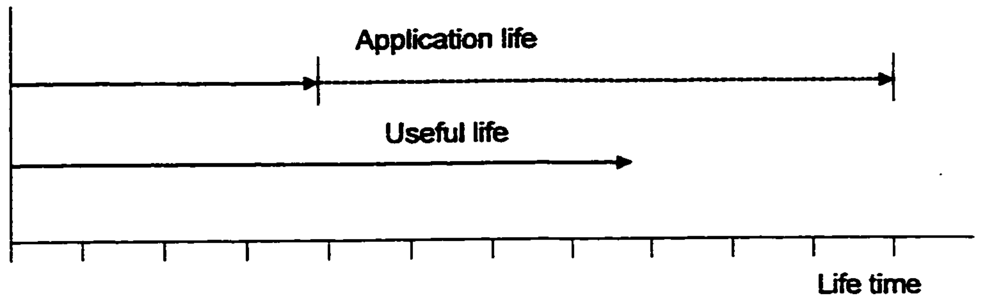


Figure 2-1. Relationship between useful life and application life for building material. The application life can be shorter or longer than the useful life depending on the expected life of the application.

Table 2-2. Application time of building materials.

Note	Building Materials	Building Components	Useful Life *	Application Life
1.	Cement	mortar	30	60
2.	Concrete	pavement	20	70
3.		column or beam	45	150
4.	Clay Brick	clay tile	30	
5.		column	45	150
6.	Steels	wall panel	30	60
7.		column or beam	45	100
8.	Aluminum	aluminum sheet column cover	30	
9.		column or beam	45	150
10.	Woods	plywood wall panel	10	
11.		post or beam	25	
12.	Plastics	vinyl floor	10	
13.		plastic lumber (temporary structure)	20	
14.	Glass	ceramic tile	20	
15.		float glass	30	

* Useful life for repair or renovation are based on fifty-year of building life (Liska, 1988).

Footnotes **

1. 15 years (Craven et al., 1994, p. 95) as awning
   30 years (Craven et al., 1994, p. 95) as flooring
   60 years (Craven et al., 1994, p. 95) as plaster
   60 years (Doran, 1993, p.25/3) as concrete tiles and slates
   25-35 years (Liska, 1988, Figure 2.4, p.33) as masonry exterior and culverts
2. 30 years (Craven et al., 1994, p. 95) as flooring and plumbing fixtures
   71 years (Woods et al., 1960, p.19-21) as reinforced-portland-cement concrete
   10-20 years (Doran, 1993, p.8/3, 8/10-11) as pavement
   20 years (Liska, 1988, Figure 2.4, p.33) as paving and walks
3. 150 years (Craven et al., 1994, p. 95) as primary structures
   100-200 years (Doran, 1993, p.14/3) as light weight concrete structure
   71 years (Woods et al., 1960, p.19-21) as reinforced-portland-cement concrete
   40-45 years (Liska, 1988, Figure 2.4, p.33) as reinforced concrete frame
4. 20 years (Liska, 1988, Figure 2.4, p.33) as paving and walks
   30 years (Liska, 1988, Figure 2.4, p.33) as retaining wall and fencing
   40-45 years (Liska, 1988, Figure 2.4, p.33) as masonry exterior
5. 150 years (Craven et al., 1994, p. 95) as primary structures
   40-45 years (Liska, 1988, Figure 2.4, p.33) as heavy masonry exterior
6. 30-60 years (Craven et al., 1994, p. 95) as flooring and piping systems
   40-50 years (Doran, 1992, p.4/9) as wrought iron
   20-30 years (Liska, 1988, Figure 2.4, p.33) as metal exterior
7. 150 years (Craven et al., 1994, p. 95) as primary structures
   70-100 or up to 140 years (Doran, 1992, p.3/11) as grey cast iron
   30-45 years (Liska, 1988, Figure 2.4, p.33) as steel frame

Table 2-2--continued.

8.	15 years (Craven et al., 1994, p. 95) as column cover
	20-30 years and up to 80 years (Doran, 1992, p.2/19) as aluminum durability
	20-30 years (Liska, 1988, Figure 2.4, p.33) as metal exterior
9.	150 years (Craven et al., 1994, p. 95) as primary structures
	30-45 years (Liska, 1988, Figure 2.4, p.33) as structural frame
10.	15 years (Craven et al., 1994, p. 95) as plywood finishing
	5-15 years (Doran, 1993, p.50/5) as plywood
	10-15 years (Liska, 1988, Figure 2.4, p.33) as interior finishing
11.	60-150 years (Craven et al., 1994, p. 95) as frame and primary structures
	15-25, or more than 25 years (Doran, 1993, p.50/5) as wood and timer depending on species, humidity, and treatment
	20-35 years (Liska, 1988, Figure 2.4, p.33) as timber, platforms, frame, and posts
12.	15 years (Craven et al., 1994, p. 95) as floor finishing
	10-20 years (Doran, 1993, p.8/3, 8/10-11) as polyvinyl chloride (PVC)
	10-15 years (Liska, 1988, Figure 2.4, p.33) as paving and walks
13.	25 years (Company's brochure and Personal communication with HDPE lumber company, 1998) as plastic (HDPE) lumber
	20 years (Liska, 1988, Figure 2.4, p.33) as plastics pipe
14.	15-30 years (Craven et al., 1994, p. 95) as floor and wall finishing
	10-20 years (Doran, 1993, p.13/3) as wall and floor tiles
	30 years (Liska, 1988, Figure 2.4, p.33) as vitrified tile
15.	60 years (Craven et al., 1994, p. 95) as windows
	20-30 years (Liska, 1988, Figure 2.4, p.33) as windows

** Underlined application times were used in evaluations.

the transformation process to make a product or service (Odum, 1996). Emergy includes all inputs of natural energy, fuel energy, goods, and services to production processes, expressed in common units of solar emjoules (abbreviated, sej). The solar emjoule is the basic unit of emergy accounting. The word emjoule describes emergy joule, and is used to differentiate between joules of energy evaluated as available energy and emjoules of emergy.

Solar Transformities and Emergy Per Gram

A solar transformity is the solar emergy required to make one joule of energy of a service or product and is expressed as solar emjoule per joule (sej/J). Transformity characterizes the position of a product in the global hierarchy. The higher the transformity of a product or service, the more energy transformations contributed to the product.

Transformity is the emergy per joule of energy. Sometimes, especially for materials, it is more convenient to express the transformity in units of emergy per gram (sej/g). In this dissertation, both transformity and emergy per gram were used to evaluate emergy requirements of building materials. The energy and material requirements for the production of a given item were multiplied by their respective transformity which yielded emergy for each required input.

Transformities and emergy per gram have been calculated for many items in previous studies. Many of these were relied on to evaluate the emergy inputs to process that were analyzed in this dissertation. In this way, an emergy evaluation was not required for every input to a process with each new process evaluated. While it is recognized that there is no one universal transformity for a given class of products, and in fact it is well understood that transformities for the same product produced in different processes vary, the use of an average transformity where the exact origin of a product is not known is appropriate. In addition to previously calculated transformities, several new transformities and emergy per gram of products and services were calculated as part of this dissertation (given as Table A-2 in appendix A). A complete list of transformities and emergy per gram that were used in this dissertation is given in Table A-1 (appendix A).

Emergy-Money Ratio

Services are necessary inputs to all human controlled processes and therefore are evaluated as the emergy expended in previous transformations that was required to provide them. To evaluate the emergy in service inputs to processes studied in this dissertation, an average emergy-money ratio was used that was calculated from the larger economy within which a given process was embedded. Since all processes studied were within the United States economy, an average emergy-money ratio for the United States economy was used. It was calculated by dividing the total emergy used in support of the economy, by the gross domestic product (GDP). Once obtained, the average emergy-money ratio was used to evaluate service inputs to material transformations by multiplying dollar costs of service inputs by the emergy-money ratio.

Data Collection for Emergy Evaluation

Figure 2-2 summarizes sources of data for emergy evaluations of materials. Data for mining and extraction of raw resources were derived from national statistical summaries of industrial at the 4 digit Standard Industrial Code (SIC) level (step 1 in Figure 2-2). Data for inputs to transformation processes were, for the most part, from

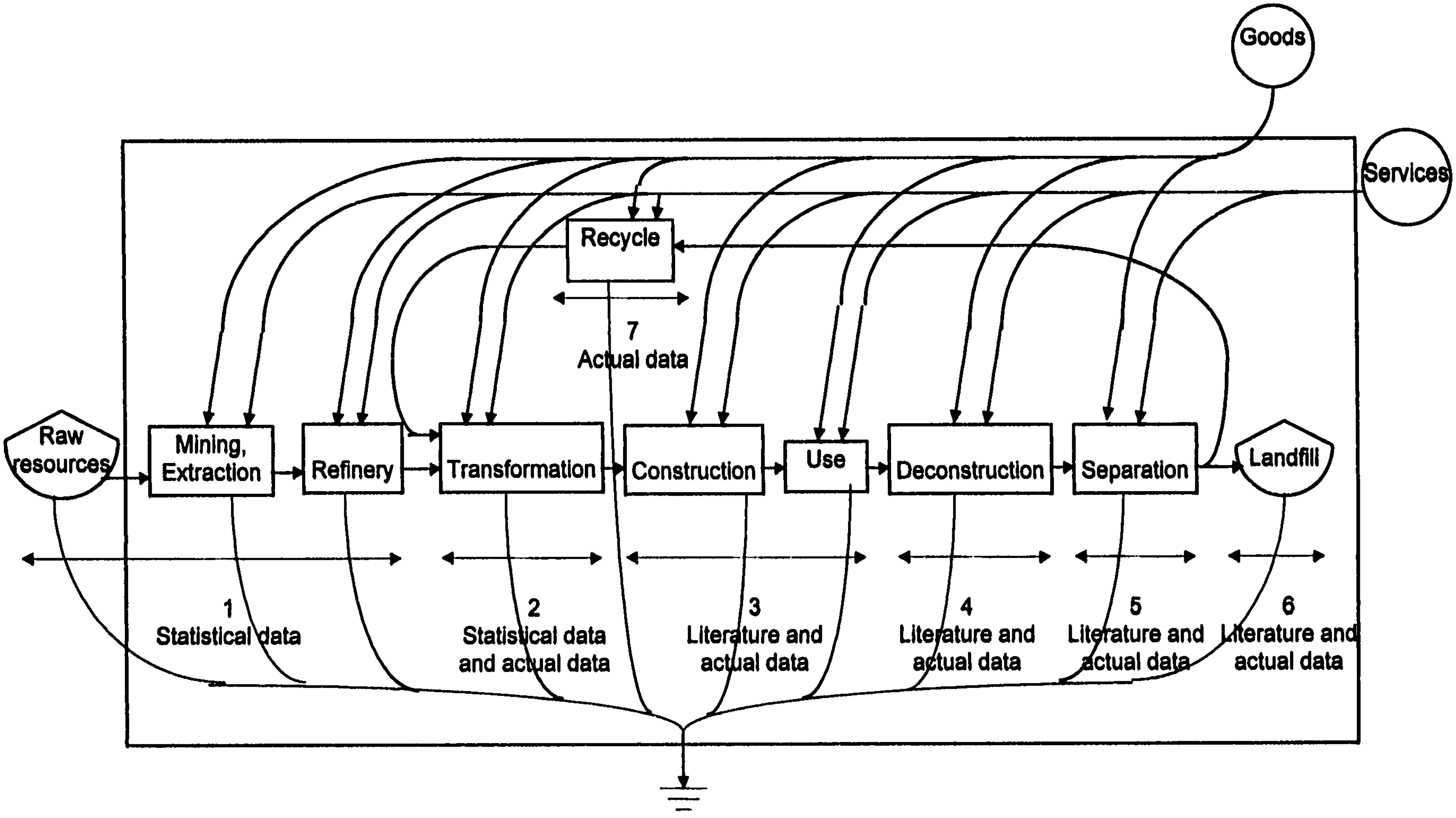


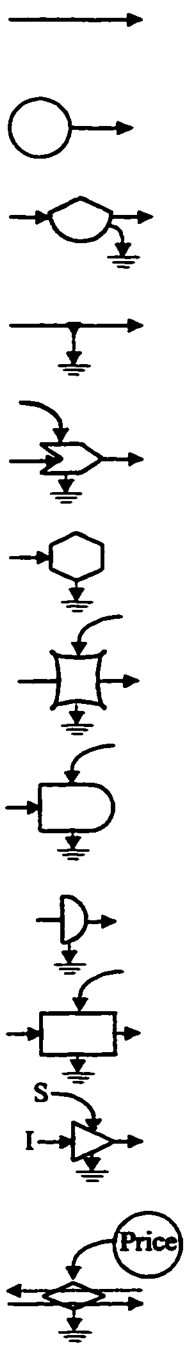
Figure 2-2. Data collection of typical recycling system assuming material is a non-renewable ore.

national statistical data, although for several materials (iron ore, aluminum ingot, sawmills, plywood, and plastics) data from actual process were used (step 2). The construction costs, useful life, and deconstruction of materials were taken from the literature and from actual data from operational systems (step 3 and 4). Separation and landfill energy requirements were derived from the literature and actual operating systems (step 5 and 6). Data for the recycle process of each material investigated were obtained from actual operating systems (step 7).

Emergy Systems Diagrams and Conventions

Symbols, illustrated in Figure 2-3, are used in this dissertation to diagram systems of recycle and reuse. Energy system symbols represent system components including sources, flows, and storage. The arrangement and connection of symbols explain the flow paths, processes and kinetics of a system. Material and energy flow between processes are represented as solid lines in the diagrams. Diagrams are arranged so that energy and materials flow from left to right. Energy sources, components, and processes are arranged according to transformity beginning with the lowest transformities at the left and progressing to higher transformities toward the right of the diagram. Flow pathways of materials and energies may coverage and be added, or interact in a production process to produce something of higher quality.

Figure 2-4 shows several different configurations for material and energy flows. A split pathway divides into two or more branches of the same kind with the same transformity (Figure 2-4c). If the process produces two or more different products or co-products, each flow is different and has different transformity. Transformities of co-



Energy circuit: A pathway whose flow is proportional to the quantity in storage upstream.

Source: Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank: A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

Heat sink: Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.

Interaction: Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.

Consumer: Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

Switching action: A symbol that indicates one or more switching actions.

Producer: Unit that collects and transforms low-quality energy under control interactions of high-quality flows.

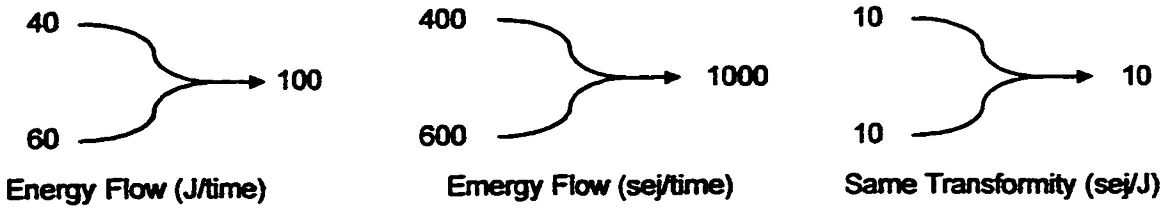
Self-limiting energy receiver: A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reaction on a circular pathway within.

Box: Miscellaneous symbol to use for whatever unit or function is labeled.

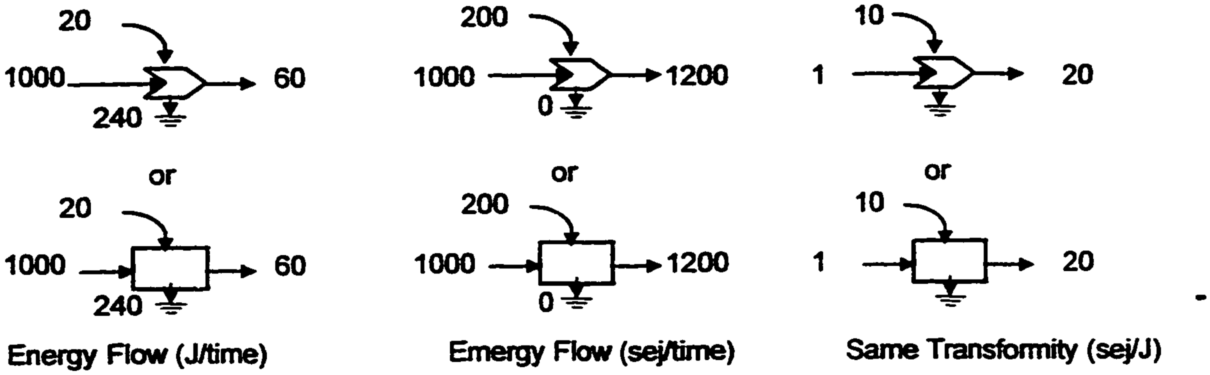
Constant-gain amplifier: A unit that delivers an output in proportion to the input I but is changed by a constant factor as long as the energy source S is sufficient.

Transaction: A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

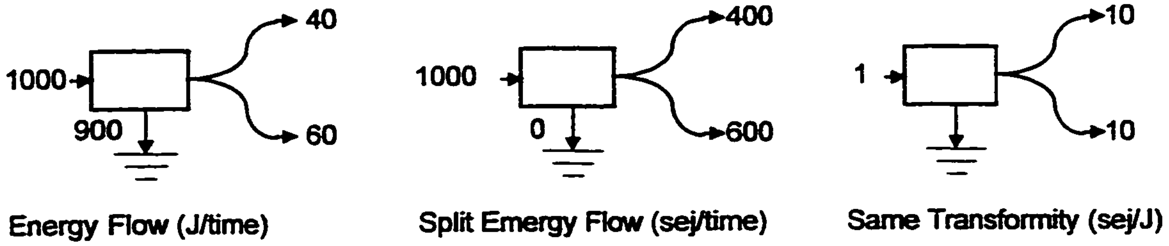
Figure 2-3. Symbols and definitions of energy systems language (Odum, 1996).



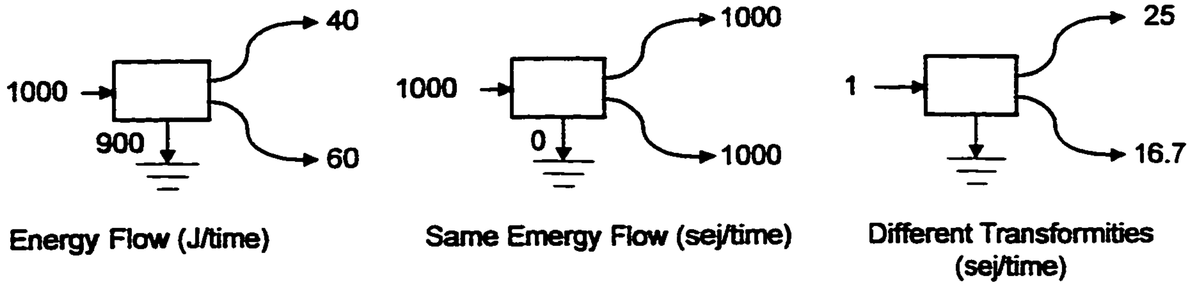
Addition
(a)



Interaction
(b)



Split Pathway
(c)



Co-product Pathway
(d)

Figure 2-4. Emergy flow patterns through systems (Odum, 1996), showing: a) the addition of two flows of the same form of energy; b) the interaction of two different forms of energy; c) a split pathway where the same energy is "split" for two different uses, and d) a co-product pathway where a process has two different energy outputs of different form.

products are different since each product contains the same emergy value but has a different energy or material output from the process (Odum, 1996).

Energy Systems Diagramming

Energy language system diagrams were drawn to explain the life cycle of building materials to combine data and sources associated with the system, and organize their relationships. The diagram of the system was then used to construct a table of data requirements for the emergy analysis. Diagrams were drawn step by step as follows (Odum, 1996):

1. The boundary was defined as a window to frame the system.
2. Important sources were listed. To be listed, a source had to be at least five percent or more of the total system function.
3. To define the system scale, the important principal components within the boundary are listed.
4. A list of flows, interactions, and production and consumption processes, etc. was made including important money flows and transactions.
5. Energy systems diagrams were then assembled by using the symbols in Figure 2-3.

Emergy Evaluation

After system diagrams were drawn, an emergy evaluation table was constructed. Each source that crosses the system boundary was an entry in the Table. Flows of materials and energy were normally made on a yearly basis. Each table was constructed using the same format (Odum, 1996) with six columns as follows:

1 Footnote	2 Item	3 Input resource (J, g, $)	4 Solar Emergy per unit (sej/J, sej/g, sej/$)	5 Solar Emergy (sej)	6 Emdollar (Em$/yr.)

Column one is a list of line item numbers indicating the source of raw data and detail calculations at the end of the table.

Column two is a name of the evaluated item and identified on the accompanying system diagrams.

Column three contains input resources given in physical units of joules, grams, or dollars. The data are collected from industry, or from published literature and statistical reports. All data are shown on an annual basis. Calculations and references are shown in each footnote.

Column four is solar emergy per unit. Its units are sej/J for energy, sej/g, for mass or sej/$ for money. Input data in column three are multiplied by solar transformities in column four to obtain solar emergy values (sej/yr) in column five.

Column five is solar emergy values of each evaluated input resource. These values are calculated by multiplying input resource data in column three by solar transformity values in column four.

Column six is Emdollar value. Emdollar values are calculated by dividing solar emergy in column five by solar emergy per dollar ratio of specific year. The solar emergy per dollar ratio is calculated by dividing annual solar emergy values of the country by Gross Domestic Product (GDP) of that year.

A key aspect of emergy analysis is the transformity or emergy per mass which is used to convert inputs to process into units of emergy. Many transformities have been previously calculated (Odum, 1996) and were used in this dissertation. Several transformities were calculated specifically for this dissertation (transportation, landfilling, construction, and deconstruction). Transformities and emergy per mass calculated by others that were used in this dissertation are given in appendix A.

Emergy Indices

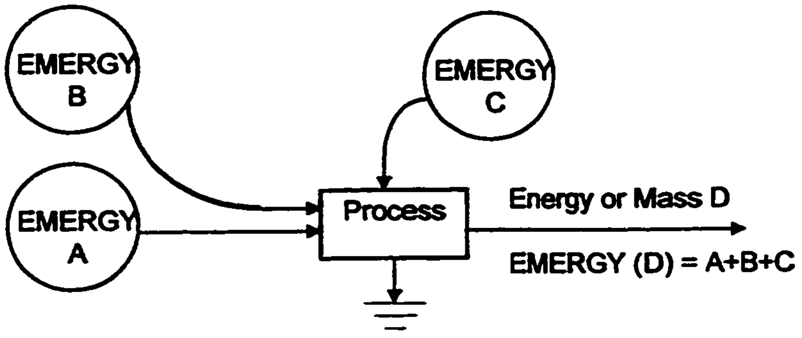
After the emergy analysis tables were completed, indices were calculated to achieve perspective and aid in decision-making. Several different criteria were used to judge alternatives and make recommendations. In general, the alternative that contributed the most emergy to the public and minimized environmental losses was recommended.

Several emergy indices and their calculation are illustrated in Figure 2-5. The emergy investment ratio (IR) is the ratio of emergy from the economy (F) to the emergy from the environment. It gives an indication of the relative intensity of a process and its competitive position. To be competitive, a process should have a similar ratio to competing processes. The emergy yield ratio (EYR) is the output emergy (Y) divided by the input emergy purchased from the economy.

The solar transformity is the solar emergy required to make one joule of a service or product. Its units are solar emjoule per joule (sej/J). The solar emergy per mass is the solar emergy required to make one gram of a product. Its units are solar emjoules per gram (sej/g). Solar transformity and emergy per mass indicate the energy transformations that contributed to a product. The more solar emergy required or used in a process, the higher the transformity or emergy per mass of the product. The transformity and solar emergy per mass represent position of product in the system hierarchy. The solar transformities and solar emergy per mass used in this dissertation are given in Appendix A.

Emergy Intensity of Recycling Operations

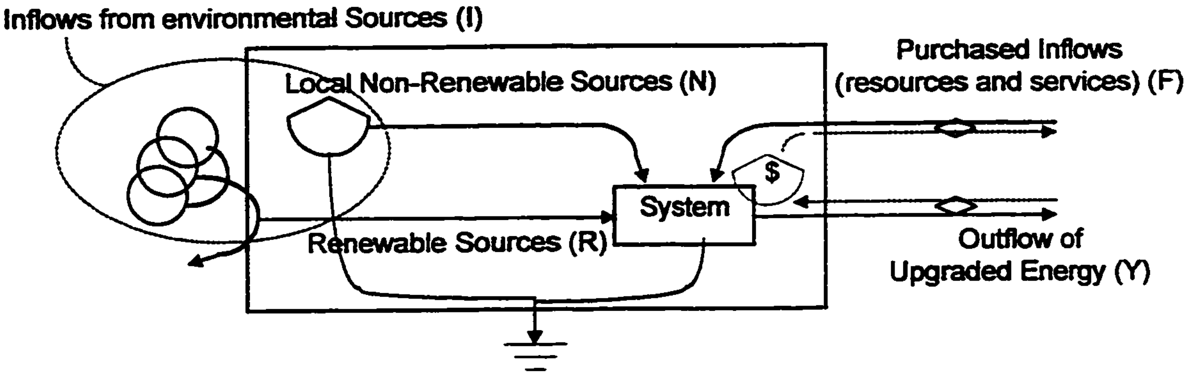
In recycling facilities, such as material recovery facility (MRF), curbside collection, separation facility, emergy inputs were evaluated as emergy intensity (emergy per gram of other inputs besides building material itself). Emergy intensity is not transformity or emergy per gram. Emergy intensity reflects the energy inputs required to bring a material back to a previous stage, in which its transformity or emergy per gram is



Transformity D (sej/J) $= \frac{\text{EMERGY A+B+C (sej/time)}}{\text{Energy D (J/time)}}$

Emergy per mass D (sej/g) $= \frac{\text{EMERGY A+B+C (sej/time)}}{\text{Mass D (g/time)}}$

(a)



EMERGY Investment Ratio = F/I (Odum, 1996)

EMERGY Yield Ratio = Y/F (Odum, 1996)

(b)

Figure 2-5. Simplified emergy diagrams illustrating emergy indices (Odum, 1996) used in this dissertation. a) Calculation of the transformity and emergy per gram. b) Calculation of emergy indices.

the same as a raw material input at that stage. Only the emergy required in recycling facilities is added into the evaluated processes to avoid double counting.

Building Material Mass and Price

Prices of building materials are usually given in varying units of measure such as dollars per sheet (plywood), dollars per board foot (lumber), dollars per cubic foot (concrete), and so forth. To standardize price, prices were expressed as mass of material per dollar. First, prices of materials from the literature and current cost estimate guides were compiled and expressed as units of material per dollar (i.e. board feet/$). Then mass units per reporting unit were calculated using average mass per unit from the literature (i.e. g/board foot). Finally dollars per unit mass were calculated by multiplying reporting unit per dollar by ratio of mass per reporting unit (i.e. board feet/$ * g/board foot = g/$).

Comparison of Major Building Materials

To compare different materials, several indices were calculated using emergy content, dollar costs, and useful life. The emergy content of each material was evaluated using emergy analysis diagrams and tables as described above. Using standard building cost code calculators (RS means, 1998), the dollar costs per gram of material were determined (price) for each material and expressed as grams of material per dollar (g/$). The emergy per dollar was calculated and compared for different materials. Useful life of a material affects the total emergy commitment for a particular application. Choice of material selection criteria may be influenced by the emergy commitment in a material over its entire useful life. The following indices were calculated for each material:

Price (P) - The ratio of mass of material received to dollars paid. P = g/$

Emergy per mass - The total emergy required to make a material per unit of mass. Units are sej/g.

Emprice - The product of the emergy per gram and price. The units of emprice are sej/$.

Ratio of emergy per useful life - The ratio of total emergy used in making a material divided by its useful life.

Life Cycle emergy intensity - The sum of emergy required to make a building material, and dispose of it, either through recycling or landfilling. Units are sej/g.

Recycling Indices

Figure 2-6 shows aggregated patterns of material use. In the top diagram, a conventional material cycle is shown where raw materials are refined, used, and discarded. The refining of raw materials entering from the left requires an emergy input of fuels, good and services (A1). Transforming the refined materials into a product requires emergy inputs of fuels, goods, and services (B1). The emergy in the product (D1) is the sum of the emergy in the raw materials and the emergy inputs for refining and transforming (R1+A1+B1). After use, the product is disposed of requiring emergy inputs of fuels, goods and services for collection and disposal (C1). The emergy of disposal includes lifetime requirements for maintenance and operation of the landfill as well as the one time emergy used in collection. The emergy content of the waste product (E1), is the sum of all emergy inputs (R1+A1+B1+C1).

An aggregated recycling system is shown in the bottom diagram in Figure 2-6. Raw resources inflow and are refined requiring an emergy input of fuels, goods, and services (A2). At this point in the process, recycled material (G) is substitutable for the output from the refining stage; thus the input to the transformation stage is composed of some material from the raw resource pathway, and some material from the recycle pathway. Transformation requires an emergy input of fuels, goods, and services (B2). The emergy in the product (D2) is the sum of the emergy in the raw materials and all the emergy inputs required to maintain the cycle of the material system (R2+A2+B2+C2+F).

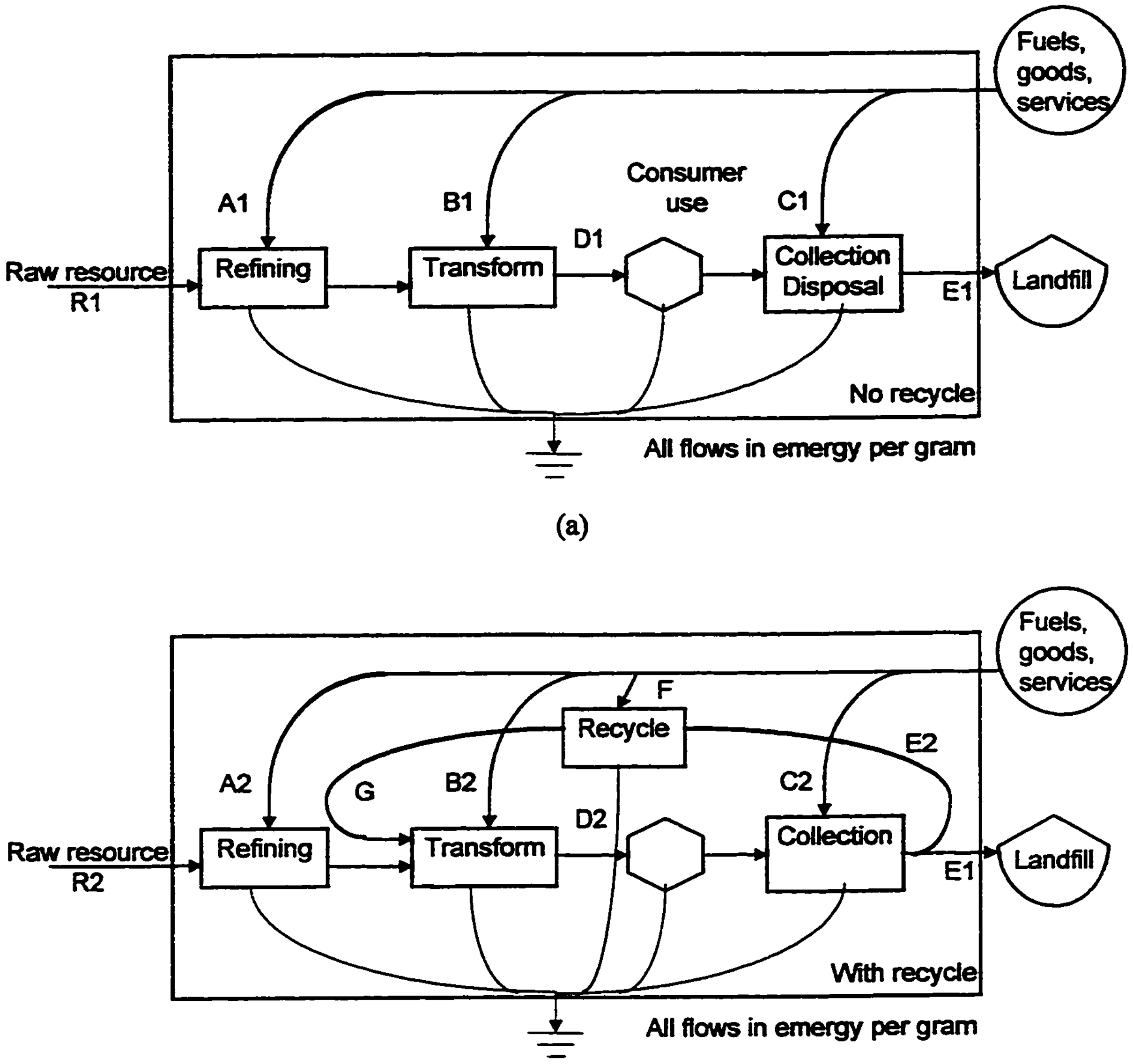
Several recycle indices were calculated for the materials evaluated. Using Figure 2-6 as a guide the following indices were calculated and compared for each material and recycle pattern:

<u>Recycle Benefit Ratio (RBR)</u> - The ratio of emergy used in providing a material from raw resources (A1) to the emergy used in recycle (C2+F). The larger this ratio the greater the advantage of recycle. RBR = A1 / (C2+F)

<u>Recycle Yield Ratio (RYR)</u> - The ratio of emergy in recycled material (G) to emergy used for recycle (C2+F). RYR = G / (C2+F)

<u>Landfill to Recycle Ratio (LRR)</u> - The ratio of emergy required for landfilling a material (C1) to the emergy required for recycle (C2+F). LRR = C1 / (C2+F)

<u>Recycle Efficiency Ratio (RER)</u> - The ratio of material and energy conserved to the emergy required for recycle when recycle materials are used. RER = (R1+A1+B1+C1) / (C2+F)



(a)

(b)

R1 = Emergy of raw resource
A1 = Emergy for refinery
B1 = Emergy for transformation
C1 = Emergy of collection and landfilling
D1 = The sum of R1, A1, and B1

R2 = Emergy of raw resource
A2 = Emergy for refinery
B2 = Emergy for transformation
C2 = Emergy of collection and landfilling
D2 = The sum of R2, A2, B2, C2, and F
G = Emergy of recycled material
F = Emergy of recycling inputs

Figure 2-6. General diagrams illustrating the various recycling indices (see text) used to compare alternative recycling patterns and uses of materials. The conventional pattern of consumption and disposal is shown in (a) contrasting with a general recycle pattern in (b).

CHAPTER 3
RESULTS

Results of the evaluation of recycle and building materials are organized in two parts. First results of emergy evaluation of major building materials are presented including both conventional production processes and alternative processes that include some forms of recycle. Alternatives included the use of byproducts from one production process in the production of some other material, recycle of post-consumer "wastes," reuse of materials, and internal recycle of production wastes with in the same production process. Comparative analyses of materials are presented that compare economic costs, emergy requirements, and useful life.

In the second part of the results, recycle systems are compared. Emergy evaluations of several recycle processes such as demolition, sorting, landfilling, and transportation are given. Four recycle indices are calculated for materials that are used to compare recycle potential and efficiency of different configurations of recycle, byproduct use, and material reuse.

Building Materials

In this section, first detailed emergy evaluations and comparisons of major building materials are presented. In each case, the conventional production process is evaluated first and then alternative systems of production that include some form of recycle or reuse are presented.

Figures are given that illustrate a detailed and summary diagram for each material. The summary diagram shows emergy of main material and other material inputs, purchased inputs, and production output of 1 gram of that product. Supporting analyses, such as coal fly ash, pig iron, aluminum ingot, and plastics, are given in Appendix C.

Concrete Material

Cement (as mortar)

Given in Table 3-1 and summarized in Figure 3-1 and 3-2, taken from national statistics, are the emergy analysis of cement mortar with coal fly ash is a byproduct recycling pattern. The use of coal fly ash is mainly considered an environmental clean up. With its addition, the volume of cement yield is increased by about 2%. Commonly the proportions of portland cement and fly-ash (class C or F) are 70:30 (Doran, 1992). The emergy in fly ash input was evaluated (Table C-1, appendix C) using the coal combustion process in power plant and assuming the heat, fly ash, and bottom ash as co-products.

Data for the analysis of cement were obtained from national summaries of industry wide practices. The cement transformity was 1.98E+9 sej/g and coal fly ash transformity was 1.4E+10 sej/g. Transformity of cement product with fly ash was 2.2E+9 sej/g. The emergy of lime stone and cement rock were the largest inputs, together comprising over 60% of the total. Nationally, coal is a large portion of energy used in the production of cement. Transportation is very small flow since raw materials are on-site. In this analysis, the transportation of the cement product to market is not considered.

Table 3-1. Emergy evaluation of cement production (with coal fly ash) in the United States (1995).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
A. Conventional cement product (Figure 3-1)					
1	Limestone	g	8.01E+13	1.00E+09	801.42
2	Cement rock	g	2.42E+13	1.00E+09	241.64
3	Coral	g	6.80E+11	1.00E+09	6.80
4	Clay	g	4.29E+12	2.00E+09	85.88
5	Shale	g	4.38E+12	1.00E+09	43.78
6	Bauxite	g	9.67E+11	8.55E+08	8.27
7	Sand and sand stone	g	2.95E+12	1.00E+09	29.51
8	Iron ore	g	1.52E+12	1.32E+09	20.10
9	Gypsum	g	4.00E+12	1.00E+09	39.97
10	Coal	J	2.98E+17	4.00E+04	119.21
11	Natural gas	J	4.06E+16	4.80E+04	19.50
12	Oil	J	1.65E+15	6.60E+04	1.09
13	Liquid fuel, waste	J	2.30E+13	6.60E+04	0.02
14	Tires, waste	J	3.67E+15	2.10E+04	0.77
15	Electricity	J	3.97E+16	1.74E+05	69.15
16	Transport (Boat)	ton-mile	2.61E+08	1.17E+11	0.31
17	Transport (Railroad)	ton-mile	3.44E+08	5.07E+10	0.17
18	Transport (Truck)	ton-mile	9.14E+07	9.65E+11	0.88
19	Labor	$	6.16E+08	1.25E+12	7.71
20	Annual Yield (Y)	g	7.55E+13	1.98E+09	1496.17
B. Byproduct use cement product (Figure 3-2)					
21	Limestone	g	8.01E+13	1.00E+09	801.42
22	Cement rock	g	2.42E+13	1.00E+09	241.64
23	Coral	g	6.80E+11	1.00E+09	6.80
24	Clay	g	4.29E+12	2.00E+09	85.88
25	Shale	g	4.38E+12	1.00E+09	43.78
26	Bauxite	g	9.67E+11	8.55E+08	8.27
27	Sand and sand stone	g	2.95E+12	1.00E+09	29.51
28	Iron ore	g	1.52E+12	1.32E+09	20.10
29	Gypsum	g	4.00E+12	1.00E+09	39.97
30	Fly ash	g	1.40E+12	1.40E+10	195.44
31	Coal	J	2.98E+17	4.00E+04	119.21
32	Natural gas	J	4.06E+16	4.80E+04	19.50
33	Oil	J	1.65E+15	6.60E+04	1.09
34	Liquid fuel, waste	J	2.30E+13	6.60E+04	0.02
35	Tires, waste	J	3.67E+15	2.10E+04	0.77
36	Electricity	J	3.97E+16	1.74E+05	69.15
37	Transport (Boat)	ton-mile	2.61E+08	1.17E+11	0.31
38	Transport (Railroad)	ton-mile	3.44E+08	5.07E+10	0.17
39	Transport (Truck)	ton-mile	9.14E+07	9.65E+11	0.88
40	Labor	$	6.16E+08	1.25E+12	7.71
41	Annual Yield (Y)	g	7.69E+13	2.20E+09	1691.61

Footnotes are given in appendix B, Table B-1

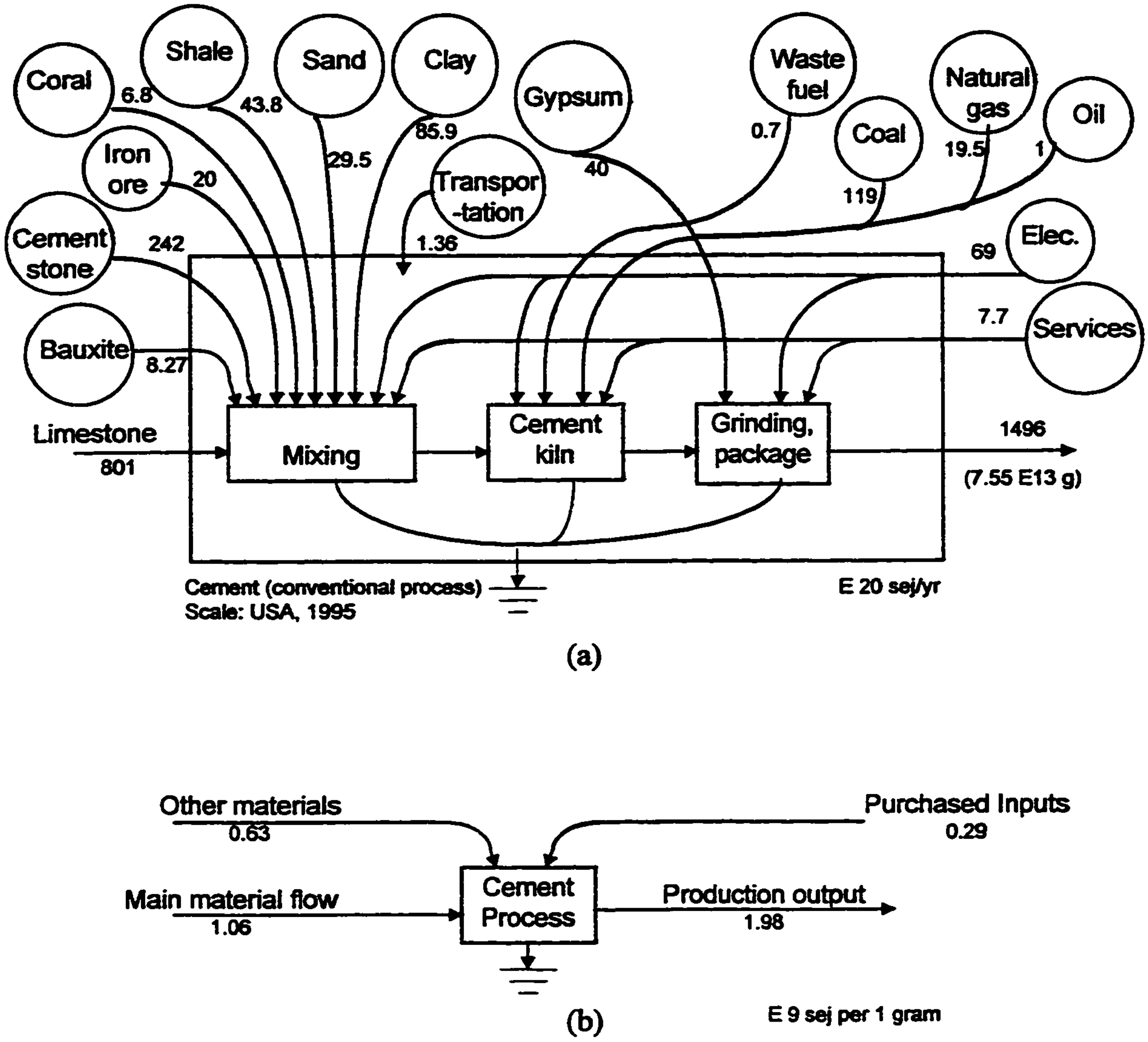
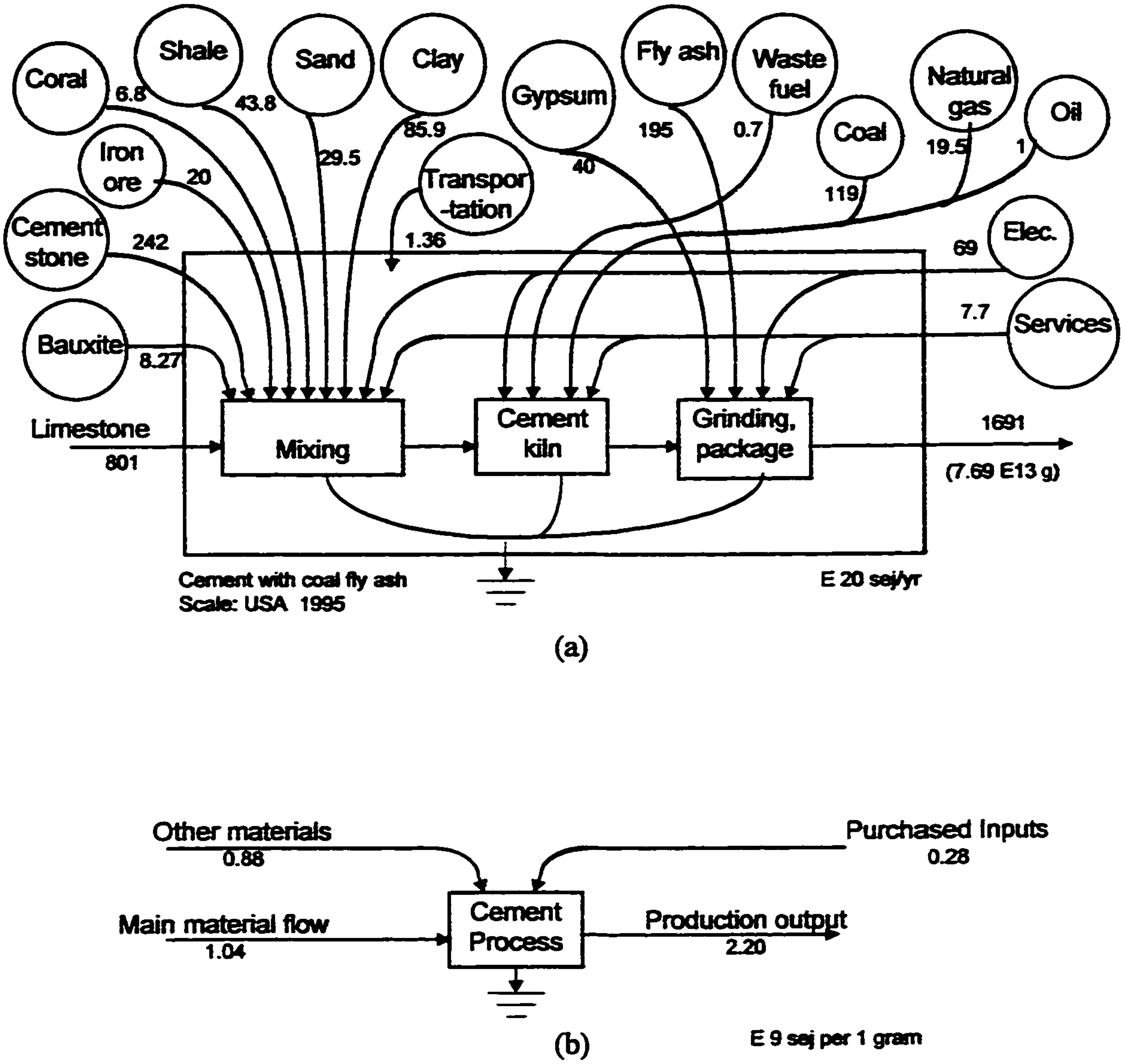


Figure 3-1. Emergy systems diagram of cement production (a) and summary diagram (b). Data are from Table 3-1.



(a)

(b)

Figure 3-2. Emergy systems diagram of cement with coal fly ash (a) and summary diagram (b). Data are from Table 3-1.

Concrete

Table 3-2 and Figure 3-3, 3-4, and 3-5 summarize the emergy evaluation of ready-mixed concrete, taken from manufacturer. There are two alternatives of recycle patterns used in ready-mixed concrete. In the first, coal fly ash is added to the concrete mixture, substituting for a small amount of the cement. In the second, demolished and crushed concrete is added to the ready-mixed concrete in place of stone aggregate. The use of coal fly ash in ready-mixed concrete (Table 3-2B and Figure 3-4), which saves some cement, (about 6%) is a primary example of environmental clean up, as the incorporation of coal fly ash into concrete sequesters an otherwise trouble some byproduct to useful structure. Coal fly ash recycled into concrete is considered a byproduct recycle process.

Demolished and crushed concrete substituting for aggregate (Table 3-2C and Figure 3-5) is not appropriate for structural purposes as it has a variety of physical properties that causes lower strength such as concrete pavement.

In the conventional ready-mixed concrete process, aggregate is the largest input to the process (about 30% of total emergy). Sand and cement, each approximately 20% of total emergy, are the next most important inputs. Transport of raw materials is also important comprising about 20% of total inputs. For concrete with crushed concrete as pavement, construction input is the largest flow since a large amount of services, machines, fuel, and others convert materials to building. Crushed concrete aggregate is a composite material composed of gravel, sand, steels, and cement. Approximately 54E+18 sej in recycled concrete aggregate (Table 3-2C) is provided by crushed concrete aggregate. By natural aggregates, it has emergy cost of 42E+18 sej which closes to

Table 3-2. Emergy evaluation of ready-mixed concrete production (with coal fly ash and recycled concrete aggregate) 1996.

Note	**Item**	**Unit**	**Input Resource**	**Solar emergy per unit (sej/unit)**	**Emergy (sej) 1.00E+18**
A. Conventional ready-mixed concrete product (Figure 3-3)					
1	Sand	g	3.36E+10	1.00E+09	33.59
2	Aggregates	g	4.29E+10	1.00E+09	42.90
3	Cement	g	1.32E+10	2.31E+09	30.60
4	Water	J	3.63E+10	4.80E+04	0.0017
5	Electricity	J	1.20E+12	1.74E+05	0.21
6	Transport (Truck)	ton-mile	3.46E+07	9.65E+11	33.42
7	Machinery	g	5.80E+06	6.70E+09	0.04
8	Labor	$	9.45E+04	1.20E+12	0.11
9	Annual Yield (Y)	g	9.71E+10	1.44E+09	140.65
B. Byproduct use ready-mixed concrete product (Figure 3-4)					
10	Sand	g	3.36E+10	1.00E+09	33.59
11	Aggregates	g	4.29E+10	1.00E+09	42.90
12	Cement	g	1.24E+10	2.31E+09	28.60
13	Fly ash	g	8.58E+08	1.40E+10	12.01
14	Water	J	3.63E+10	4.80E+04	0.0017
15	Electricity	J	1.20E+12	1.74E+05	0.21
16	Transport (Truck)	ton-mile	3.46E+07	9.65E+11	33.42
17	Machinery	g	5.80E+06	6.70E+09	0.04
18	Labor	$	9.45E+04	1.20E+12	0.11
19	Annual Yield (Y)	g	9.71E+10	1.55E+09	150.89
C. Material recycling ready-mixed concrete product (Figure 3-5)					
20	Sand	g	3.36E+10	1.00E+09	33.59
21	Cement	g	1.32E+10	2.31E+09	30.60
22	Crushed concrete	g	4.29E+10	1.26E+09	54.10
23	Demolition	g	4.29E+10	4.87E+07	2.07
24	Crushing	g	4.29E+10	1.66E+07	0.71
25	Water	J	3.63E+10	4.80E+04	0.0017
26	Electricity	J	1.20E+12	1.74E+05	0.21
27	Transport (Truck)	ton-mile	3.46E+07	9.65E+11	33.42
28	Machinery	g	5.80E+06	6.70E+09	0.04
29	Labor	$	9.45E+04	1.20E+12	0.11
30	Annual Yield (Y)	g	9.71E+10	1.59E+09	154.79

Footnotes are given in appendix B, Table B-2

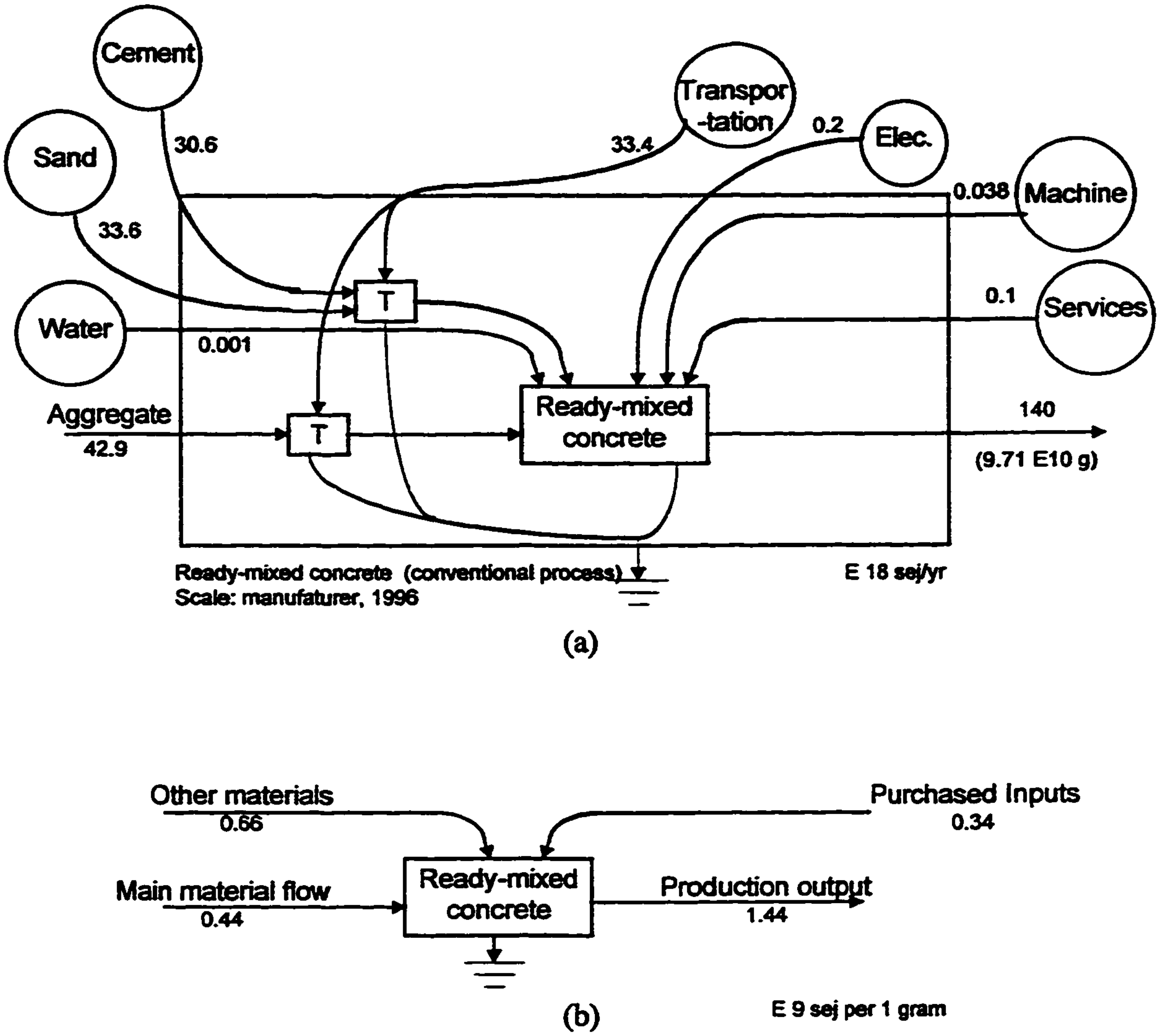


Figure 3-3. Emergy systems diagram of ready-mixed concrete (a) and summary diagram (b). Data are from Table 3-2.

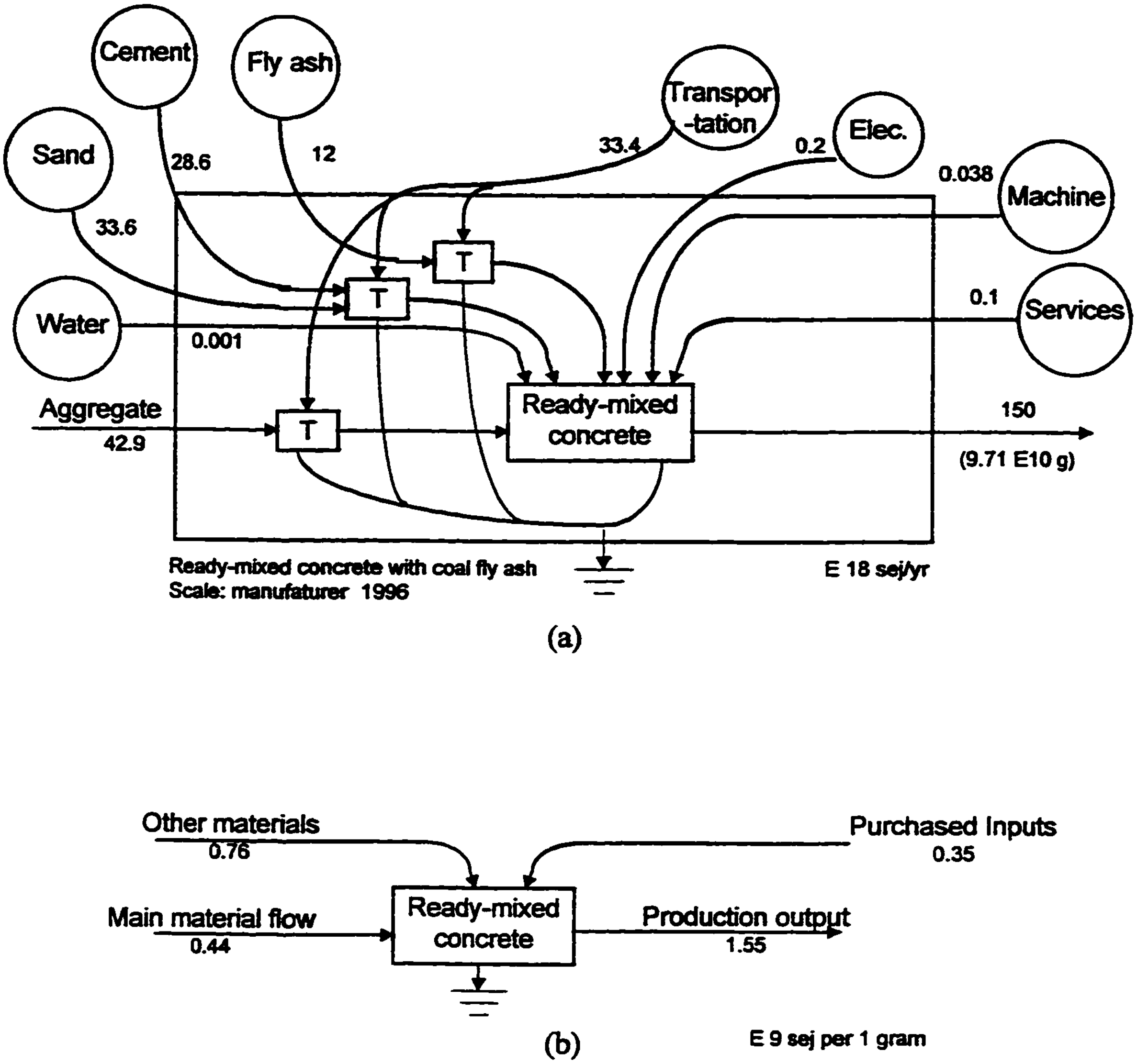


Figure 3-4. Emergy systems diagram of ready-mixed concrete with coal fly ash (a) and summary diagram (b). Data are from Table 3-2.

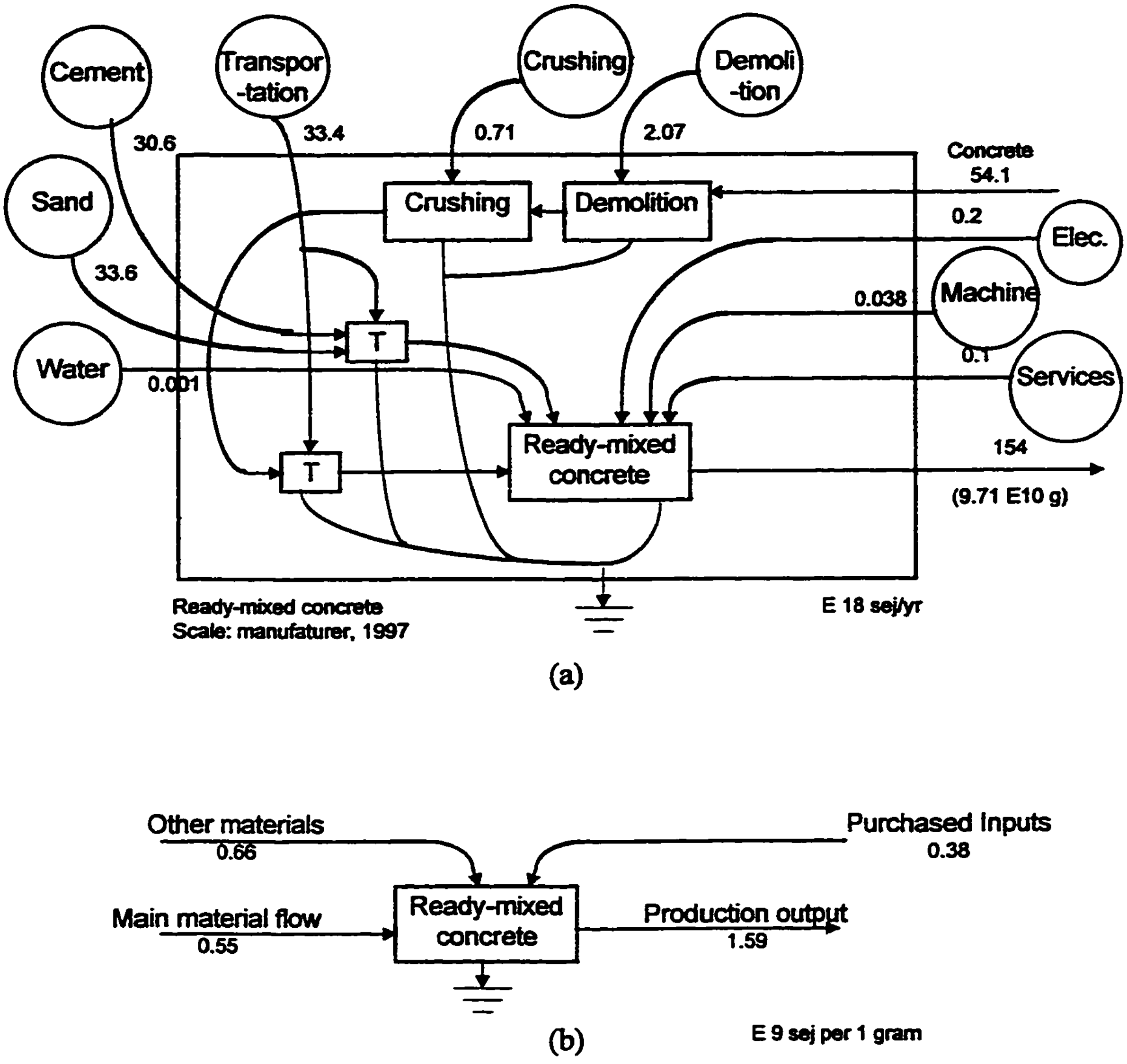


Figure 3-5. Emergy systems diagram of ready-mixed concrete with crushed concrete aggregate (a) and summary diagram (b). Data are from Table 3-2.

crushed concrete aggregate of 54E+18 sej. Emergy per gram of conventional ready-mixed concrete, with fly ash, and with crushed aggregates, are 1.44E+9, 1.55E+9, and 1.59E+9 sej/g respectively.

Masonry Material (clay brick and tile)

Analysis of the conventional process for manufacturing bricks, taken from manufacturer, is given in Table 3-3A and summarized in Figure 3-6. The largest input, by far, was the emergy in clay, comprising nearly 90% of the total inputs. Two recycle patterns are shown for making clay brick and tile using byproducts from other processes. Using data from the literature, total flows were re-evaluated assuming typical rates of substitution from existing processes. In the first, (Table 3-3B) sawdust, a byproduct from lumber manufacture is substituted for a portion of the natural gas. This results in a lower overall total input to the process as sawdust has a lower emergy per unit of heat output than natural gas. In the second recycle evaluation (Table 3-3C), oil-contaminated soil is combined with the clay and sawdust is used substituted for some of the natural gas. The use of oil-contaminated soil is an environmental clean up, of a "byproduct."

The substitution of sawdust for natural gas lowers the emergy per mass of fired brick by about 5% since the main input to the process is the emergy of the clay. However the sawdust reduces the requirement for natural gas by 75%, a significant reduction. In part C, the use of the byproduct oil-contaminated soil and sawdust, reduces the emergy per mass of the fired brick by about 15%.

Table 3-3. Emergy evaluation of fired clay brick with oil-contaminated soil, natural gas, and sawdust fuel (1997).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
A. Conventional fired clay brick product (Figure 3-6)					
1	Clay	g	6.77E+11	2.00E+09	13.50
2	Water	J	8.97E+11	4.80E+04	0.0004
3	Natural gas	J	2.67E+15	4.80E+04	1.28
4	Machinery	g	8.00E+07	6.70E+09	0.0054
5	Labor	$	1.71E+07	1.15E+12	0.20
6	Annual Yield (Y)	g	6.77E+11	2.22E+09	15.01
B. Byproduct use (sawdust) fired clay brick product (Figure 3-7)					
7	Clay	g	6.77E+11	2.00E+09	13.50
8	Water	J	8.97E+11	4.80E+04	0.0004
9	Natural gas	J	6.68E+14	4.80E+04	0.32
10	Sawdust fuel	J	2.01E+15	1.56E+04	0.31
11	Machinery	g	8.00E+07	6.70E+09	0.0054
12	Labor	$	1.71E+07	1.15E+12	0.20
13	Annual Yield (Y)	g	6.77E+11	2.12E+09	14.03
C. Byproduct use (oil-contaminated soil) fired clay brick product (Figure 3-8)					
14	Clay	g	5.42E+11	2.00E+09	10.84
15	Oil-contaminated soil	g	1.35E+11	1.00E+09	1.35
16	Water	J	8.97E+11	4.80E+04	0.0004
17	Natural gas	J	6.68E+14	4.80E+04	0.32
18	Sawdust fuel	J	2.01E+15	1.56E+04	0.31
19	Transport (Railroad)	ton-mile	2.24E+06	5.07E+10	0.0011
20	Transport (Truck)	ton-mile	2.24E+06	9.65E+11	0.02
21	Machinery	g	8.00E+07	6.70E+09	0.0054
22	Labor	$	1.71E+07	1.15E+12	0.20
23	Annual Yield (Y)	g	6.77E+11	1.93E+09	13.05

Footnotes are given in appendix B, Table B-3

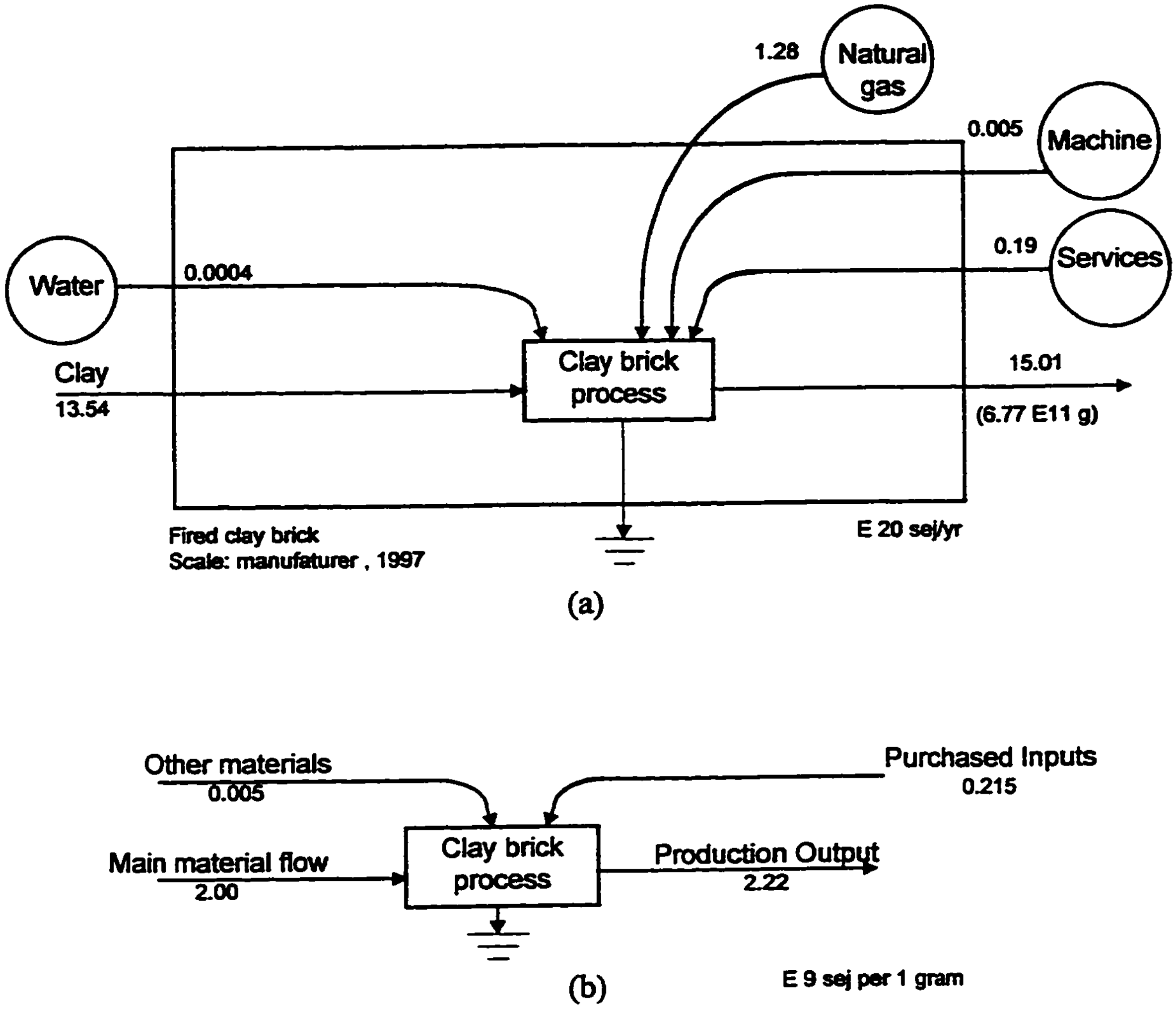


Figure 3-6. Emergy systems diagram of natural gas fired clay brick (a) and summary diagram (b). Data are from Table 3-3.

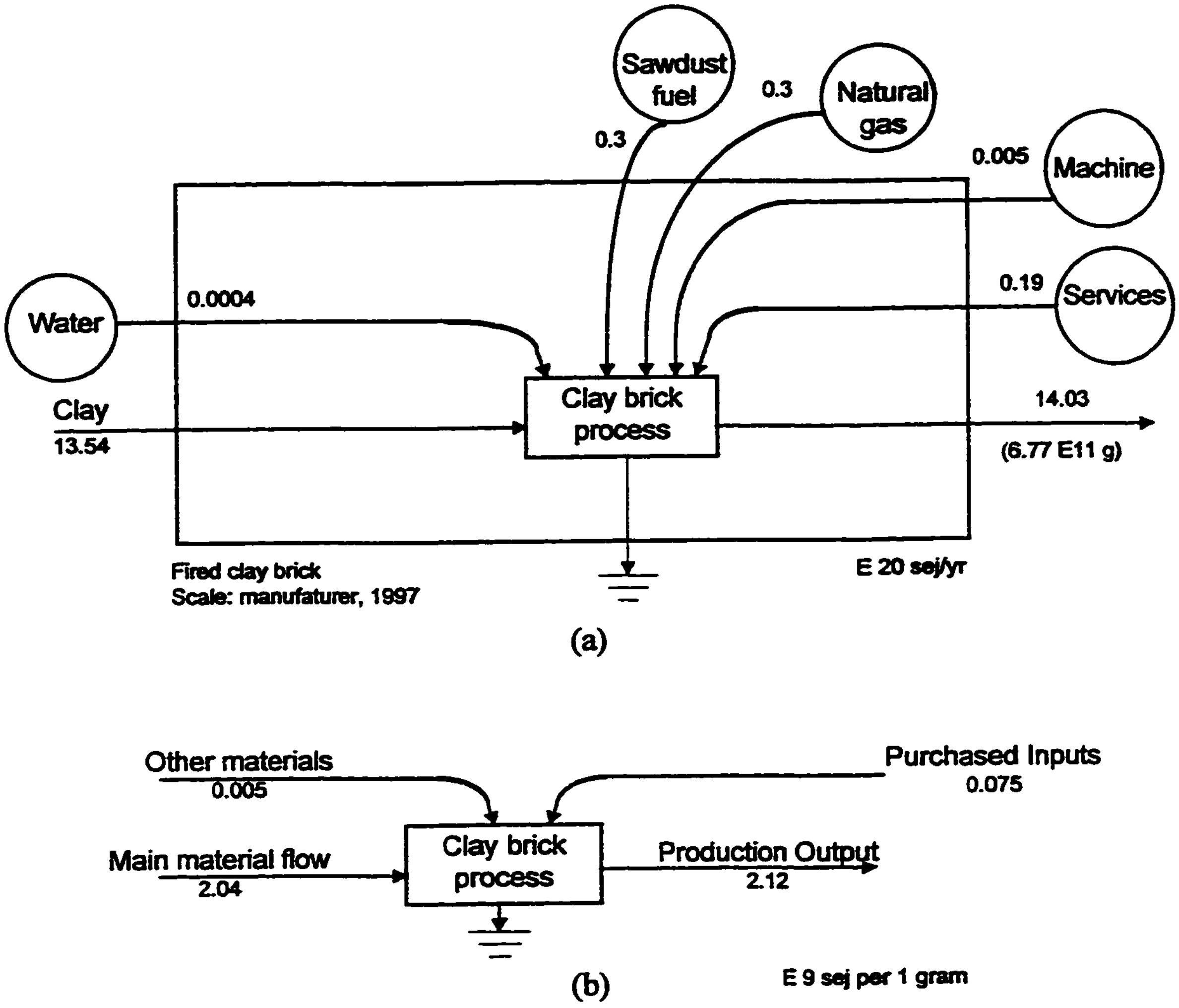


Figure 3-7. Emergy systems diagram of sawdust fuel fired clay brick (a) and summary diagram (b). Data are from Table 3-3.

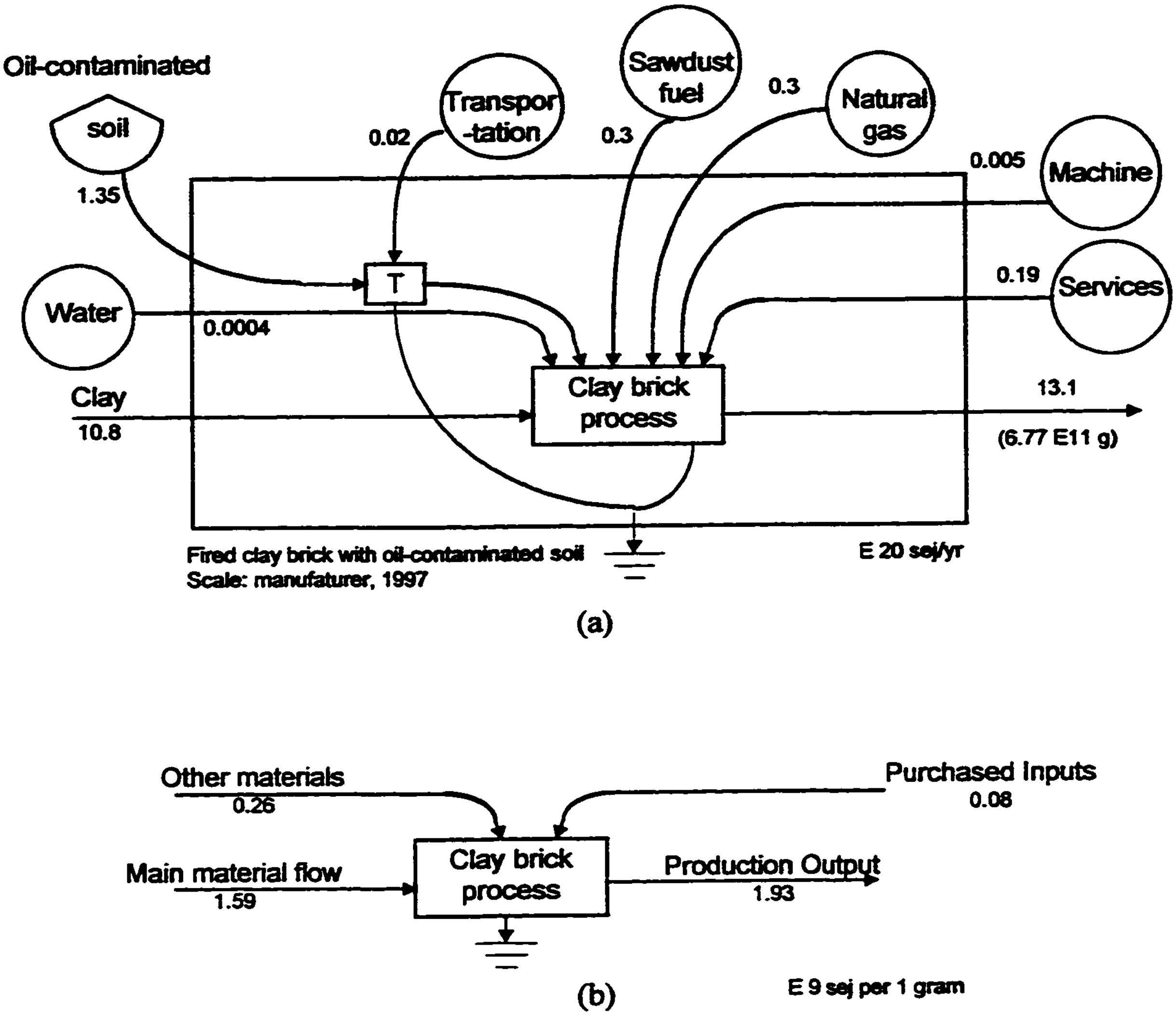


Figure 3-8. Emergy systems diagram of oil-contaminated soil and sawdust fired clay brick (a) and summary diagram (b). Data are from Table 3-3.

Metal Materials

Ferrous metal - steel

Steel, for both structure and finishing, is produced from the same processes. Data were taken from national statistics (Personal communication with American Iron and Steel Institute (AISI), 1998). There are two furnace processes, Electric Arc Furnace (EAF) and Basic Oxygen Furnace (BOF), that are widely used in the United States. The electric arc furnace can use 100% scarp steel as an input, while the basic oxygen furnace may contain only a small amount of high quality scrap steel. Table 3-4 and Figures 3-9 to 3-11 give the emergy analysis of the EAF process. In part A the conventional steel process is evaluated showing all the input material coming from pig iron. The pig iron is the largest input comprising about 70% of the total. The fuels and electricity represent about 25% of total inputs. Two recycling alternatives are given in parts B and C, and summarized in Figures 3-10 and 3-11. In part B (Figure 3-10), post-consumer scrap steel is substituted for the pig iron input. The resulting emergy per mass is higher than the conventional process because of the increased emergy inputs for collection and separation. The increase in emergy per mass is about 6%. In part C (Figure 3-11), byproduct steel from the production process and post-consumer scrap steel are combined and substituted for the pig iron input. The resulting emergy per mass is about 2% higher than the conventional process. Table 3-5 and Figures 3-12 and 3-13 summarize the emergy evaluation of the Basic Oxygen Furnace process. As in the EAF process, the main input to the BOF process is pig iron, comprising about 50% of the total inputs. Fuels and electricity account for about 45% of total inputs. The emergy per mass of steel produced

Table 3-4. Emergy evaluation of steel and steel recycling alternatives (Electric Arc Furnace process) 1996.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
A. Conventional steel product (Figure 3-9)					
1	Pig iron	g	4.53E+13	2.83E+09	1283.00
2	Natural gas	J	3.17E+17	4.80E+04	152.38
3	Other fuels	J	2.80E+16	6.60E+04	18.51
4	Electricity	J	1.84E+17	1.74E+05	319.45
5	Transport (Railroad)	ton-mile	7.50E+09	5.07E+10	3.80
6	Transport (Truck)	ton-mile	7.50E+09	9.65E+11	72.34
7	Labor	$	1.58E+09	1.20E+12	18.98
8	Annual Yield (Y) (EAF steel products)	g	4.49E+13	4.15E+09	1867.60
B. Material recycling steel product (Figure 3-10)					
9	Post-consumer steels	g	4.53E+13	2.83E+09	1283.00
10	Post-consumer steel collection	g	4.53E+13	2.51E+08	113.00
11	Post-consumer steel separation	g	4.53E+13	8.24E+06	3.70
12	Natural gas	J	3.17E+17	4.80E+04	152.38
13	Other fuels	J	2.80E+16	6.60E+04	18.51
14	Electricity	J	1.84E+17	1.74E+05	319.45
15	Transport (Railroad)	ton-mile	7.50E+09	5.07E+10	3.80
16	Transport (Truck)	ton-mile	7.50E+09	9.65E+11	72.34
17	Labor	$	1.58E+09	1.20E+12	18.98
18	Annual Yield (Y) (EAF steel products)	g	4.49E+13	4.41E+09	1983.30
C. Material recycling and byproduct use steel product (Figure 3-11)					
19	Post-consumer steels	g	1.36E+13	2.83E+09	385.01
20	Steel scrap or slag	g	3.17E+13	2.83E+09	898.36
21	Post-consumer steel collection	g	1.36E+13	2.51E+08	34.13
22	Post-consumer steel separation	g	1.36E+13	8.24E+06	1.12
23	Natural gas	J	3.17E+17	4.80E+04	152.38
24	Other fuels	J	2.80E+16	6.60E+04	18.51
25	Electricity	J	1.84E+17	1.74E+05	319.45
26	Transport (Railroad)	ton-mile	7.50E+09	5.07E+10	3.80
27	Transport (Truck)	ton-mile	7.50E+09	9.65E+11	72.34
28	Labor	$	1.58E+09	1.20E+12	18.98
29	Annual Yield (Y) (EAF steel products)	g	4.49E+13	4.24E+09	1904.09

Footnotes are given in appendix B, Table B-4

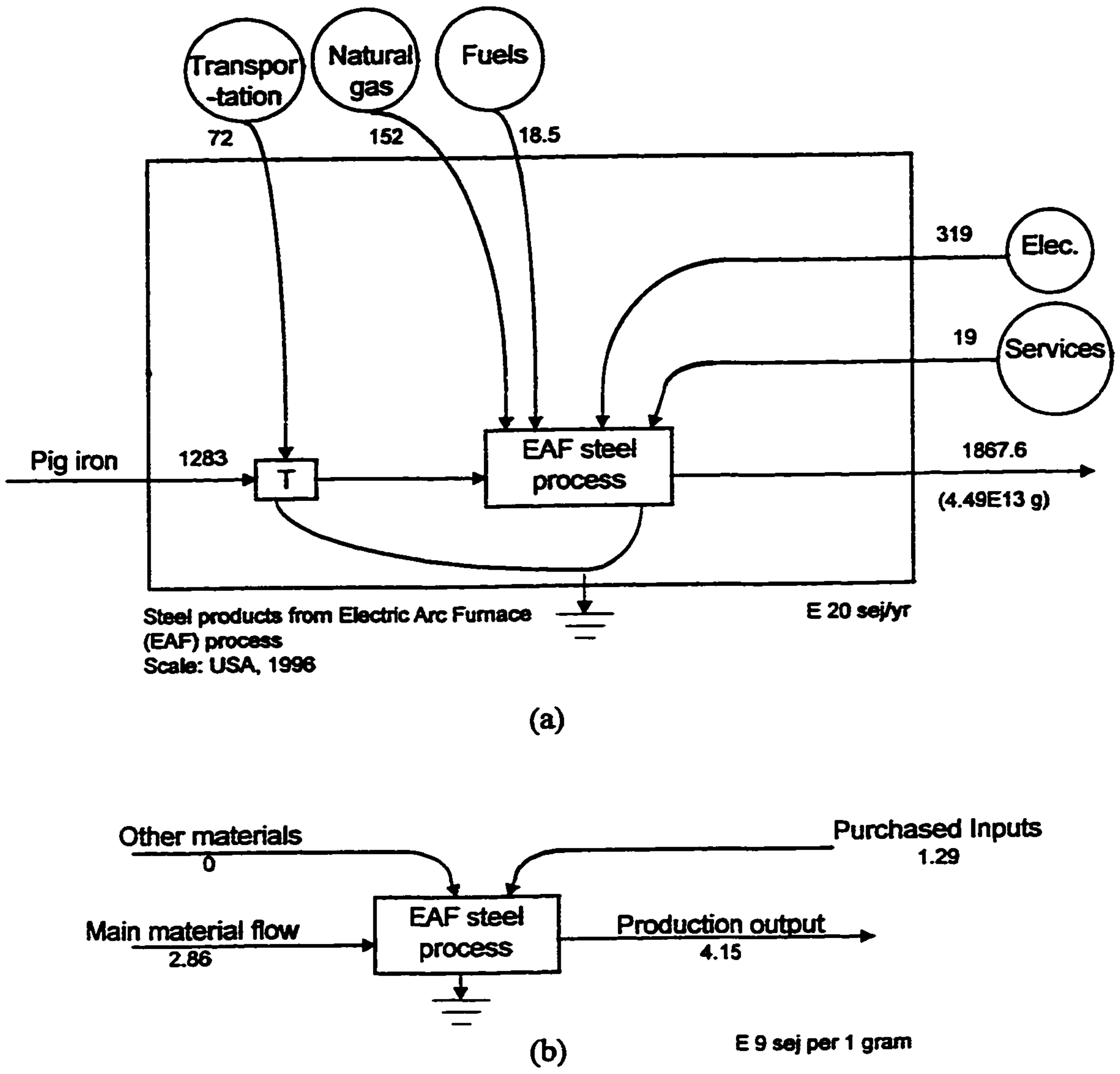


Figure 3-9. Emergy systems diagram of steel production (electric arc furnace (EAF) process) (a) and summary diagram (b). Data are from Table 3-4.

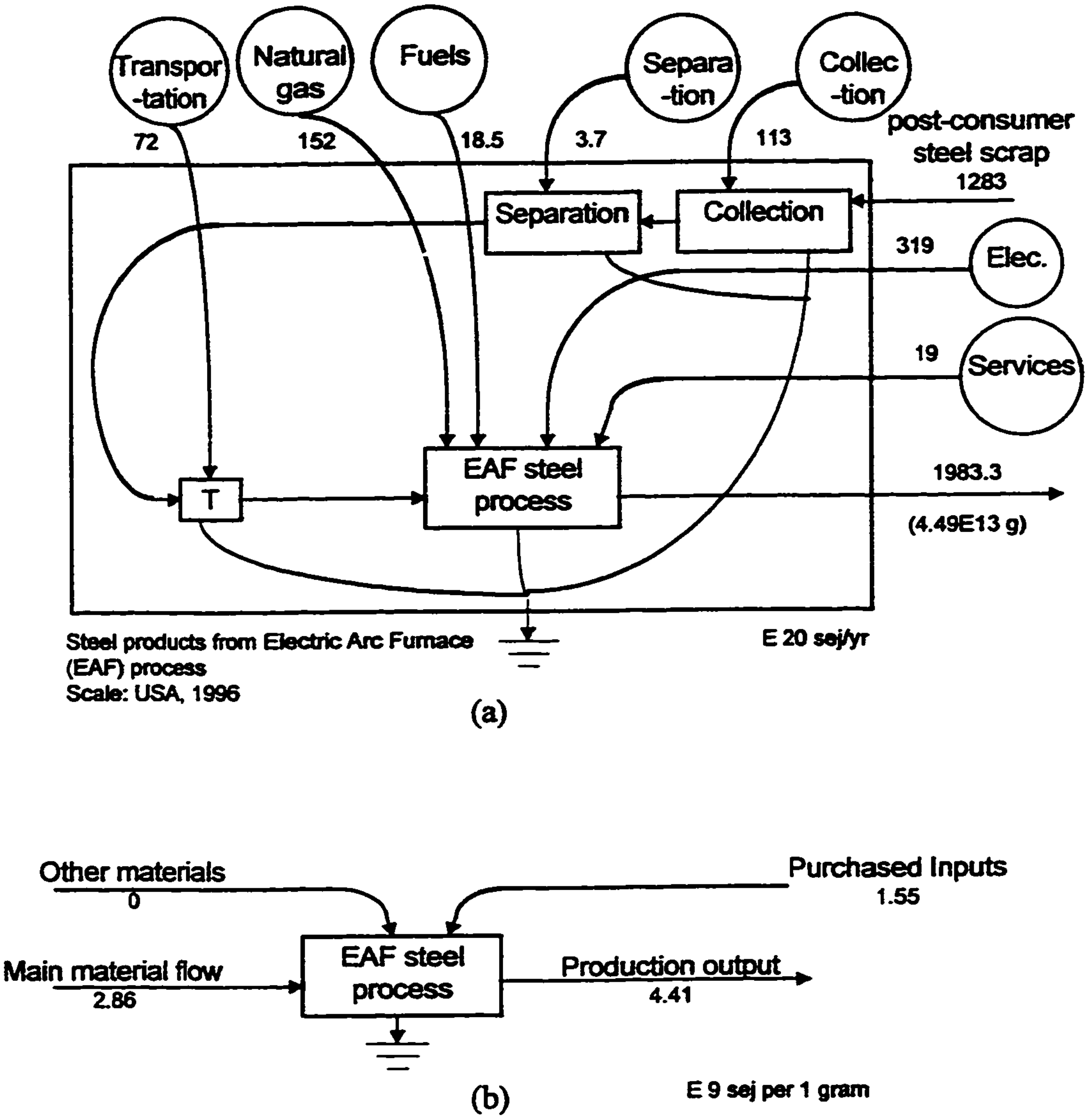


Figure 3-10. Emergy systems diagram recycling alternative of steel production (electric arc furnace (EAF) process) using post-consumer steel scrap (a) and summary diagram (b). Data are from Table 3-4.

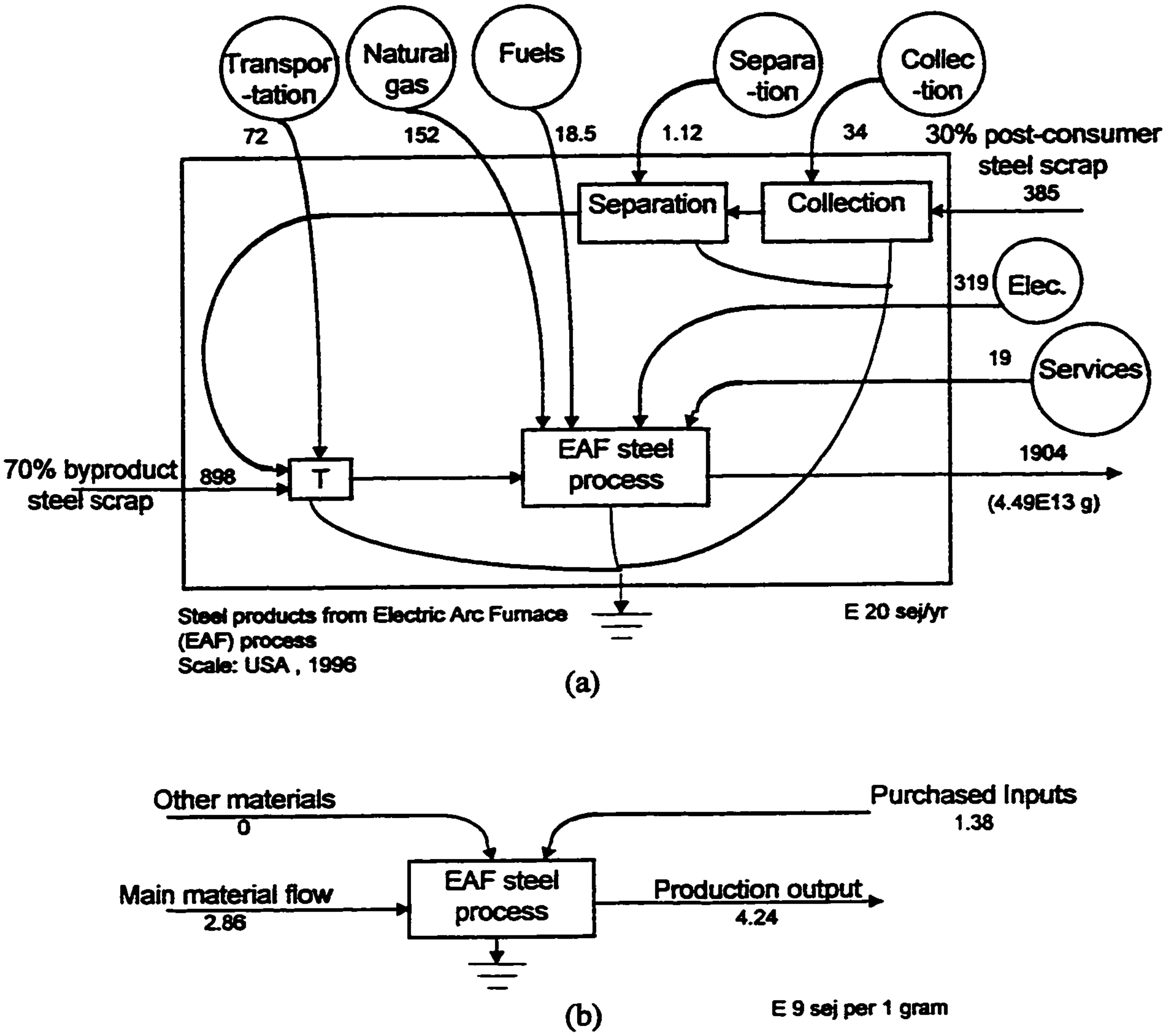


Figure 3-11. Emergy systems diagram of steel production (electric arc furnace (EAF) process) using 70% byproduct and 30% post-consumer steel scrap (a) and summary diagram (b). Data are from Table 3-4.

Table 3-5. Emergy evaluation of in-house recycling of steel production (Basic Oxygen Furnace process) 1996.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
A. Conventional steel product (Figure 3-12)					
1	Pig iron	g	6.11E+13	2.83E+09	1730.00
2	Water	J	4.06E+15	4.80E+04	1.95
3	Coal/Coke	J	8.22E+17	4.00E+04	328.77
4	Natural gas	J	2.82E+17	4.80E+04	135.36
5	Other fuels	J	2.37E+17	6.60E+04	156.19
6	Electricity	J	4.92E+17	1.74E+05	855.62
7	Labor	$	2.43E+09	1.20E+12	29.11
8	Annual Yield (Y) (BOF steel products)	g	6.04E+13	5.35E+09	3233.42
B. In-house material recycling steel product (Figure 3-13)					
9	In-house steel scrap	g	1.53E+13	2.83E+09	431.60
10	Pig iron	g	4.58E+13	2.83E+09	1294.81
11	Water	J	4.06E+15	4.80E+04	1.95
12	Coal/Coke	J	8.22E+17	4.00E+04	328.77
13	Natural gas	J	2.82E+17	4.80E+04	135.36
14	Other fuels	J	2.37E+17	6.60E+04	156.19
15	Electricity	J	4.92E+17	1.74E+05	855.62
16	Labor	$	2.43E+09	1.20E+12	29.11
17	Annual Yield (Y) (BOF steel products)	g	6.04E+13	5.35E+09	3233.42

Footnotes are given in appendix B, Table B-5

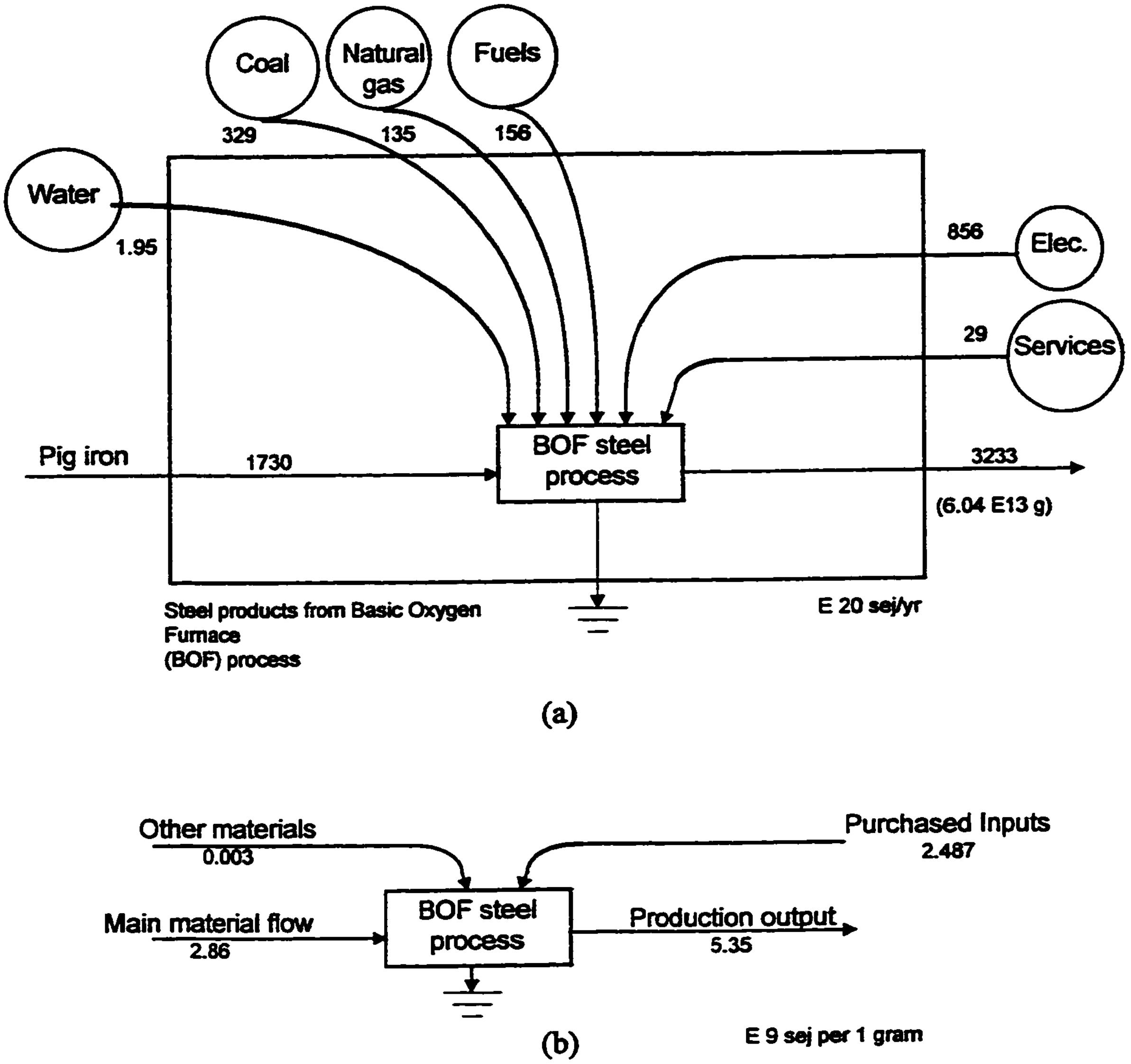


Figure 3-12. Emergy systems diagram of steel production (basic oxygen furnace (BOF) process) (a) and summary diagram (b). Data are from Table 3-5.

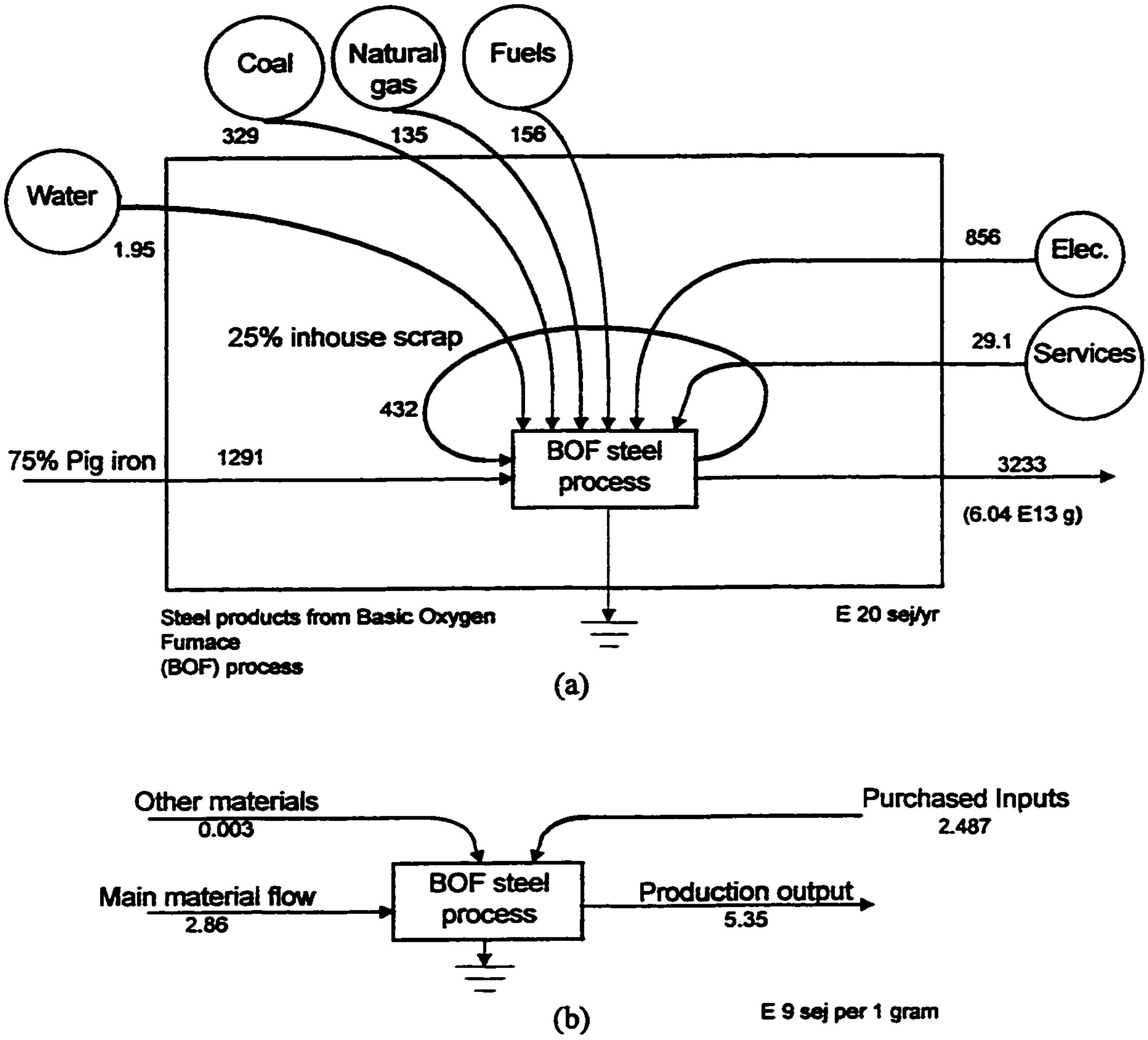


Figure 3-13. Emergy systems diagram of steel products (basic oxygen furnace (BOF) process) using 25% in-house scrap (a) and summary diagram (b). Data are from Table 3-5.

in the BOF process is higher than steel produced in the EAF process. The emergy per mass of BOF steel is about 30% higher than EAF steel. In part B of Table 3-5 the evaluation of the BOF process is modified through the use of in-house scrap steel as a substitute for some of the pig iron. About 25% of the pig iron can be substituted with the scrap. Since the scrap steel has the same emergy per mass as the pig iron, there is no change in the emergy per mass of the yield.

Non-ferrous metal (aluminum)

Given in Table 3-6 and summarized in Figures 3-14 to 3-16 are the emergy analysis of aluminum production including two alternatives of recycling processes. Data were taken from the manufacturer. As in other production process involving transformation of raw non-renewable resources, the main emergy input is in primary aluminum, comprising 95% of the total input. Electricity and labor account for about 4% and 1% of inputs respectively. The emergy per mass of aluminum is 1.27 E+10 sej/g.

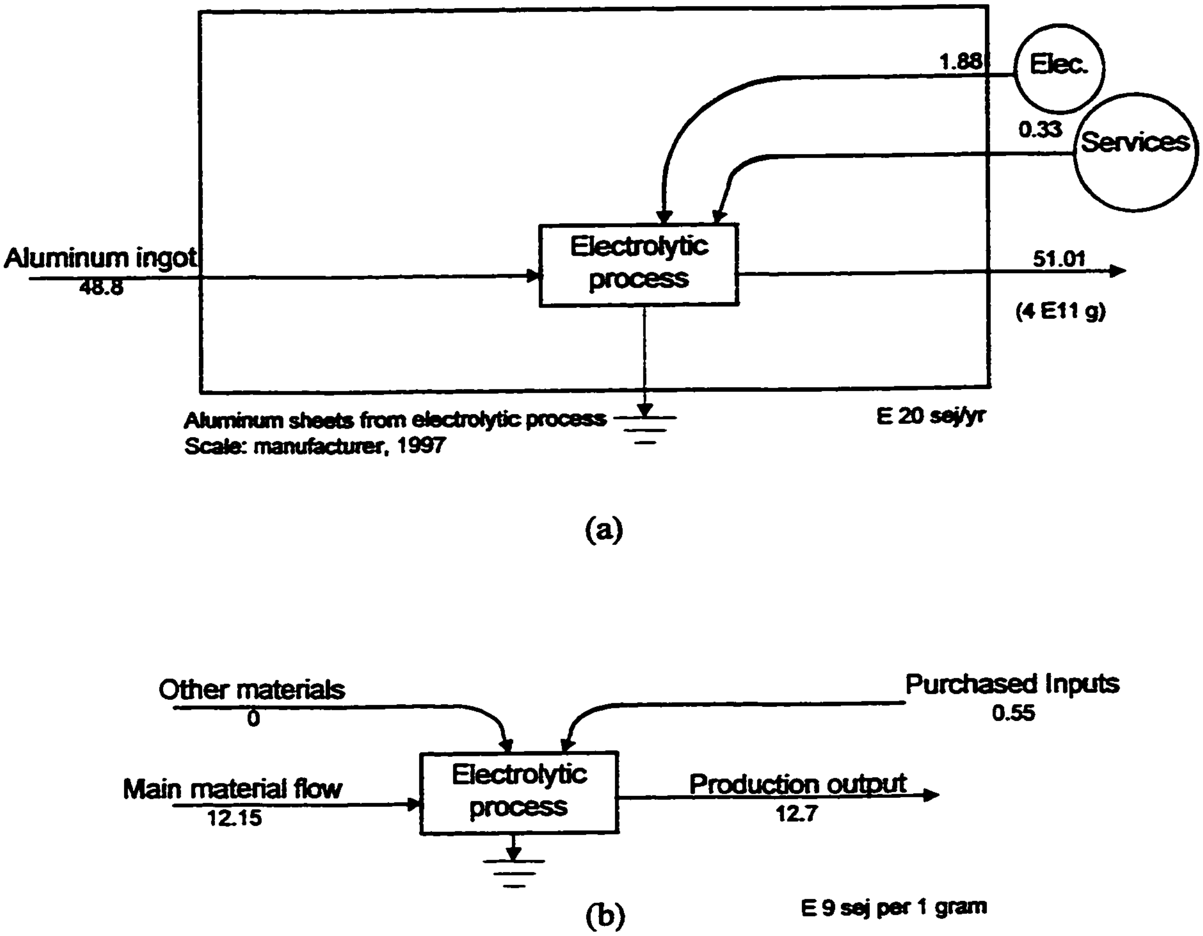
The first recycle process (Table 3-6B and Figure 3-15) involves recycle of post-consumer scrap aluminum. In the recycle pattern, additional emergy is used in collection and separation as well as transportation. These inputs add about 2% to the total inputs to the aluminum production process. The resulting emergy per mass is about 2% higher than the conventional process or about 1.30 E+10 sej/g.

The last recycle pattern (Table 3-6C and Figure 3-16) combines post-consumer aluminum scrap (55%), production byproduct aluminum (15%), and aluminum ingot (30%). Collection, separation, and transportation inputs are about 1.5% of total inputs.

Table 3-6. Emergy evaluation of aluminum sheet production (electrolytic process) 1997.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
A. Conventional aluminum sheet product (Figure 3-14)					
1	Primary aluminum (ingot)	g	4.17E+11	1.17E+10	48.80
2	Electricity	J	1.08E+15	1.74E+05	1.88
3	Labor	$	2.90E+07	1.15E+12	0.33
4	Annual Yield (Y) aluminum sheets	g	4.00E+11	1.27E+10	51.01
B. Material recycling aluminum sheet product (Figure 3-15)					
5	Used aluminum can	g	4.17E+11	1.17E+10	48.80
6	Used AL can collection	g	4.17E+11	2.51E+08	1.04
7	Used AL can separation	g	4.17E+11	8.24E+06	0.03
8	Electricity	J	1.08E+15	1.74E+05	1.88
9	Transport (Truck)	ton-mile	1.38E+07	9.65E+11	0.13
10	Labor	$	2.90E+07	1.15E+12	0.33
11	Annual Yield (Y) aluminum sheets	g	4.00E+11	1.30E+10	52.21
C. Material recycling and byproduct use aluminum sheet product (Figure 3-16)					
12	Used aluminum can	g	2.29E+11	1.17E+10	26.81
13	Primary aluminum (ingot)	g	1.25E+11	1.17E+10	14.63
14	Aluminum scrap	g	6.25E+10	1.17E+10	7.31
15	Used AL can collection	g	2.29E+11	2.51E+08	0.57
16	Used AL can separation	g	2.29E+11	8.24E+06	0.02
17	Electricity	J	1.08E+15	1.74E+05	1.88
18	Transport (Truck)	ton-mile	2.82E+07	9.65E+11	0.27
19	Labor	$	2.90E+07	1.15E+12	0.33
20	Annual Yield (Y) aluminum sheets	g	4.00E+11	1.29E+10	51.82

Footnotes are given in appendix B, Table B-6



(a)

(b)

Figure 3-14. Emergy systems diagram of aluminum sheet production (electrolytic process) (a) and summary diagram (b). Data are from Table 3-6.

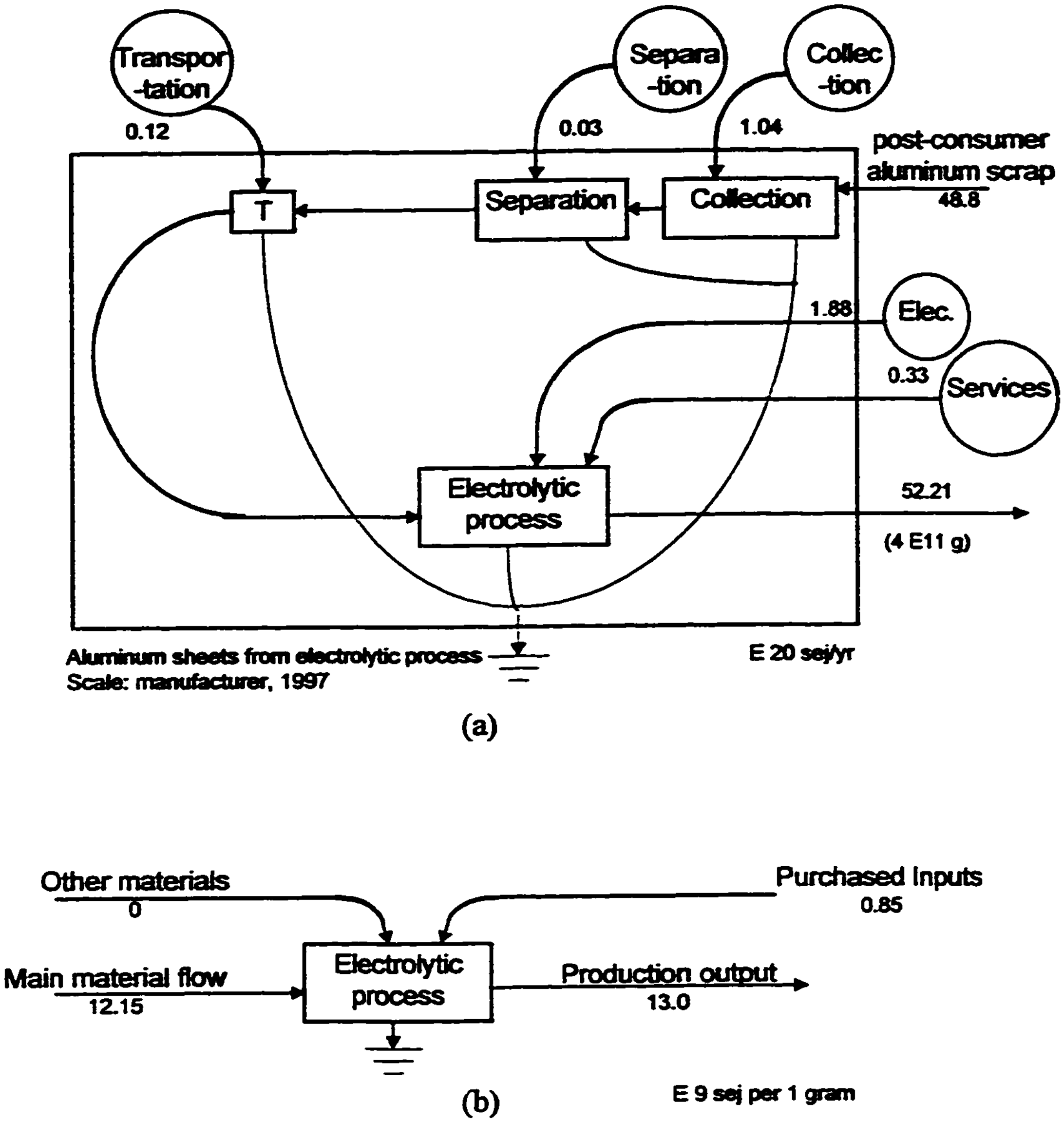


Figure 3-15. Emergy systems diagram traditional recycling alternative of aluminum sheet production using post-consumer aluminum scrap (a) and summary diagram (b). Data are from Table 3-6.

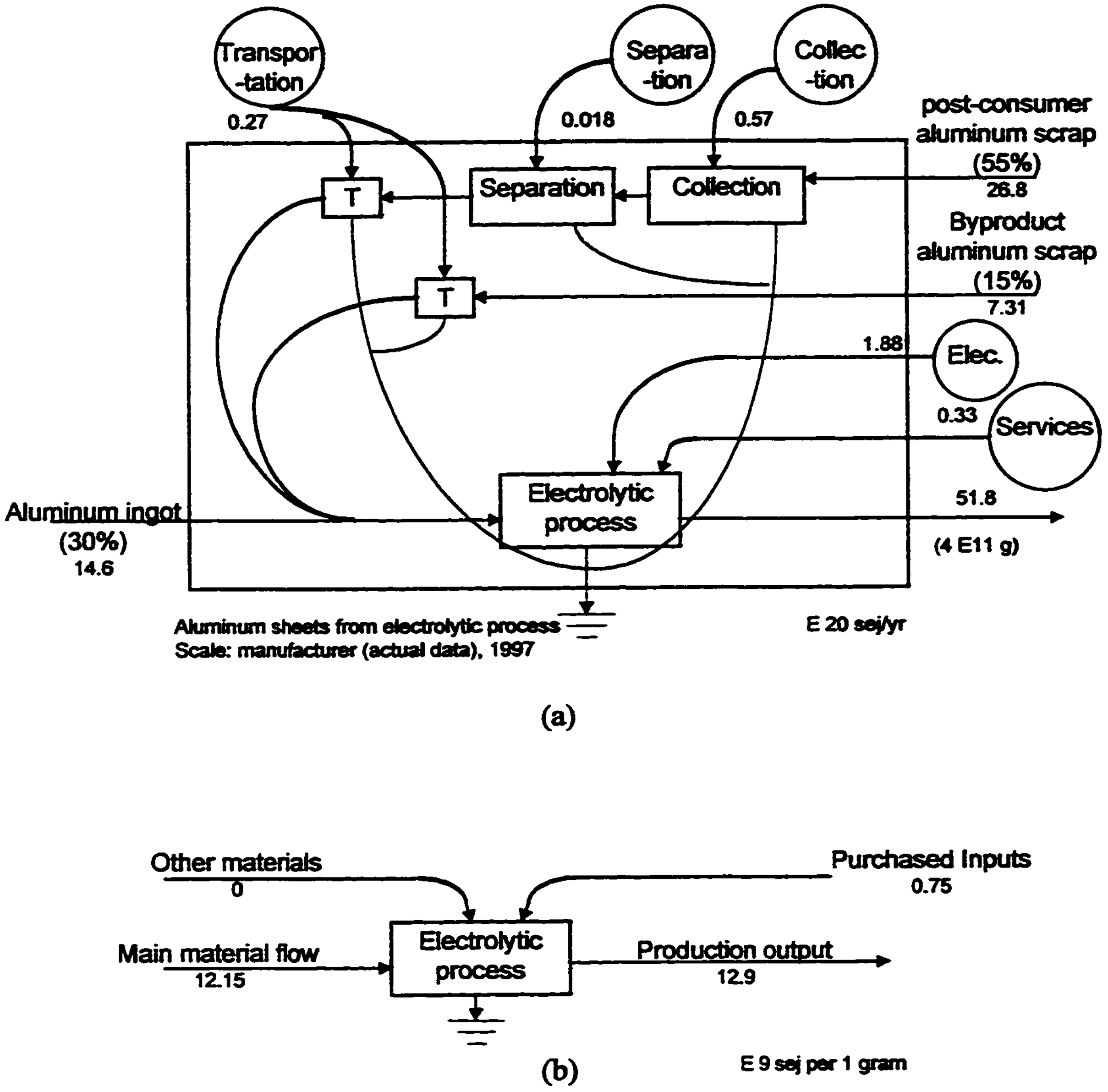


Figure 3-16. Emergy systems diagram of aluminum sheet production using 55% post-consumer and 15% byproduct scrap with 30% aluminum ingot (a) and summary diagram (b). Data are from Table 3-6.

These are smaller than in the 100% post-consumer recycle system since the volume of post-consumer scrap aluminum is smaller. The emergy per mass is 1.29 E+10 sej/g.

Wood

Given in Tables 3-7 and 3-8 and summarized in Figures 3-17 and 3-18 are emergy analyses of conventional plywood production and plywood production that uses shaved wood byproduct from lumber production. Table 3-7 is based on national data for the entire softwood plywood production sector of the economy (Census of Manufactures, 1992c), while Table 3-8 is based on data from an individual plant.

In Table 3-7, the largest emergy input is in the raw material inputs including hardwood and softwood logs, veneer, plywood, and hardboard, comprising about 80% of the total inputs. Direct energy inputs account for 13% and labor for 7% of total inputs. The emergy per mass of softwood plywood is 1.21E+9 sej/g.

Tables 3-9 and 3-10 give emergy evaluation of lumber production and recycled lumber respectively. These data are summarized in Figures 3-19 and 3-20. The evaluation of lumber production in Table 3-9 is based on national data for the industry as a whole. The input of logs and lumber for resawing represent about 88% of the total emergy inputs to the lumber production process. Direct energy inputs of oil and electricity comprise 6% of inputs while labor accounts for about 5%. The emergy per mass is 8.79 E+8 sej/g.

The evaluation in Table 3-10 is based on an individual used lumber reprocessing operation. When lumber is recycled (Table 3-10 and Figure 3-20), there are significant inputs required for demolition (about 80% of total inputs). Transportation accounts for about 6% of required inputs and the lumber itself comprises about 20%. As a result of the

Table 3-7. Emergy evaluation of softwood plywood production (1992).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Hardwood logs	J	4.28E+16	8.01E+03	3.43
2	Softwood logs	J	1.51E+18	8.01E+03	120.82
3	Lumber	J	2.71E+14	4.40E+04	0.12
4	Hardwood veneer	J	6.39E+14	4.40E+04	0.28
5	Softwood plywood	J	5.76E+14	4.40E+04	0.25
6	Hardboard	J	1.14E+13	1.27E+05	0.01
7	Oil (fuel)	J	4.96E+15	6.60E+04	3.27
8	Electricity	J	9.61E+15	1.74E+05	16.72
9	Labor	$	8.27E+08	1.43E+12	11.83
10	Annual Yield (Y) plywood and veneer	g	1.30E+13	1.21E+09	156.74

Footnotes are given in appendix B, Table B-7

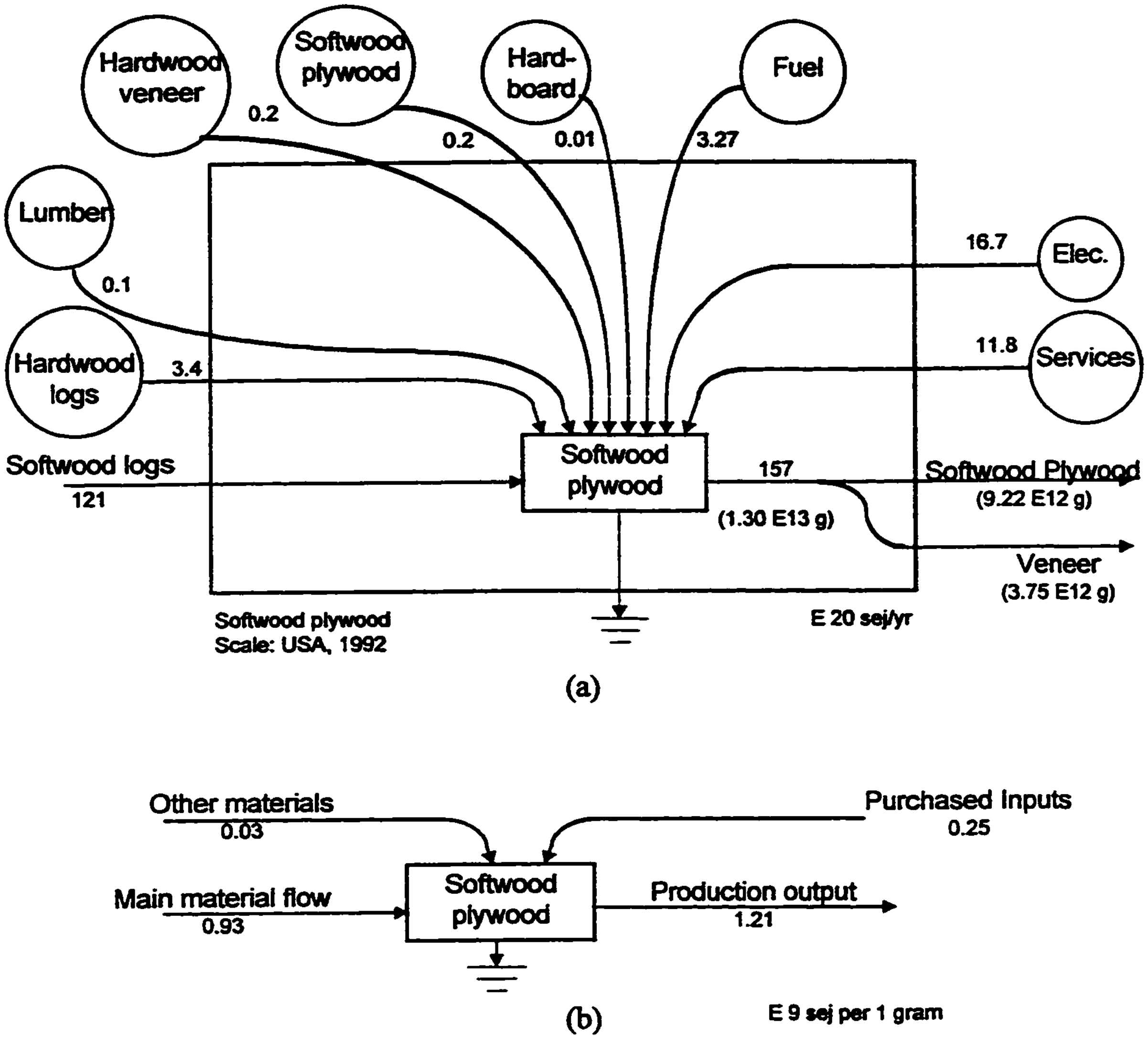


Figure 3-17. Emergy systems diagram of softwood plywood production (a) and summary diagram (b). Data are from Table 3-7.

Table 3-8. Emergy evaluation of laminated plywood production using shaved wood byproduct (1997).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
1	Shaved lumber	g	7.25E+09	8.79E+08	6.37
2	Veneer	g	5.80E+09	1.21E+09	7.01
3	Plastics resin	g	1.45E+09	3.28E+09	4.75
4	Water	J	4.30E+09	4.80E+04	0.0002
5	Natural gas	J	3.04E+13	4.80E+04	1.46
6	Oil (fuel)	J	3.04E+13	6.60E+04	2.00
7	Electricity	J	1.73E+11	1.70E+05	0.03
8	Labor	$	1.85E+06	1.15E+12	2.12
9	Annual Yield (Y) laminated plywood	g	1.45E+10	1.64E+09	23.75

Footnotes are given in appendix B, Table B-8

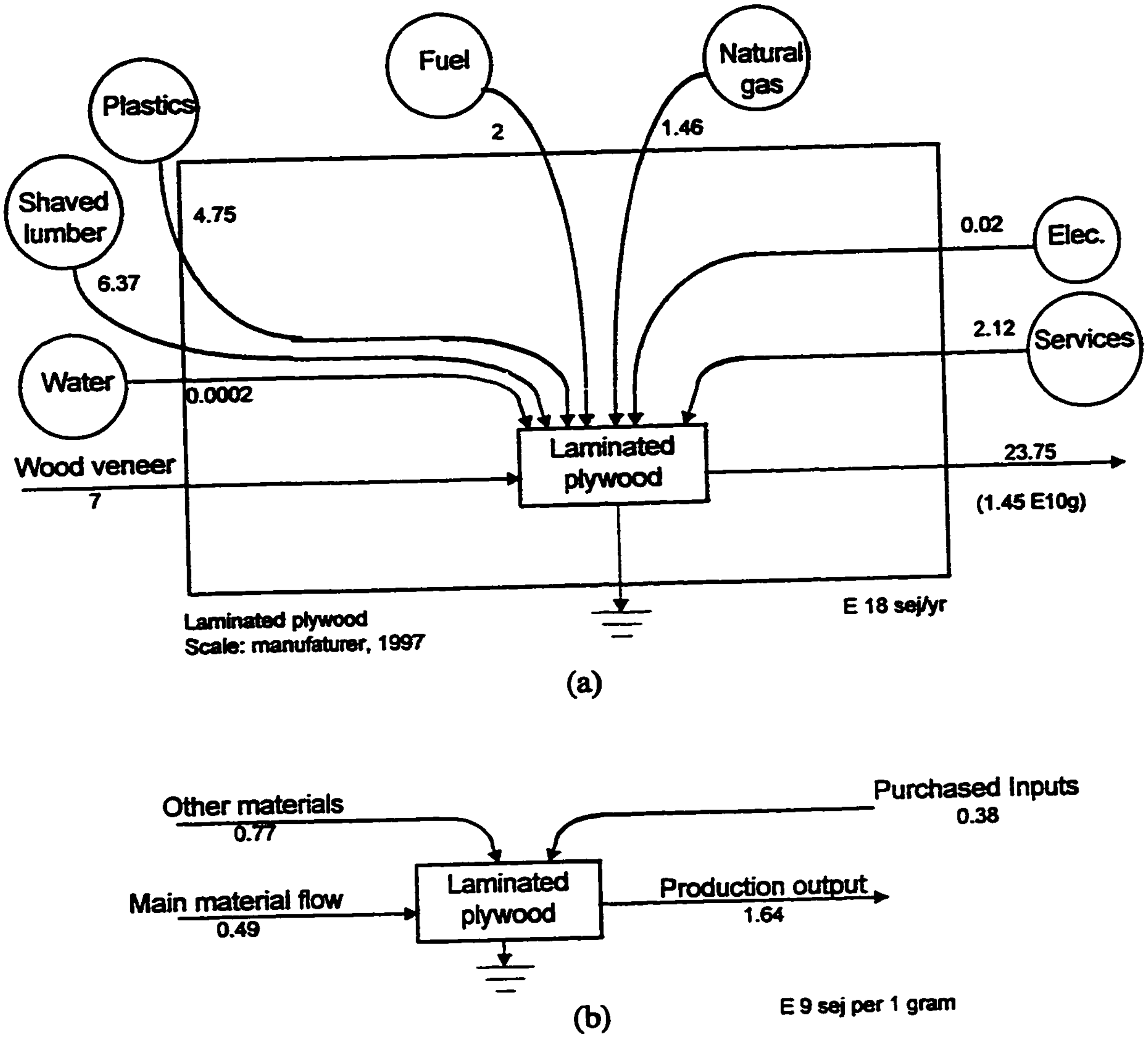
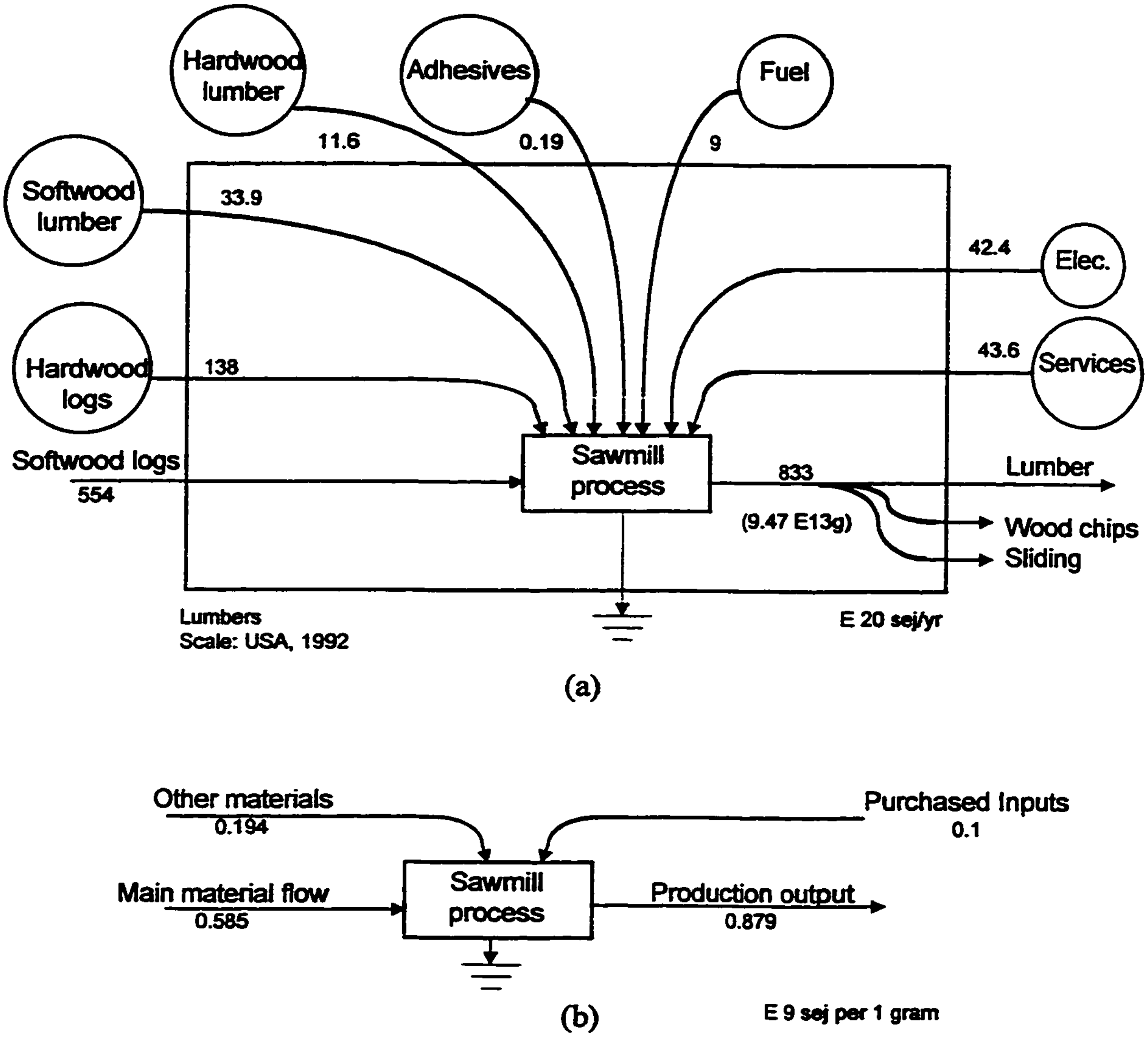


Figure 3-18. Emergy systems diagram of laminated plywood using recycled wood shaved (a) and summary diagram (b). Data are from Table 3-8 .

Table 3-9. Emergy evaluation of lumber production (1992).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Hardwood logs	J	1.72E+18	8.01E+03	137.63
2	Softwood logs	J	6.92E+18	8.01E+03	554.39
3	Hardwood lumber	J	2.64E+16	4.40E+04	11.64
4	Softwood lumber	J	7.70E+16	4.40E+04	33.90
5	Glue and Adhesives	g	5.20E+10	3.80E+08	0.20
6	Oil (fuel)	J	1.39E+16	6.60E+04	9.19
7	Electricity	J	2.43E+16	1.74E+05	42.36
8	Labor	$	3.05E+09	1.43E+12	43.55
9	Annual Yield (Y) lumber	g	9.47E+13	8.79E+08	832.86

Footnotes are given in appendix B, Table B-9



(a)

(b)

Figure 3-19. Emergy systems diagram of lumber production (a) and summary diagram (b). Data are from Table 3-9.

Table 3-10. Emergy evaluation of recycled lumber (1997).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+16
1	Used lumber	g	2.94E+08	8.79E+08	26.00
2	Propane gas	J	2.31E+10	4.80E+04	0.11
3	Oil (fuel)	J	2.64E+10	6.60E+04	0.17
4	Transport (Truck)	ton-mile	9.72E+04	9.65E+11	9.00
5	Labor (demolition)	$	8.58E+05	1.15E+12	99.00
6	Annual Yield (Y) reprocessed lumbers	g	1.99E+08	6.74E+09	134.28

Footnotes are given in appendix B, Table B-10

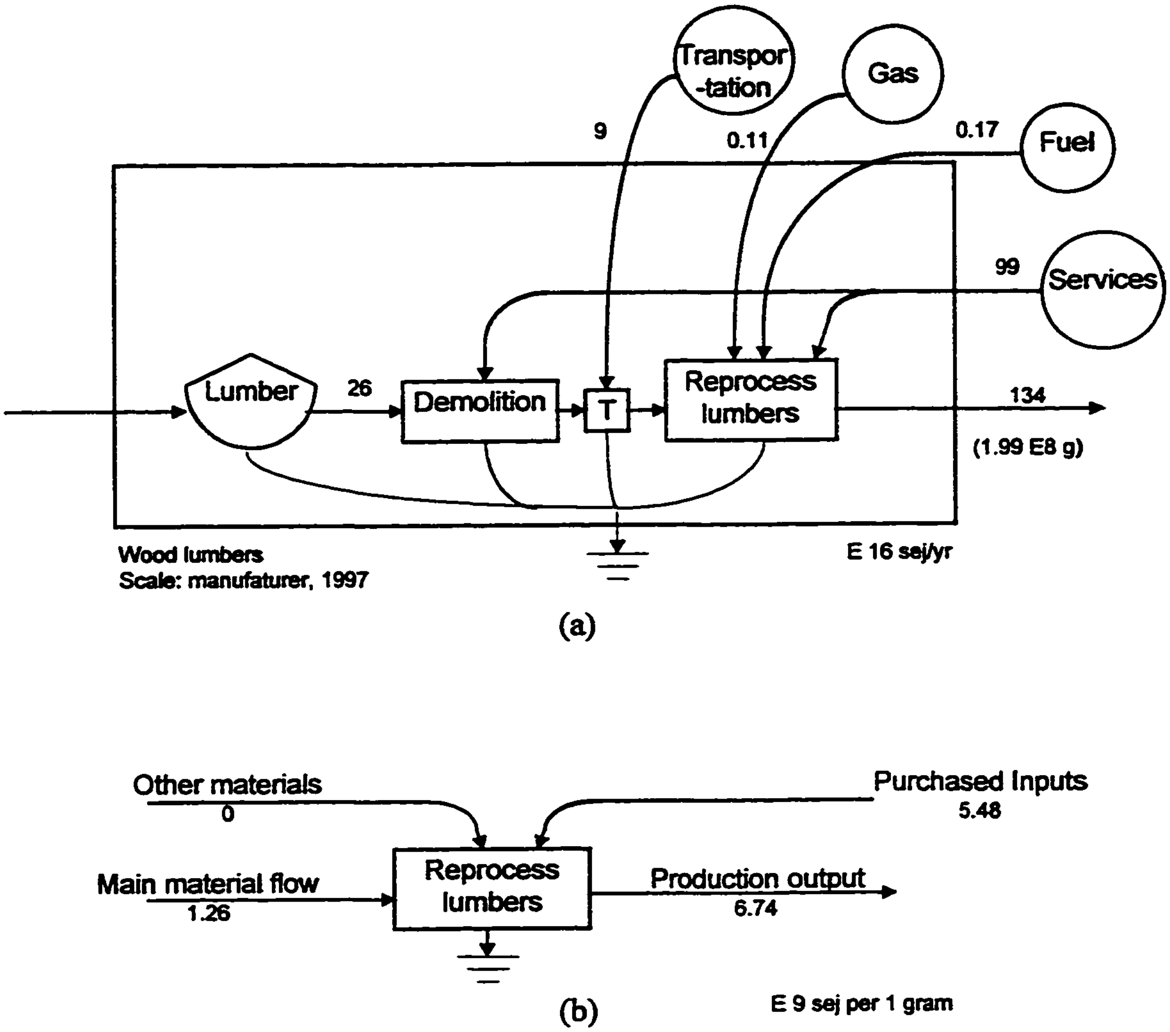


Figure 3-20. Emergy systems diagram of recycled lumber (a) and summary diagram (b). Data are from Table 3-10.

demolition, sorting, and transportation costs, the emergy per mass of recycled lumber is 6.74 E+9 sej/g. The inputs of lumber are about 32% higher than the yield. The difference between input and yield is scrap that is used to generate on-site electricity.

Plastics

The use of byproduct Polyvinyl Chloride (PVC) for vinyl flooring has steadily increased as sources of byproduct have increased. In the process evaluated in Table 3-11 and summarized in Figure 3-21, byproduct PVC is substituted for virgin PVC resin in the production of vinyl flooring. The evaluation is based on an individual plant. The PVC input represents about 90% of total emergy inputs, while services and transportation account for about 5% and 1% respectively. The emergy per mass of vinyl flooring is 6.32 E+9 sej/g.

Emergy evaluation of plastic lumber is given in Table 3-12 and summarized in Figures 3-22 and 3-23. In the conventional process (part A of Table 3-12 and Figure 3-22), HDPE plastics are mixed with wood fiber at a ratio of 85% plastic to 15% wood fiber. The largest emergy input to the process is HDPE comprising about 77% of total inputs. The wood fiber is about 2% of inputs, while electricity accounts for 4%. Labor is the second largest input, accounting for about 12% of total inputs. The emergy per mass is 5.75 E+9 sej/g. In part B (and Figure 3-23) post-consumer plastic (milk bottles) and paper are substituted for the HDPE resin and wood fiber. There are associated costs of collection and sorting, therefore the emergy per mass reuse of plastic milk bottles results in an emergy per mass of 6.33 E+9 sej/g, or about 10% higher than the conventional process.

Table 3-11. Emergy evaluation of vinyl floor production using byproduct PVC (1997).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
1	Plastics (PVC)	g	5.67E+09	5.87E+09	33.26
2	Electricity	J	1.73E+12	1.74E+05	0.30
3	Transport (Truck)	ton-mile	6.24E+05	9.65E+11	0.60
4	Machinery	g	9.08E+05	6.70E+09	0.0061
5	Labor	$	1.45E+06	1.15E+12	1.67
6	Annual Yield (Y) vinyl floor	g	5.67E+09	6.32E+09	35.84

Footnotes are given in appendix B, Table B-11

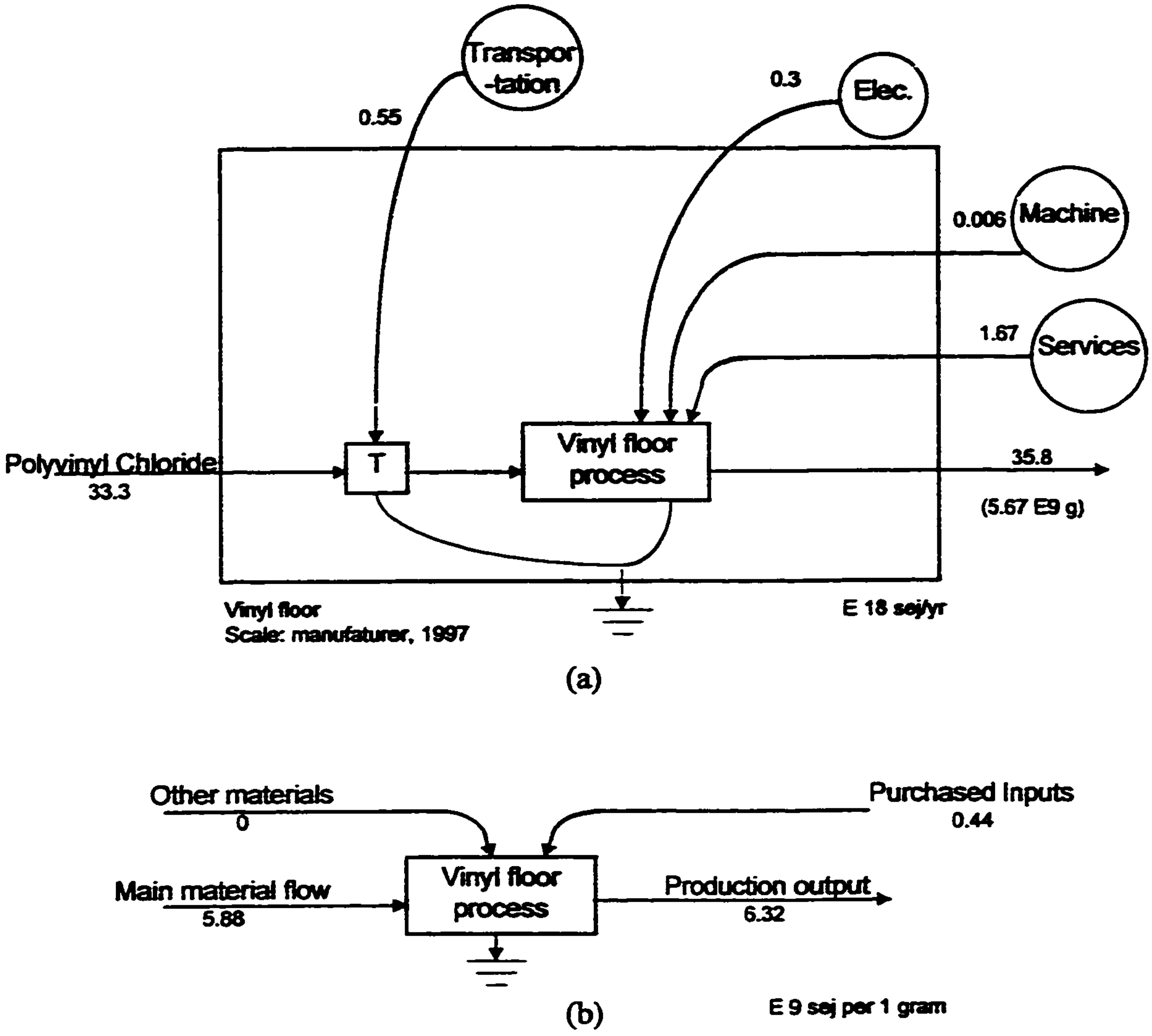
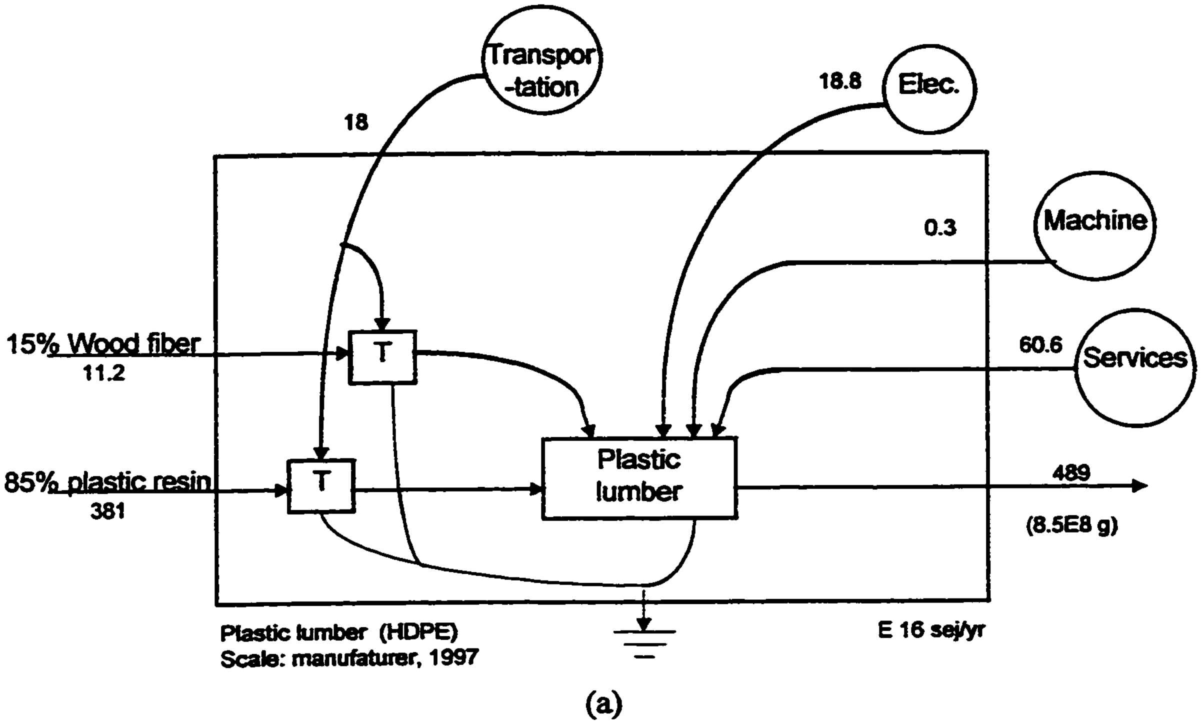


Figure 3-21. Emergy systems diagram of vinyl floor production from byproduct polyvinyl chloride (PVC) plastic (a) and summary diagram (b). Data are from Table 3-11.

Table 3-12. Emergy evaluation of plastic lumber (HDPE) production (1997).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+16
A. Conventional plastic lumber (HDPE) product (Figure 3-22)					
1	Wood fiber	J	2.67E+12	4.20E+04	11.20
2	Plastic resin	g	7.22E+08	5.27E+09	380.71
3	Electricity	J	1.08E+12	1.74E+05	18.79
4	Transport (Truck)	ton-mile	1.87E+05	9.65E+11	18.04
5	Machinery	g	4.84E+05	6.70E+09	0.32
6	Labor	$	5.27E+05	1.15E+12	60.64
7	Annual Yield (Y)	g	8.50E+08	5.75E+09	489.47
B. Adaptive reuse plastic lumber (HDPE) product (Figure 3-23)					
8	Post-consumer paper	J	2.67E+12	1.42E+05	37.89
9	Post-consumer plastic	g	7.22E+08	5.27E+09	380.71
10	Collection	g	8.49E+08	2.51E+08	21.33
11	Separation	g	8.49E+08	8.24E+06	0.70
12	Electricity	J	1.08E+12	1.74E+05	18.79
13	Transport (Truck)	ton-mile	1.87E+05	9.65E+11	18.04
14	Machinery	g	4.84E+05	6.70E+09	0.32
15	Labor	$	5.27E+05	1.15E+12	60.64
16	Annual Yield (Y)	g	8.50E+08	6.33E+09	538.41

Footnotes are given in appendix B, Table B-12



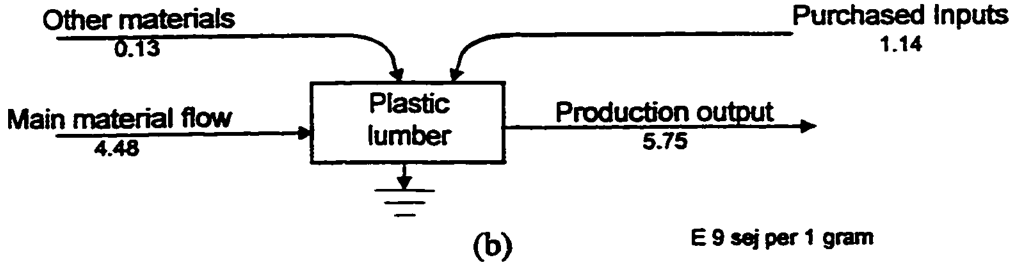


Figure 3-22. Emergy systems diagram of plastic lumber (HDPE) production (a) and summary diagram (b). Data are from Table 3-12.

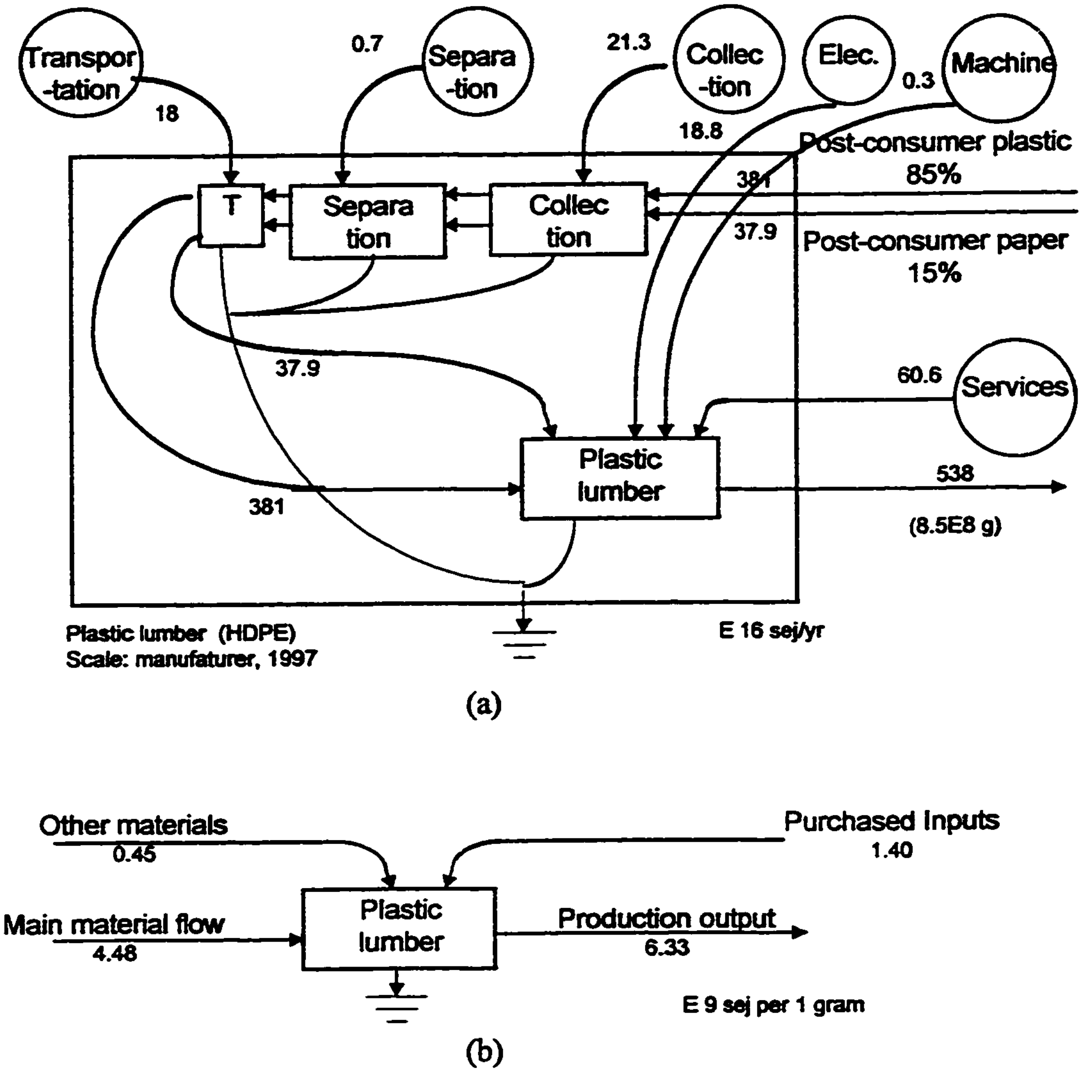


Figure 3-23. Emergy systems diagram of plastics lumber (HDPE) production using recycled plastic bottles and paper (a) summary diagram (b). Data are from Table 3-12.

Glass

Glass (ceramic tile)

Given in Table 3-13 and summarized in Figures 3-24, 3-25, and 3-26 are the emergy evaluation of ceramic tile. Presented are data from an individual industry for the conventional process that uses silica and clay as main inputs (Part A of Table 3-13 and Figure 3-24) and two recycle options using different types of post-consumer glass; bottles and windshields (Parts B and C of Table 3-13 and Figures 3-25 and 3-26).

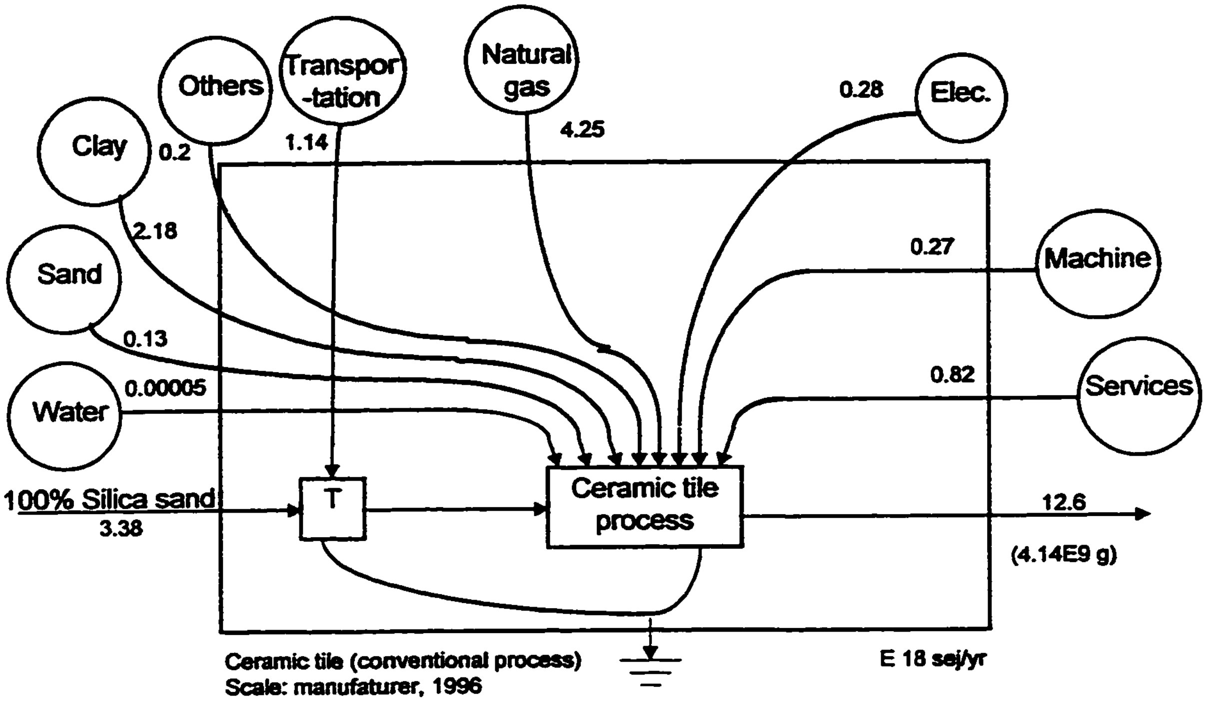
In the conventional process, the largest input is natural gas required for melting the silica (about 33% of total inputs). The silica and clay account for 28% and 17% of inputs respectively. The annual yield of ceramic tile has an emergy per mass of 3.06 E+9 sej/g.

In the two recycle options, post-consumer glass from automobile windshields (Part B and Figure 3-25) and from bottles (Part C and Figure 3-26) are substituted for the silica sand. A smaller mass of each is required (about 76% of the volume of silica sand). However, the emergy per mass of these finished products is higher than that of silica. Glass recycle has significant energy savings as the amount of direct energy used in melting post-consumer glass about 25-32% less than required for melting silica (SIRI, 1997). In all, there are sorting and transportation costs associated with the recycle pathways, so that the emergy per mass of the ceramic tile made from windshields and glass bottles are higher than the conventional process (3.42 E+9 sej/g, and 3.38 E+9 sej/g, respectively).

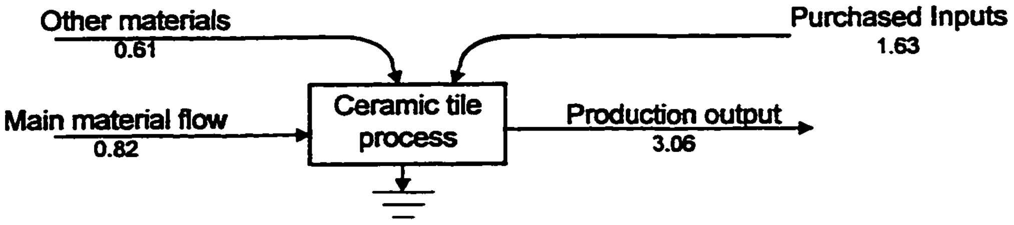
Table 3-13. Emergy evaluation of ceramic tile production (1996).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
A. Conventional ceramic tile product (Figure 3-24)					
1	Silica sand	g	3.38E+09	1.00E+09	3.38
2	Sand	g	1.31E+08	1.00E+09	0.13
3	Clay	g	1.09E+09	2.00E+09	2.18
4	Others	g	2.18E+08	1.00E+09	0.22
5	Water	J	1.08E+09	4.80E+04	0.000052
6	Natural gas	J	8.85E+13	4.80E+04	4.25
7	Electricity	J	1.61E+12	1.74E+05	0.28
8	Transport (Truck)	ton-mile	1.19E+06	9.65E+11	1.14
9	Machinery	g	4.08E+07	6.70E+09	0.27
10	Labor	$	6.85E+05	1.20E+12	0.82
11	Annual Yield (Y) ceramic tile	g	4.14E+09	3.06E+09	12.69
B. Adaptive reuse ceramic tile product with windshield glass (Figure 3-25)					
12	Sand	g	1.31E+08	1.00E+09	0.13
13	Clay	g	1.09E+09	2.00E+09	2.18
14	Post-consumer windshield glass	g	2.70E+09	1.90E+09	5.13
15	Others	g	2.18E+08	1.00E+09	0.22
16	Used windshield glass (collection)	g	2.70E+09	9.65E+11	0.86
17	Used windshield glass (separation)	g	2.70E+09	8.24E+06	0.02
18	Water	J	1.08E+09	4.80E+04	0.000052
19	Natural gas	J	6.65E+13	4.80E+04	3.19
20	Electricity	J	1.21E+12	1.74E+05	0.21
21	Transport (Truck)	ton-mile	1.19E+06	9.65E+11	1.14
22	Machinery	g	4.08E+07	6.70E+09	0.27
23	Labor	$	6.85E+05	1.20E+12	0.82
24	Annual Yield (Y) ceramic tile	g	4.14E+09	3.42E+09	14.16
C. Adaptive reuse ceramic tile product with post-consumer glass bottles (Figure 3-26)					
25	Sand	g	1.31E+08	1.00E+09	0.13
26	Clay	g	1.09E+09	2.00E+09	2.18
27	Post-consumer glass bottles	g	2.70E+09	1.90E+09	5.13
28	Others	g	2.18E+08	1.00E+09	0.22
29	Used glass bottles (collection)	g	2.70E+09	2.51E+08	0.67
30	Used glass bottles (separation)	g	2.70E+09	1.32E+07	0.03
31	Water	J	1.08E+09	4.80E+04	0.000052
32	Natural gas	J	6.65E+13	4.80E+04	3.19
33	Electricity	J	1.21E+12	1.74E+05	0.21
34	Transport (Truck)	ton-mile	1.19E+06	9.65E+11	1.14
35	Machinery	g	4.08E+07	6.70E+09	0.27
36	Labor	$	6.85E+05	1.20E+12	0.82
37	Annual Yield (Y) ceramic tile	g	4.14E+09	3.38E+09	14.03

Footnotes are given in appendix B, Table B-13



(a)



(b)

Figure 3-24. Emergy systems diagram of conventional ceramic tile production (a) and summary diagram (b). Data are from Table 3-13.

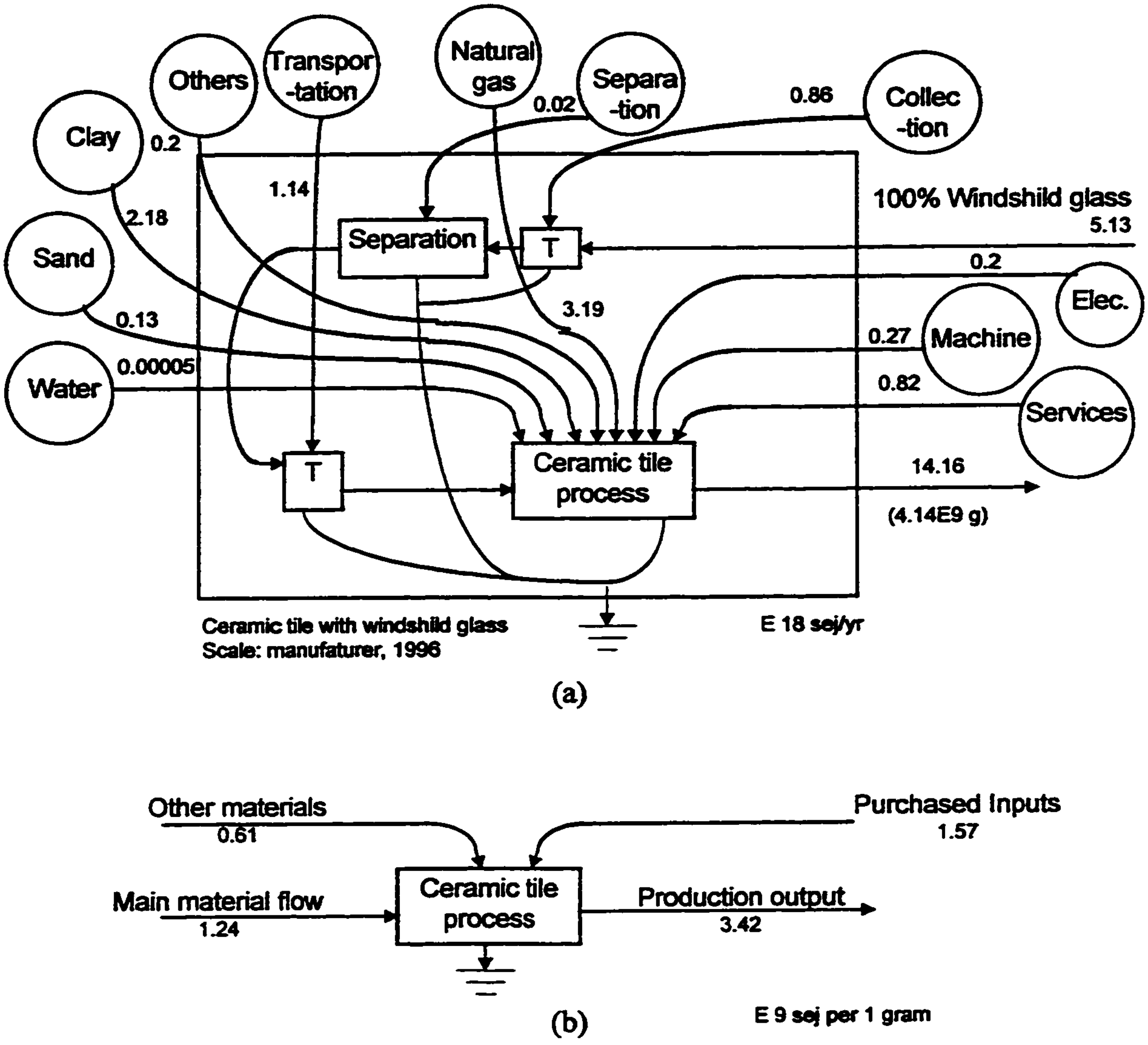


Figure 3-25. Emergy systems diagram of ceramic tile production using windshield glass (a) and summary diagram (b). Data are from Table 3-13.

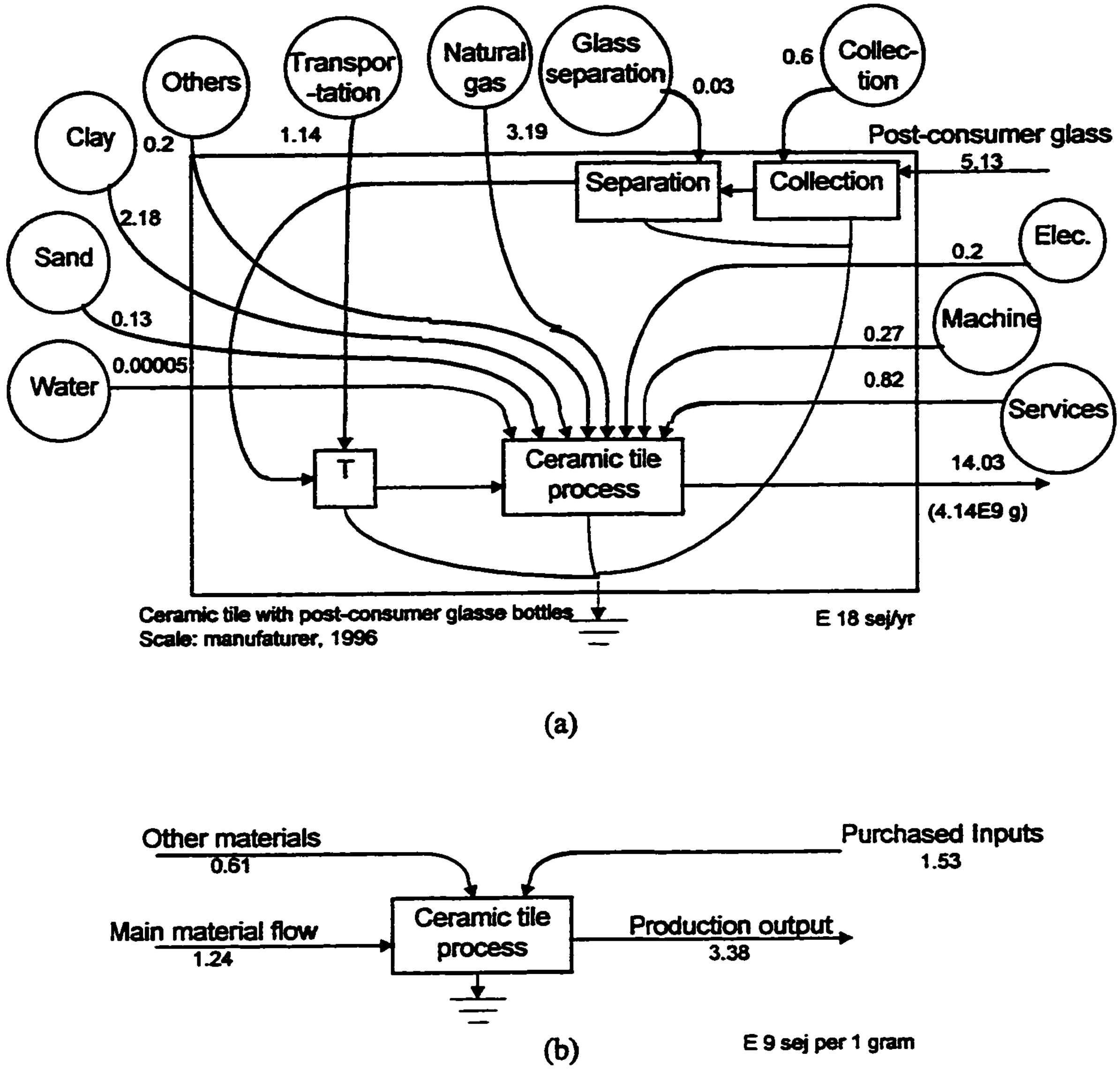


Figure 3-26. Emergy systems diagram of ceramic tile production using 100% post-consumer glass bottles (a) and summary diagram (b). Data are from Table 3-13.

Glass (float glass)

Table 3-14 and Figures 3-27 and 3-28 give the emergy analysis of float glass from data provided by an individual industry. In the conventional process given in Table 3-14A and summarized in Figure 3-27, silica is the main raw material input (17% of total inputs) and the direct energy use of oil is 79% of total. Labor accounts for 2.5% of total inputs. When high quality scrap glass is used, the requirement for silica is reduced by 46% and the direct energy input of oil is reduced by 6.5%. As the scrap glass has to be very high quality, it is produced as a byproduct from another glass manufacturing process, thus there are no collection and separation requirements. The emergy per mass for the conventional process is higher that the recycle option; 7.87 E+9 and 7.66 E+9 respectively.

Comparison of Building Materials

One method of comparing building materials is based on their dollar costs. Given in Table 3-15 are dollar costs for most of the major building materials on a mass basis. In the fourth column, bulk density of materials are given as kilograms per cubic meter. As might be suspected, structural steel has the highest density, while plywood, wood lumber and plastic lumber have the lowest densities. The final column in Table 3-15 gives price as grams per dollar (g/$). It is important to note that the price given here is the amount of material received for money spent, thus the higher the number in the fifth column, the more weight material received per dollar spent. Ready-mixed concrete has the highest mass per dollar followed by cement and brick.

Table 3-14. Emergy evaluation of float glass production (1997).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
A. Conventional float glass product (Figure 3-27)					
1	Silica (SiO2)	g	1.72E+11	1.00E+09	172.00
2	Soda ash (Na2O)	g	1.91E+10	3.80E+08	7.27
3	Lime (CaO)	g	1.27E+10	6.70E+06	0.09
4	Magnesium oxide (MgO)	g	3.82E+09	3.80E+08	1.45
5	Others	g	2.55E+09	3.80E+08	0.97
6	Oil	J	1.20E+16	6.60E+04	790.00
7	Transport (Railroad)	ton-mile	6.37E+07	5.07E+10	3.23
8	Transport (Truck)	ton-mile	2.39E+06	9.65E+11	2.31
9	Labor	$	2.18E+07	1.15E+12	25.01
10	Annual Yield (Y)	g	1.27E+11	7.87E+09	1000.00
B. In-house traditional recycling float glass product (Figure 3-28)					
11	Silica (SiO2)	g	9.18E+10	1.00E+09	91.77
12	Soda ash (Na2O)	g	1.91E+10	3.80E+08	7.27
13	Lime (CaO)	g	1.27E+10	6.70E+06	0.09
14	Magnesium oxide (MgO)	g	3.82E+09	3.80E+08	1.45
15	Others	g	2.55E+09	3.80E+08	0.97
16	Glass scrap	g	5.46E+10	1.90E+09	103.79
17	Oil	J	1.12E+16	6.60E+04	740.80
18	Transport (Railroad)	ton-mile	6.37E+07	5.07E+10	3.23
19	Transport (Truck)	ton-mile	2.39E+06	9.65E+11	2.31
20	Labor	$	2.18E+07	1.15E+12	25.01
21	Annual Yield (Y)	g	1.27E+11	7.66E+09	976.68

Footnotes are given in appendix B, Table B-14

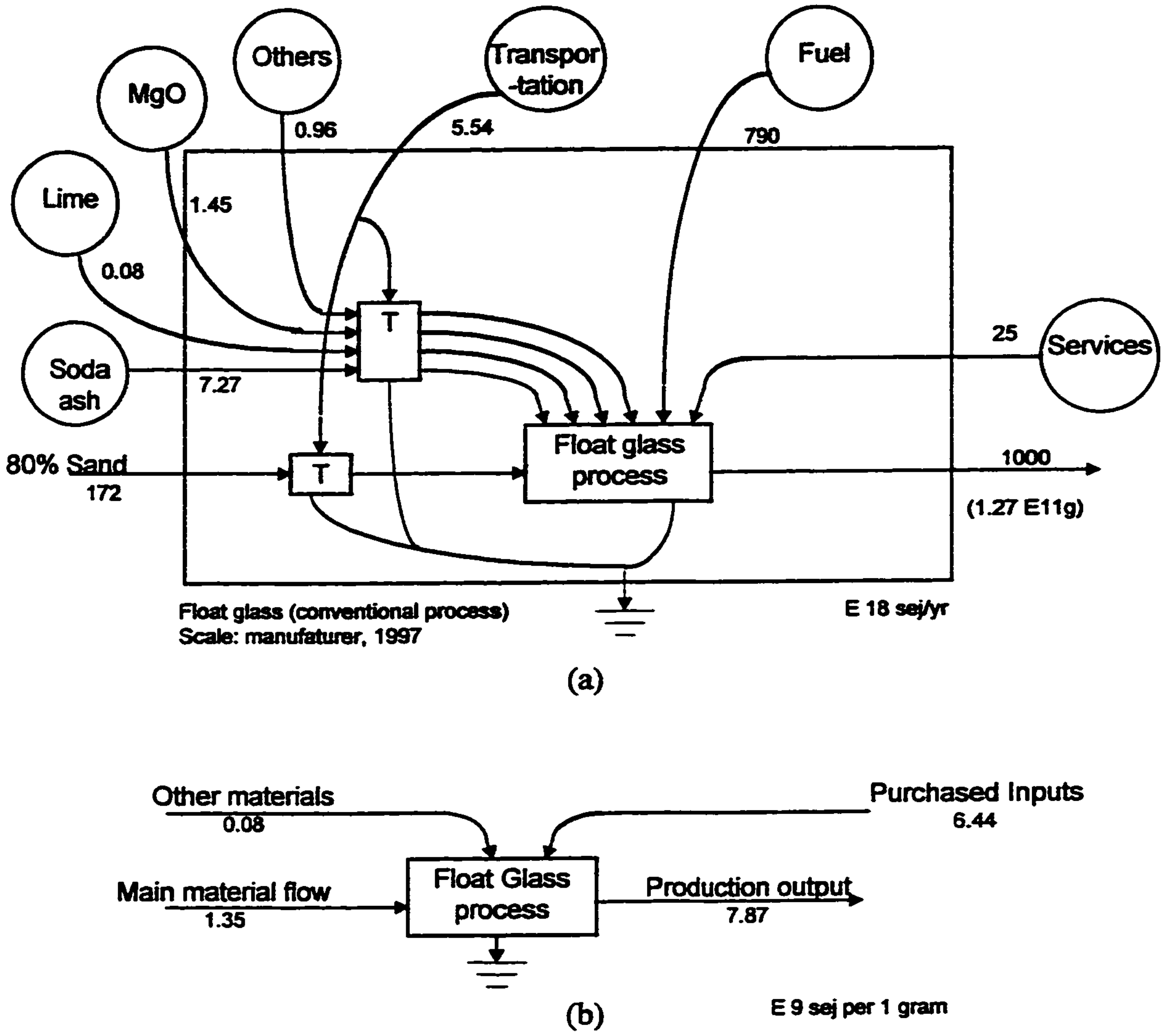


Figure 3-27. Emergy systems diagram of float glass production (a) and summary diagram (b). Data are from Table 3-14.

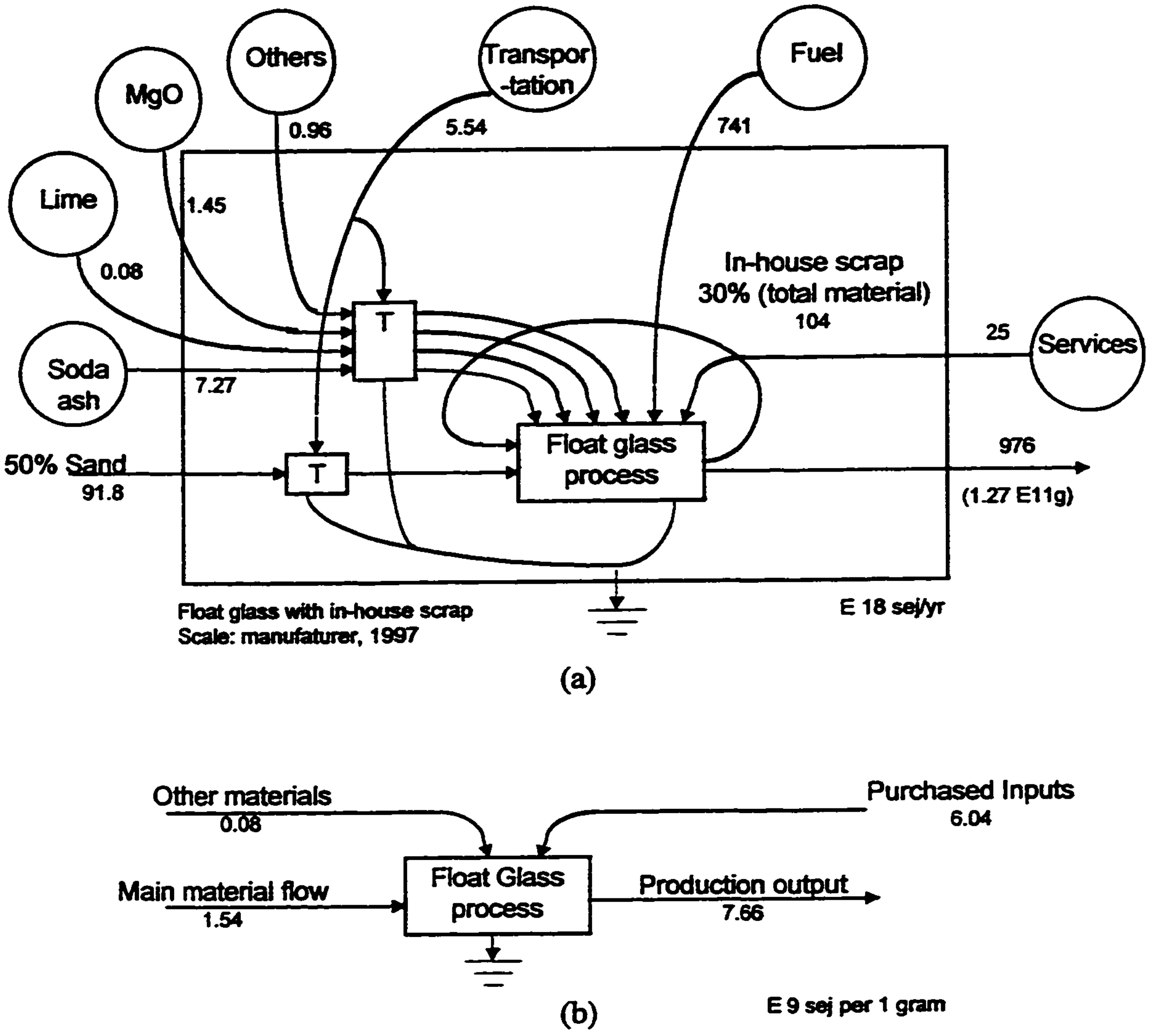


Figure 3-28. Emergy systems diagram of float glass production using in-house scrap (a) and summary diagram. Data are from Table 3-14.

Table 3-15. Building materials concentrations and prices.

Note	Building Materials	Prices in 1998 (RS means, 1998) $/unit	Bulk Density (weight/volume) kg/cu.m.	Price g/$
1	Cement	$5.44/bag	1400	7845
2	Ready-mixed concrete			
	(2000-6000 psi)	average $62.5/cu.yd.	2375	29056
	(8000-12000 psi)	average $160.5/cu.yd.	2375	11315
	Precast concrete (4"x 8"x 5')	$5.8/L.F.	2375	2457
3	Face brick (4"x2-2/3"x8")	$370/1000 bricks	2033	7325
4	Column brick (8"x8"x9")	$3.22/V.L.F.	2033	8527
5	Steel sheet			
	28 gauge	$0.79/sq.ft.	8100	377
	24 gauge	$1.02/sq.ft.		467
	16 gauge	$1.74/sq.ft.		685
6	Structural steel (W8x48)	$31/L.F.	8100	703
7	Aluminum sheet (3/16" thick)	$3.73/sq.ft.	2905	329
8	Structural aluminum	$1.74/lb.	2905	261
9	Plywood (4'x8'x1/2")	$1.6/sq.ft.	481	355
10	Wood lumber (2"x4")	$0.38/L.F.	641	2628
11	Vinyl floor (12"x12")	1/8" $0.98/sq.ft.	2077	625
12	Plastic lumber (2"x4")	$0.57/L.F. (Personal communication with plastic lumber manufacture, 1998)	561	1533
13	Ceramic tile (4-1/4"x4-1/4"x1/4")	$2.03/sq.ft.	2560	709
14	Float glass	1/4" $3.99/sq.ft.	2560	361
		1/2" $13.3/sq.ft.		217

Table 3-15--continued.

Footnotes

1 94 lb/bag (Hornbostel, 1978, p.151), 454 g/lb
1400 kg/cu.m. (Doran, 1992, p. 18/5)

2 4000 lb/cu.yd. (Hornbostel, 1978, p.205), 0.7646 cu.m./cu.yd., 454 g/lb
(4000 lb/cu.yd.)(454 g/lb)/(0.7646 cu.m./cu.yd.) = 2375 kg/cu.m.
(4"*2.5 cm./in.)(8"*2.5 cm./in.)(30 cm.)(2.375 g/cu.cm.)

3 0.07 lb/cu.in., 5.97 lb/brick (Hornbostel, 1978, p.125), 2.03392 g/cu.cm.
[(0.07 lb/cu.in)(454 g/lb)/(2.5*2.5*2.5 cu.cm./cu.in)](1E+6 cu.cm./cu.m.) = 2033.9 kg/cu.m.

4 40.32 lb/brick (Hornbostel, 1978, p.125), 1.5 brick/V.L.F.
2033.9 kg/cu.m.

5 0.28 lb/cu.in. (Reynolds, 1954, Table 7, p.104-105)
7860 kg/cu.m. (Doran, 1992, p. 5/14) or [(0.28 lb/cu.in.)(454 g/lb)/(2.5*2.5*2.5 cu.cm./cu.in)](1E+6 cu.cm./cu.m.) = 8100 kg/cu.m.
28 gauge, 0.656 lb/sq.ft., 0.016" thick; 24 gauge, 1.05 lb/sq.ft., 0.025" thick; 16 gauge, 2.625 lb/sq.ft., 0.063" thick (SSINA, 1998).

6 0.28 lb/cu.in. (Reynolds, 1954, Table 7, p.104-105), 48 lb/L.F.
7860 kg/cu.m. (Doran, 1992, p. 5/14) or 8100 kg/cu.m.

7 2.7 g/cu.cm. (Doran, 1992, p. 2/16) or 0.1 lb/cu.in. (Reynolds, 1954, Table 7, p.104-105), 2.9 lb/sq.ft.
(0.1 lb/cu.in.)(454 g/lb)/(2.5*2.5*2.5 cu.cm/cu.in.)](1E+6 cu.cm./cu.m.) = 2905 kg/cu.m.

8 2.7 g/cu.cm. (Doran, 1992, p. 2/16)
2905 kg/cu.m.

9 2.5 lb/bd.ft. (1/4" $1.03-1.49/sq.ft., 3/4" $3.3-5.05/sq.ft.)
(30 lb/cu.ft.)(454 g/lb)(27 cu.ft./cu.yd.)/(0.7646 cu.m./cu.yd.) = 481 kg/cu.m.

10 0.055 cu.ft./L.F., 3.3 lb/bd.ft., 40 lb/cu.ft. or 0.024 lb/cu.in. (Reynolds, 1954, Table 7, p.104-105)
(40 lb/cu.ft.)(454 g/lb)(27 cu.ft./cu.yd.)/(0.7646 cu.m./cu.yd.) = 641 kg/cu.m.

11 1.35 lb/1/8" sq.ft. (12"x12"x1/16" $0.86/sq.ft.)
(1.35 lb/1/8" sq.ft.)(454 g/lb)(8*12)(27 cu.ft./cu.yd.)/(0.7646 cu.m./cu.yd.) = 2077 kg/cu.m.

12 35 lb/cu.ft. (Personal communication with plastic lumber manufacturer company, 1998)
(35 lb/cu.ft.)(454 g/lb)(27 cu.ft./cu.yd.)/(0.7646 cu.m./cu.yd.) = 561 kg/cu.m.

13 562.5 cu.cm./sq.ft. of 1/4", (6"x6"x3/8" $2.35/sq.ft.)
2560 kg/cu.m. (Doran, 1992, p.29/6)

14 (3/16" $3.47/sq.ft., 3/8" $8.3/sq.ft.)
2560 kg/cu.m. (Doran, 1992, p.29/6)

Table 3-16. Life cycle emergy intensity of building materials.

Figures	Building Materials	Raw materials (a) (E9sej/g)	Refinery (b) (E9sej/g)	Produc-tion process (c) (E9sej/g)	Other material inputs (d) (E9sej/g)	Transpor-tation (e) (E9sej/g)	Construc-tion process (f) (E9sej/g)	Demoli-tion process (g) (E9sej/g)	Collection (h) (E9sej/g)	Separation (i) (E9sej/g)	Landfill process (j) (E9sej/g)	Life cycle emergy intensity (k) (E9sej/g)
3-1	Cement	1.06		0.92		0.002	2.14	0.048	0.019		0.013	4.20
3-2	Cement with coal fly ash	1.04		0.92	0.24	0.002	2.14	0.048	0.019		0.013	4.42
3-3	Concrete	0.44		0.68		0.32	2.14	0.048	0.019		0.013	3.66
3-5	Concrete with recycled concrete	0.44		0.68	0.12	0.32	2.14	0.068	0.019	0.016		3.80
3-6	Clay brick	2.00		0.22			2.14	0.048	0.019		0.013	4.44
3-8	Clay brick with sawdust fuel and oil-contaminated soil	1.59		0.08	0.26	0.003	2.14	0.048	0.019		0.013	4.15
3-9	Steel	2.44	0.42	1.14		0.15	2.14	0.048	0.019		0.013	6.37
3-11	Steel with post-consumer and byproduct scraps	1.70	0.30	1.14	0.86	0.15	2.14	0.048	0.109	0.009		6.46
3-14	Aluminum	2.16	9.99	0.55			2.14	0.048	0.019		0.013	14.92
3-16	Aluminum with post-consumer and byproduct scraps	0.65	3.00	0.55	8.5		2.14	0.048	0.149	0.076		15.11
3-19	Wood lumber	0.585		0.29			2.14	0.048	0.019		0.013	3.09
3-20	Wood lumber from post-consumer lumber	0.585		0.29		0.46		4.95	0.45			6.74

Table 3-16--continued.

Figures	Building Materials	Raw materials (a) (E9sej/g)	Refinery (b) (E9sej/g)	Produc-tion process (c) (E9sej/g)	Other material inputs (d) (E9sej/g)	Transpor-tation (e) (E9sej/g)	Construc-tion process (f) (E9sej/g)	Demoli-tion process (g) (E9sej/g)	Collection (h) (E9sej/g)	Separation (i) (E9sej/g)	Landfill process (j) (E9sej/g)	Life cycle emergy intensity (k) (E9sej/g)
3-22	Plastics (HDPE) lumber	3.62	0.86	0.94	0.13	0.20	2.14	0.048	0.019		0.013	7.97
3-23	Plastics (HDPE) lumber with post-consumer HDPE and paper	3.62	0.86	0.94	0.45	0.20	2.14	0.048	0.25	0.01		8.52
3-24	Ceramic tile with silica sand	0.82		1.97		0.27	2.14	0.048	0.019		0.013	5.28
3-25	Ceramic tile with post-consumer glasses	0.82		1.84	0.42	0.27	2.14	0.048	0.079	0.01	0.013	5.64
3-27	Float glass	1.35		6.48		0.04	2.14	0.048	0.019		0.013	10.09
3-28	Float glass with in-house recycle glass	0.72		6.08	0.82	0.04	2.14	0.048	0.019		0.013	9.88

(a) Main material flow from Figure 3-1 to 3-28.

(b) Data from Table 3-1 to 3-14, refining costs (see appendix C) typically include emergy costs for the 1st stage in a raw material transformation.

(c) Data from Table 3-1 to 3-14, production costs typically include emergy costs for the 2nd stage in a raw material transformation.

(d) Data from Table 3-1 to 3-14, other input costs typically include emergy costs for the product transformation.

(e) Data from Table 3-1 to 3-14, transportation costs typically include emergy costs for a raw material transportation.

(f) Data from Table D-5, building construction costs.

(g) Data from Table D-6, building demolition costs.

(h) Data from Table 3-1 to 3-14, collection costs typically include emergy costs of transportation after building demolition.

(i) Data from Table 3-1 to 3-14, separation costs.

(j) Data from Table D-2, landfill costs typically include emergy costs of landfill construction and operation which is 50 years.

(k) The total emergy through building material life.

Life cycle emergy intensity measures the total emergy used for a material from "cradle to grave." Table 3-16 gives life cycle emergy intensities for the main building materials expressed and emergy per gram (sej/g). For each material the emergy required for both the conventional and recycle life cycle are given. Aluminum has the highest life cycle emergy intensity. The majority of emergy used is in the refining process (67%). Glass has the next highest life cycle emergy intensity. The main emergy used is in the production process (65%). Plastics have high life cycle emergy intensity, but only about half that of aluminum. Highest emergy inputs to the life cycle of plastics are in the raw resource (about 45% of total inputs). Steel bas a life cycle emergy intensity about 42% of that of aluminum. Earth materials like, cement, concrete and clay brick have intermediate life cycle emergy intensities, while wood has the lowest.

In columns 3 through 12 of Table 3-16, the emergy required for each of the steps in the life cycle of the material is given. Comparison between materials shows that plastics have the highest emergy per gram (transformity) in raw resources followed by steel and aluminum. The lowest emergy in raw material is concrete followed by wood and ceramic tile.

Another method for comparing building materials is to compare the emergy intensity per year of useful life. The ratio decreases as the useful life of a material increases. Materials with longer useful lives have lower emergy requirements over their life time. In Table 3-17, useful life of materials as both a finish material and a structural material are given. As finish material, useful life is estimated as between 10 and 30 years (depending on material) while the useful life of structural components was estimated as between 25 and 45 years.

Table 3-17. Emergy per useful life of building materials.

Figures	Building Materials	Building components	Useful life (Table 2-2) (yr)	Ratio of emergy per useful life (E7 sej/g/yr)
3-1	Cement	mortar	30	6.60
3-2	Cement with coal fly ash	mortar	30	7.33
3-3	Concrete	pavement	20	7.20
		structure	45	3.20
3-4	Concrete with coal fly ash	pavement	20	7.75
		structure	45	3.44
3-5	Concrete with recycled concrete	pavement	20	7.95
		structure	45	3.53
3-6	Clay brick	finishing	30	7.40
		structure	45	4.93
3-7	Clay brick with sawdust fuel	finishing	30	7.06
		structure	45	4.71
3-8	Clay brick with sawdust fuel and oil-contaminated soil	finishing	30	6.43
		structure	45	4.28
3-9	Steel (EAF)	finishing	30	13.80
		structure	45	9.22
3-10	Steel (EAF) with post-consumer scrap	finishing	30	14.70
		structure	45	9.80
3-11	Steel (EAF) with post-consumer and byproduct scraps	finishing	30	14.13
		structure	45	9.42
3-12	Steel (BOF)	finishing	30	17.83
		structure	45	11.88
3-13	Steel (BOF) with in-house scrap	finishing	30	17.83
		structure	45	11.88
3-14	Aluminum	finishing	30	42.30
		structure	45	28.20
3-15	Aluminum with post-consumer scrap	finishing	30	43.33
		structure	45	28.88
3-16	Aluminum with post-consumer and byproduct scraps	finishing	30	43.00
		structure	45	28.60
3-17	Plywood	finishing	10	12.10
3-18	Laminated plywood	finishing	10	16.40
3-19	Wood lumber	structure	25	3.52
3-20	Wood lumber from post-consumer lumber	structure	25	26.96

Table 3-17--continued.

Figures	Building Materials	Building components	Useful life (Table 2-2) (yr)	Ratio of emergy per useful life (E7 sej/g/yr)
3-21	Plastics (vinyl floor tile) with byproduct PVC scrap	finishing	10	63.20
3-22	Plastics (HDPE) lumber	structure (temporary)	20	28.75
3-23	Plastics (HDPE) lumber with post-consumer HDPE	structure (temporary)	20	31.65
3-24	Glass (ceramic tile) with silica sand	finishing	20	15.30
3-25	Glass (ceramic tile) with windshield glass	finishing	20	17.10
3-26	Glass (ceramic tile) with bottle glass	finishing	20	16.90
3-27	Float Glass	finishing	30	26.20
3-28	Float glass with in-house scrap	finishing	30	25.50

As building structure, concrete and wood have the lowest emergy per useful life. Wood may have a lower ratio depending on the species as different species would have different useful lives. An average 25 years useful life for wood was used in this evaluation. Reprocessed wood lumber has a very high ratio since it requires a large demolition input. Aluminum has the highest, float glass the second highest, and steel the third highest ratio of emergy per useful life. As temporary structure, plastic lumber has a very high ratio compared to wood lumber. As finish component, emergy per useful life of cement, concrete, and clay brick are the lowest among the others. Plywood, steel, and ceramic tile are middling emergy intensive compared to the other materials.

Emergy Analysis of Recycle Systems

Supporting Analyses

Two types of waste recycle systems were evaluated, municipal solid wastes (MSW) and construction and demolition wastes (C&D). Table 3-18 summarizes the emergy analyses of MSW and C&D wastes given in Appendix D. MSW is usually collected at curb side, therefore the analysis includes significant amounts of truck transport costs for collection (251 E+6 sej/g). Sorting costs are about 3% of collection costs, while the emergy costs of landfilling are (includes the lifetime operation and maintenance (O&M) costs for the 50 year life of the landfill) are about 5% of the collection costs. Obviously the emergy costs of MSW handling and disposal dominates the emergy in O&M of the landfill over its life of 50 years.

Construction and demolition (C&D) wastes are collected from the jobsite and hauled directly to a landfill or other facility. Typical composition by weight of C&D

Table 3-18. Emergy intensity of various processes associated with waste recycle.

Note	Service	Emergy (E+06 sej/g)	Reference tables
Municipal solid wastes			
1	Collection	251	(Table D-1)
2	MSW Separating	8.2	(Table D-3)
3	Landfilling	13.4	(Table D-2)
Construction and demolition wastes			
4	Demolition	48.7	(Table D-6)
5	C&D hauling	21.3	(Table D-7)
6	C&D Sorting	6.7	(Table D-7)

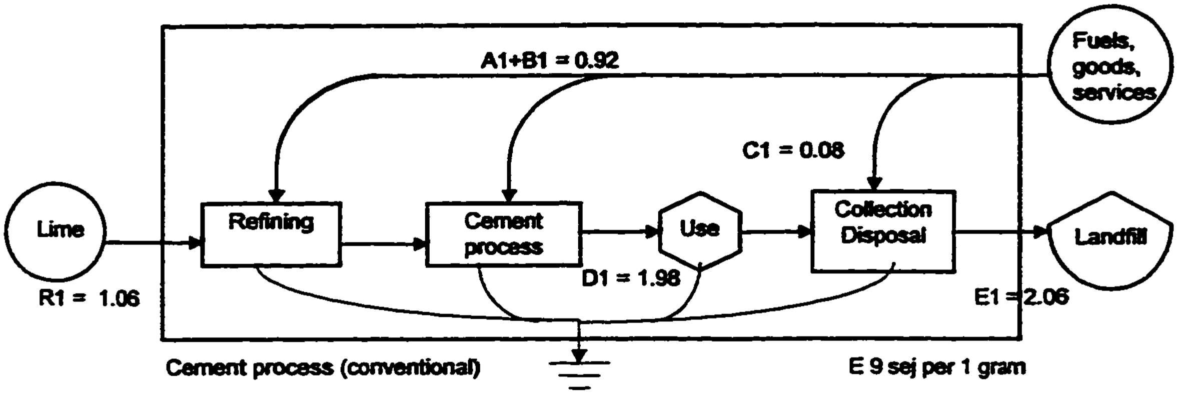
waste is: 40% concrete, 30% wood, 20% soil, 10% metals and plastics (Lund, 1993). In many circumstances, separated C&D wastes are recycled. Concrete is crushed and used for base aggregates. Wood is used for construction and sometimes as fuel to generate electricity. Soil is used in construction and fill. Metals and plastics are used in other recycling facilities.

The largest emergy cost for C&D wastes is the costs of demolition, evaluated as 48.7 E+6 sej/g. Hauling costs are less than half this amount, while sorting amounts to about 14% of the demolition costs. If the C&D wastes are landfilled, the landfilling costs were assumed to be the same as those for MSW.

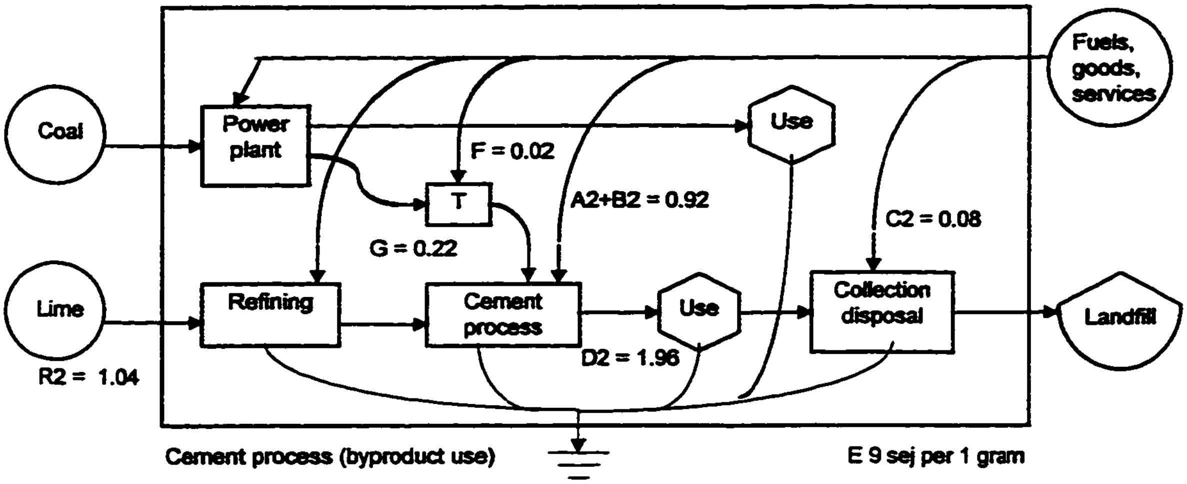
Emergy Analysis of Recycle Systems

The recycle systems for each of the main building materials were evaluated to compare costs and benefits of recycle. Given in Figures 3-29 through 3-36 are systems diagrams that summarize the data from Tables 3-1 though 3-14 on a gram of material basis. The diagram in Figure 3-29 summarizes the data for conventional cement and cement where fly ash from a coal fired power plant is substituted for a portion of the input cement. This type of recycle system is considered a byproduct use. The benefit from fly ash use is a reduction in the amount of cement necessary in the final product. The costs associated with substitution are related to transport of the fly ash to the cement production facility.

Conventional concrete production and the recycle of concrete are summarized in Figure 3-30. In the recycle alternative, concrete is broken up and used for aggregate in the making of a lower grade of concrete suitable for non-structural applications.

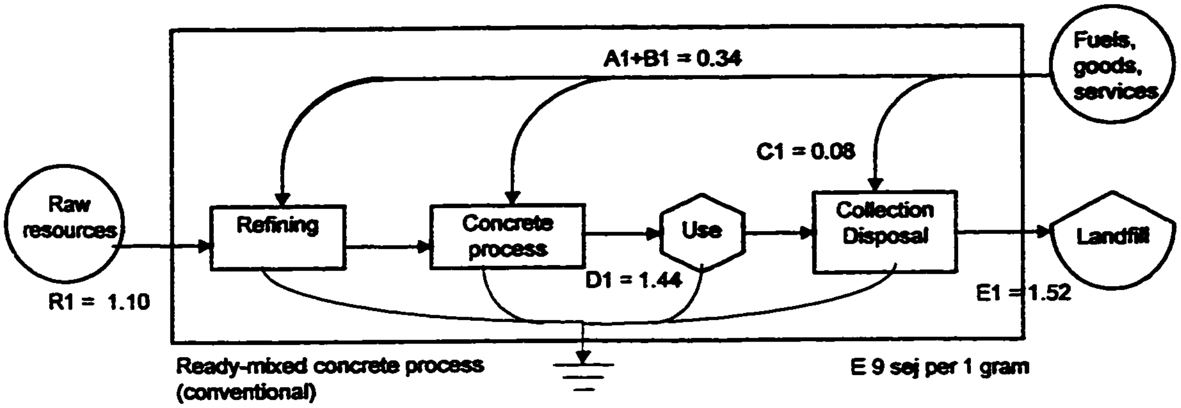


(a) Cement

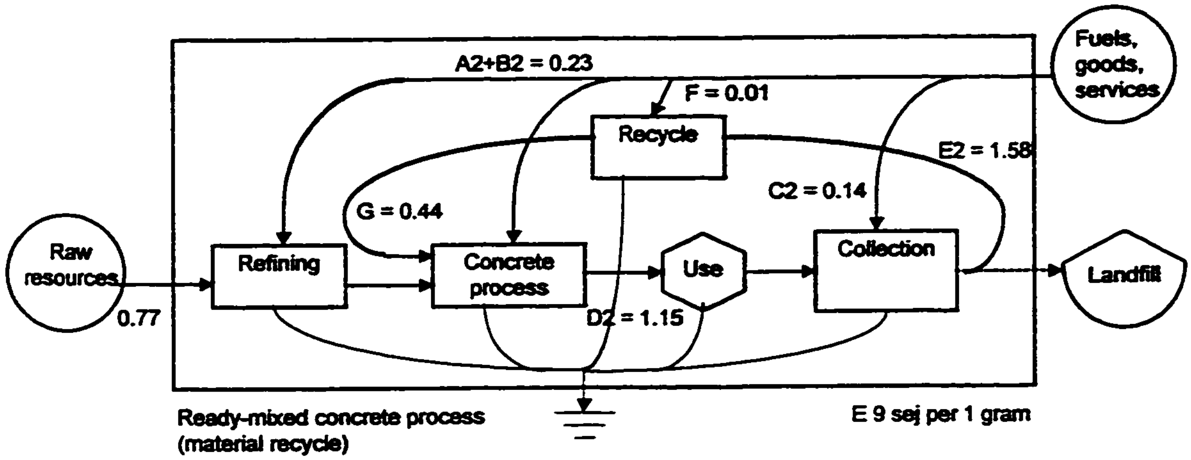


(b) Cement with coal fly ash

Figure 3-29. Comparison of cement material and its recycling alternative. Data are summarized from Table 3-1. (For definitions of lettered pathways see Figure 2-6)

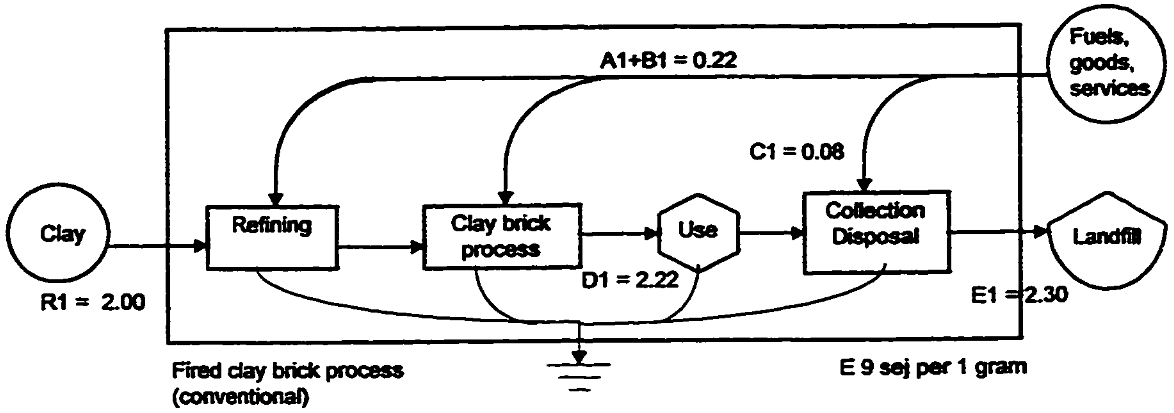


(a) Ready-mixed concrete

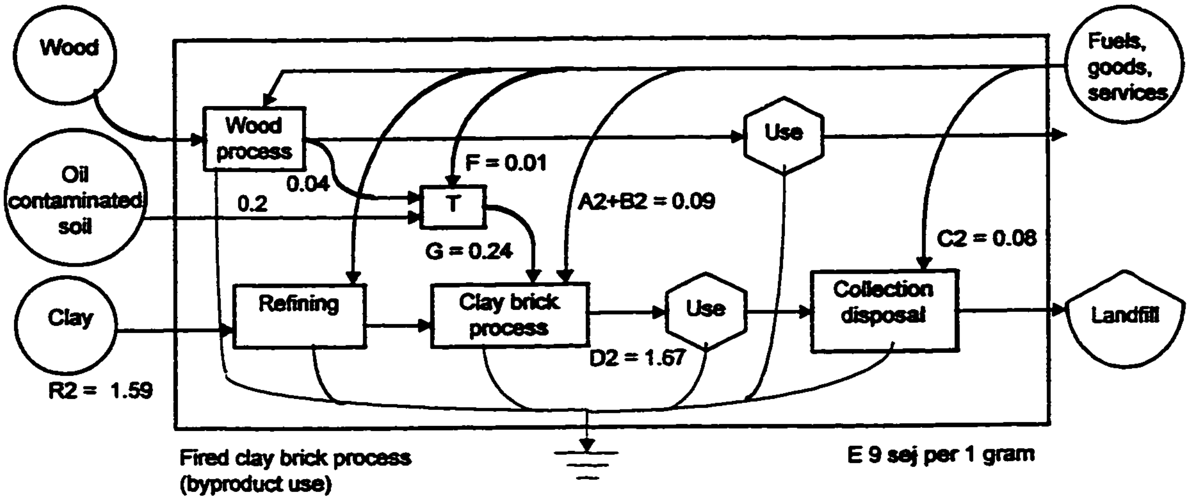


(b) Ready-mixed concrete with recycled concrete aggregate

Figure 3-30. Comparison of concrete material and its recycling alternative. Data are summarized from Table 3-2 (a and c). (For definitions of lettered pathways see Figure 2-6)

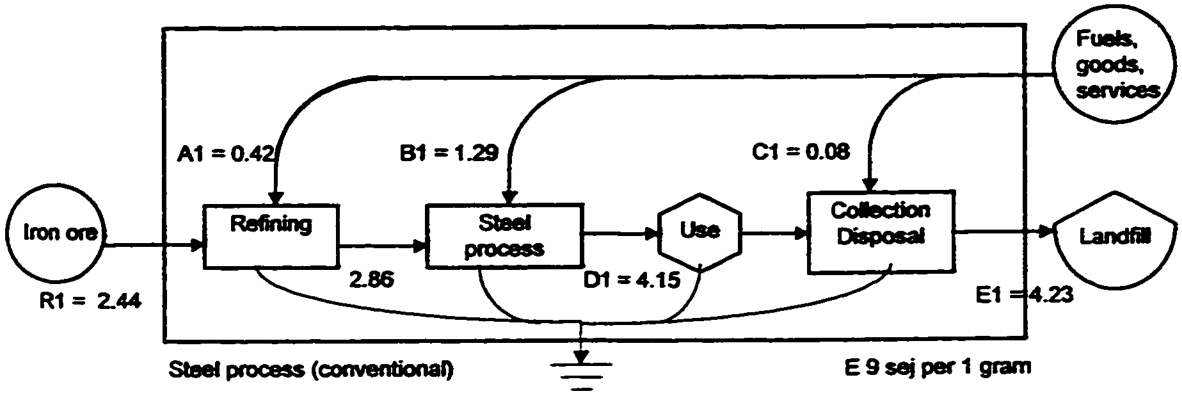


(a) Fired clay brick

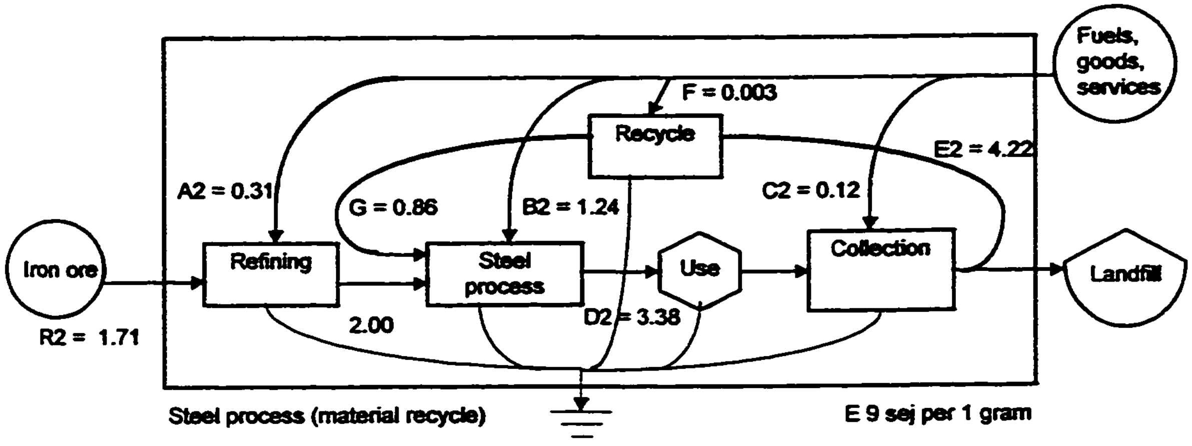


(b) Fired clay brick with sawdust fuel and oil-contaminated soil

Figure 3-31. Comparison of clay brick material and its recycling alternative. Data are summarized from Table 3-3 (a and c). (For definitions of lettered pathways see Figure 2-6)

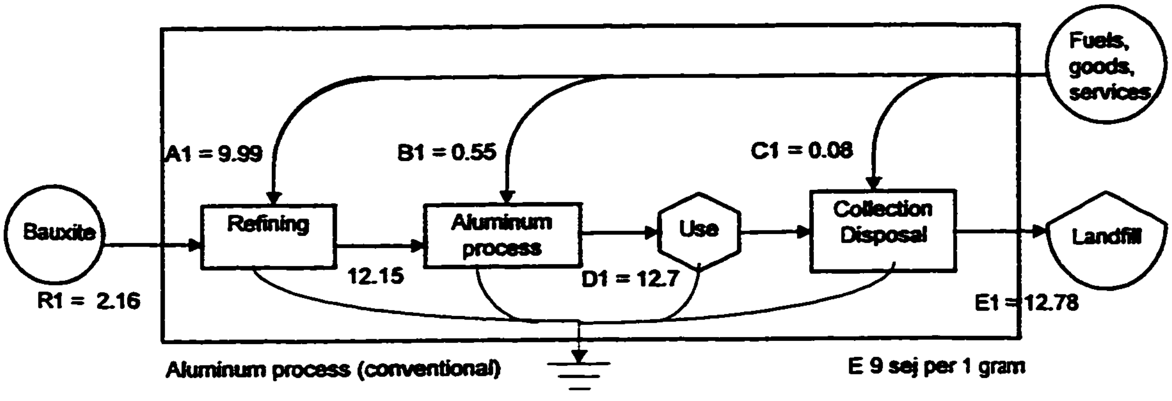


(a) Steel

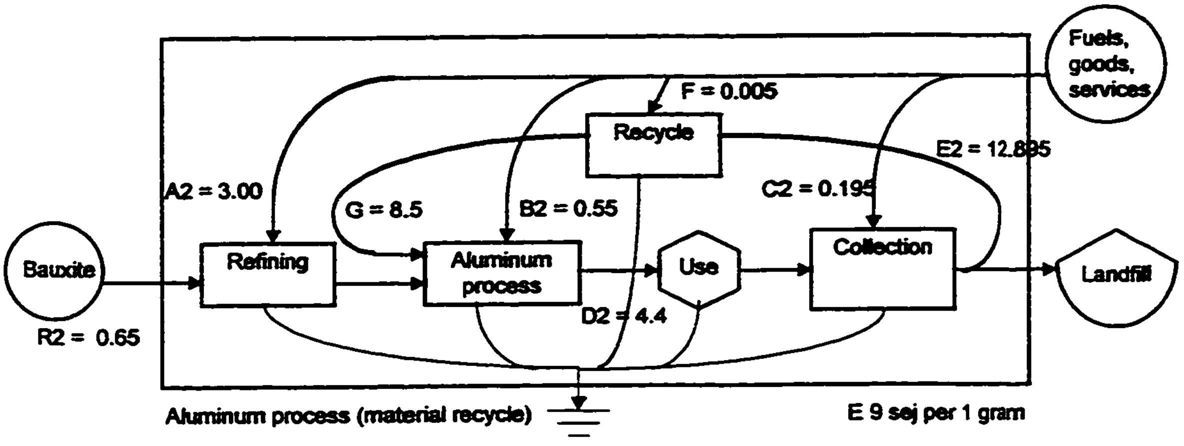


(b) Steel with post-consumer scrap

Figure 3-32. Comparison of steel material and its recycling alternative. Data are summarized from Table 3-4 (a and c). (For definitions of lettered pathways see Figure 2-6)

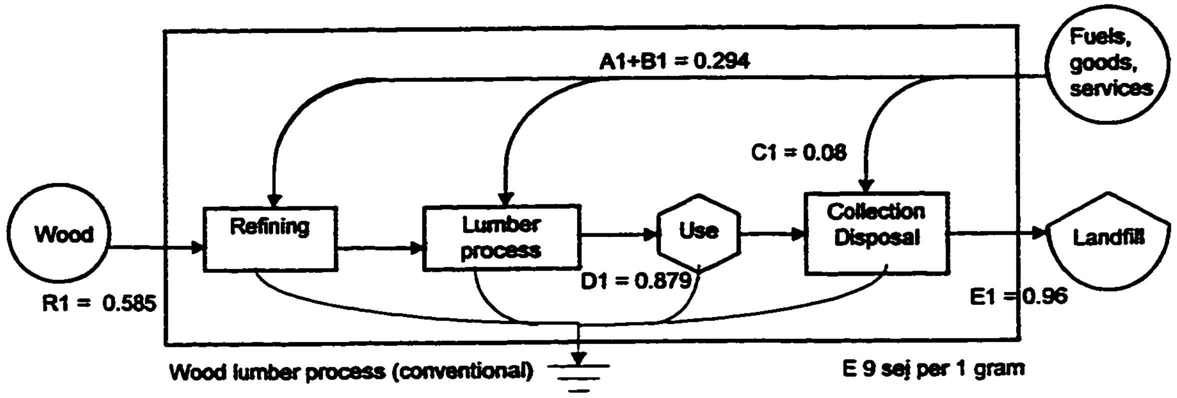


(a) Aluminum

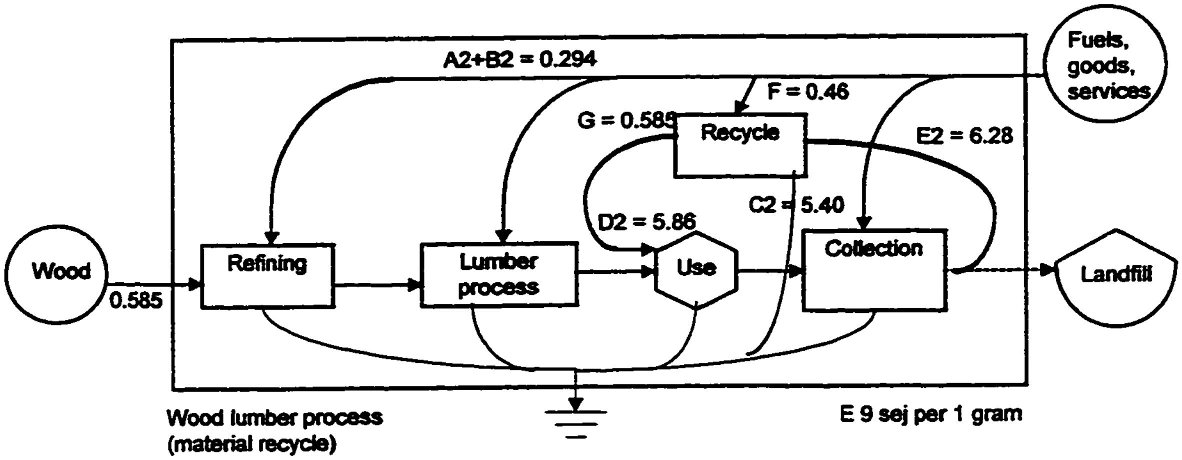


(b) Aluminum with post-consumer scrap

Figure 3-33. Comparison of aluminum material and its recycling alternative. Data are summarized from Table 3-6 (a and c). (For definitions of lettered pathways see Figure 2-6)

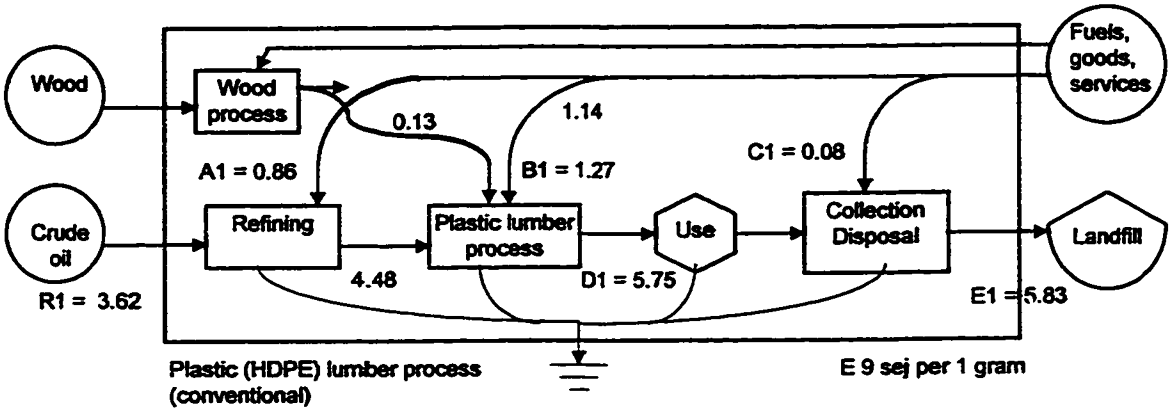


(a) Wood lumber

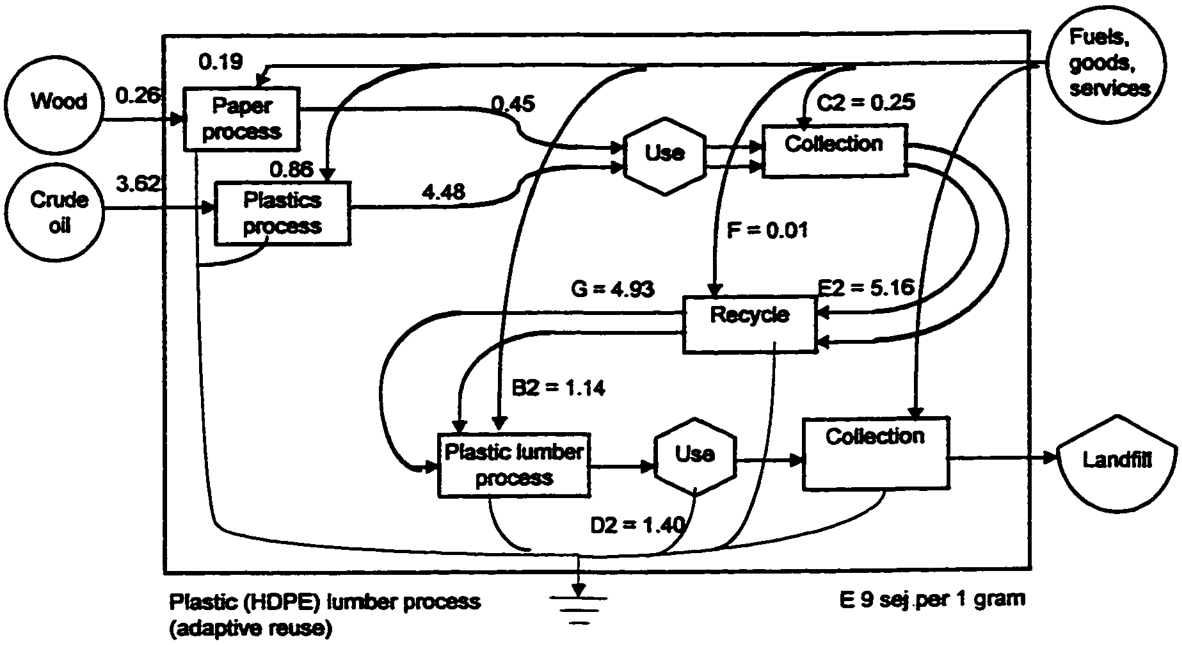


(b) Wood lumber from post-consumer lumber

Figure 3-34. Comparison of wood lumber material and its recycling alternative. Data are summarized from Table 3-9 and 3-10. (For definitions of lettered pathways see Figure 2-6)

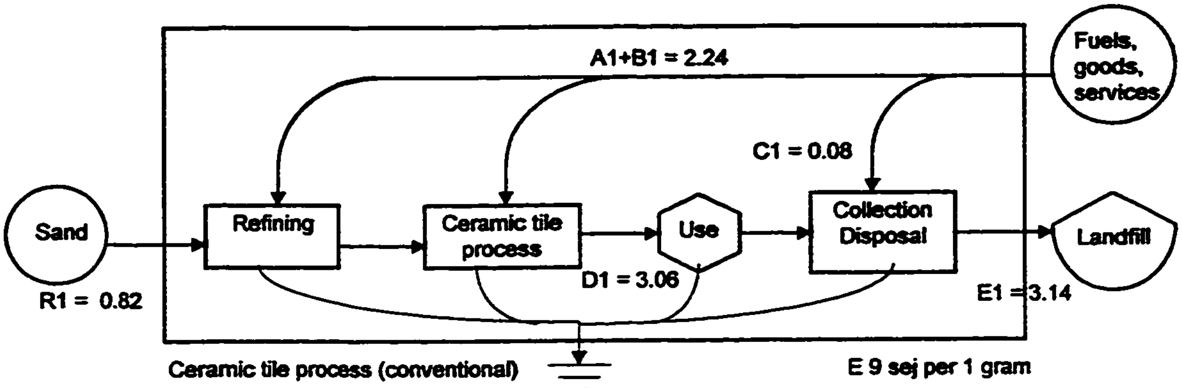


(a) Plastic (HDPE) lumber

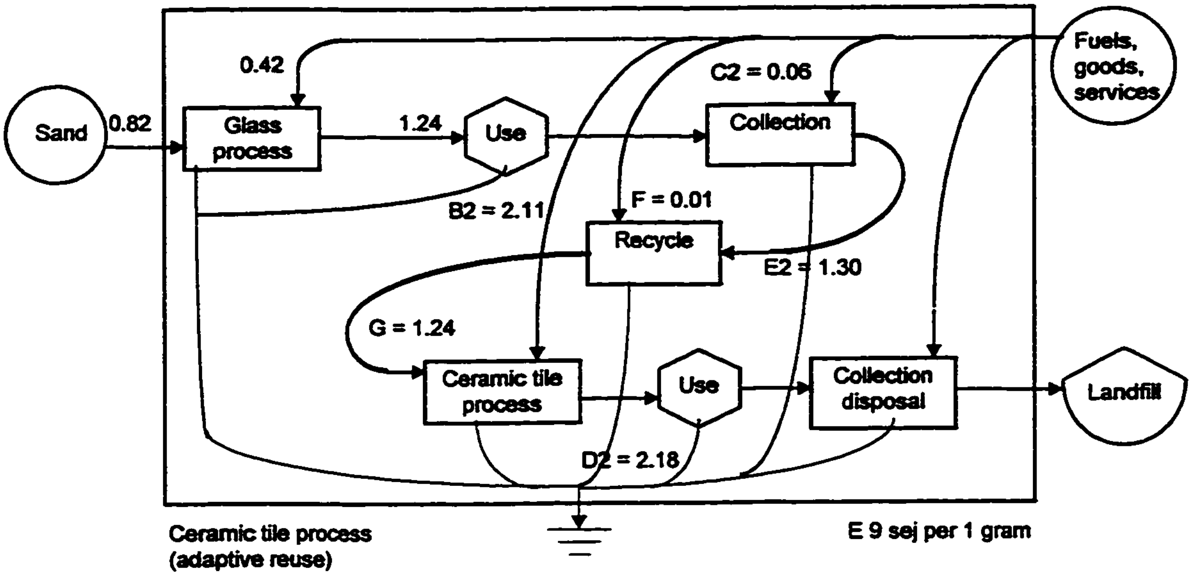


(b) Plastic (HDPE) lumber with post-consumer plastic and paper

Figure 3-35. Comparison of plastic (HDPE) lumber material and its recycling alternative. Data are summarized from Table 3-12. (For definitions of lettered pathways see Figure 2-6)



(a) Ceramic tile



(b) Ceramic tile with post-consumer glass

Figure 3-36. Comparison of ceramic tile material and its recycling alternative. Data are summarized from Table 3-13 (a and b). (For definitions of lettered pathways see Figure 2-6)

Figure 3-31 summarizes the conventional and recycle system for clay brick. This system is considered a byproduct use, since wood wastes (sawdust) and oil-contaminated soil are used in the making of the bricks, lowering both the amount of clay required and the amount of fuel necessary to fire the brick.

Steel and aluminum are easily recycled. The conventional production and recycle systems for steel and aluminum are summarized in Figures 3-32 and 3-33. The main recycle inputs are in transportation.

Conventional lumber production and the wood recycle system are summarized in figure 3-34. The recycle pathway is relatively intensive because of the labor and transport inputs.

The production of plastic lumber in the conventional process and from adaptive reuse of post-consumer paper and plastic is summarized in Figure 3-35. Significant amounts of emergy are used in collection, sorting and transport.

Figure 3-36 summarizes data for conventional production of ceramic tile and as compared to ceramic tile made with recycle post-consumer glass. As in the other post-consumer recycle systems, there are significant emergy costs in collection, sorting, and transport of the glass materials to the point of production.

Table 3-19 summarizes the recycle indices for the main building materials and their recycle systems. Four recycle indices are given: Recycle Benefit Ratio (RBR), Recycle Yield Ratio (RYR), Landfill Recycle Ratio (LRR), and the Recycle Efficiency Ratio (RER).

The recycle benefit ratio (RBR) measures the benefit of recycling a material through lower raw material inputs and processing energy. It is the ratio of the emergy saved to the emergy costs of recycling. The higher the ratio, the better benefit for invested emergy. Highest RBRs were found for steel, aluminum, and ceramic tile. The lowest ratio (in fact less than 1) is for the recycle of used lumber.

The recycle yield ratio (RYR) is the ratio of emergy value of recycled material to the costs of recycle. It measures the emergy value of recycle material received by society for the emergy invested. The larger the ratio, the better yield for invested emergy. Significant yields are obtained with recycle systems for steel, aluminum, plastics, and ceramic tile. Much lower, but still important are the RYRs for cement, concrete and clay brick. Again wood has the lowest ratio.

The landfill recycle ratio (LRR) is an index that measures the benefit of recycling verses landfilling. It is the ratio of the costs of landfilling to the costs of recycling. The higher the ratio the better. Ceramic tile has the highest LRR followed by clay brick, cement, and steel. The lowest LRR (less than 1) is wood.

The last column in Table 3-19 is the recycle efficiency ratio (RER) which is a measure of efficiency by comparing the costs of producing a material from raw resources to the emergy costs invested in recycling. Again the higher the ratio the better. Aluminum, steel, and ceramic tile have the highest efficiencies. The RER for wood is less than one.

Table 3-19. Recycle indices of building materials.

Figures	Building Materials	Recycle Benefit Ratio (RBR) A1/(C2+F)	Recycle Yield Ratio (RYR) G/(C2+F)	Landfill Recycle Ratio (LRR) C1/(C2+F)	Recycle Efficiency Ratio (RER) (R1+A1+B1+C1)/(C2+F)
3-29	Cement with fly ash	9.2	2.2	0.8	20
3-30	Concrete with recycled concrete aggregate	2.3	2.9	0.5	10
3-31	Clay brick with oil-contaminated soil and sawdust fuel	2.4	2.6	0.9	25
3-32	Steel using recycled steel	3.4	6.9	0.7	34
3-33	Aluminum using recycled aluminum	49.9	42.5	0.4	64
3-34	Wood lumber (recycled)	0.05	0.1	0.01	0.16
3-35	Plastics (HDPE) lumber using recycled plastic	3.3	18.9	0.3	22
3-36	Ceramic tile using recycled glass	32	17.7	1.1	45

RBR = The ratio of emergy required in material refinery in conventional process (A1) to the emergy used in recycle (C2+F).

RYR = The ratio of emergy yield of recycled material (G) to the emergy used in recycle (C2+F).

LRR = The ratio of emergy required for landfilling a material (C1) to the emergy required for recycle (C2+F).

RER = The ratio of material and emergy (in conventional process) conserved (R1+A1+B1+C1) to the emergy required for recycle (C2+F) when recycle materials are used.

(For definitions of lettered pathways see Figure 2-6)

CHAPTER 4
DISCUSSION

Emergy and Building Materials

A summary table of the various emergy indices comparing building materials is given in Table 4-1. Ratios and indices are given for conventional material production systems and for production systems that include some forms of recycle. The first row in each material set gives ratios and indices for the conventional process, while those that follow incorporate a recycle pathway. Comparison between different materials provides insight related to the energy requirements for their production, and comparison of ratios and indices within material groups helps to evaluate the significance of recycle process for each material group.

Price has long been the single most important comparative tool for evaluating materials. In the third column of Table 4-1, the price of materials expressed as mass per dollar (g/$) is given. Only one price for each material is given, as it is assumed that the dollar costs of recycled materials remain the same as the conventionally produced material. The larger the number the more mass is obtained for the expenditure of a dollar, and as might be expected, the more finished a material, the lower the mass purchased per dollar. Therefore glass and aluminum have relatively low mass per dollar prices since they are more finished. On the other hand, concrete and clay brick have the largest mass per dollar. Price is directly related to human service, so those materials that have the

Table 4-1. Comparison of emergy indices for building materials.

Figures	Building Materials	Price (a) (g/$)	Emergy Yield Ratio Y/F	Emergy per mass (b) (E9 sej/g)	Emprice (a)*(b) (E12 sej/$)	Ratio of emergy per useful life (E7 sej/g/yr)	Life cycle emergy intensity (E9 sej/g)
3-1	Cement	7845	6.83	1.98	15.53	6.60	4.20
3-2	Cement with coal fly ash		7.86	1.96	15.37	6.53	4.42
3-3	Concrete	11315	4.24	1.44	16.29	7.20	3.66
3-5	Concrete with recycled concrete		4.18	1.15	13.01	5.75	3.80
3-6	Clay brick	8527	10.33	2.22	18.93	4.93	4.44
3-8	Clay brick with sawdust fuel and oil-contaminated soil		24.13	1.67	14.24	3.71	4.15
3-9	Steel (EAF)	703	3.22	4.15	2.92	9.22	6.37
3-11	Steel (EAF) with post-consumer and byproduct scraps		3.07	3.38	2.38	7.51	6.46
3-14	Aluminum sheet	329	23.09	12.7	4.18	42.30	14.92
3-16	Aluminum sheet with post-consumer and byproduct scraps		17.20	4.4	1.45	14.66	15.11
3-19	Wood lumber	2628	8.79	0.879	2.31	3.52	3.09
3-20	Wood lumber from post-consumer lumber		1.23	5.86	15.40	23.44	6.74
3-22	Plastics (HDPE lumber)	1533	5.04	5.75	8.81	28.75	7.97
3-23	Plastics (HDPE lumber) with post-consumer HDPE		4.55	1.40	2.15	7.00	8.52

Table 4-1--continued.

Figures	Building Materials	Price (a) (g/$)	Emergy Yield Ratio Y/F	Emergy per mass (b) (E9 sej/g)	Emprice (a)*(b) (E12 sej/$)	Ratio of emergy per useful life (E7 sej/g/yr)	Life cycle emergy intensity (E9 sej/g)
3-24	Ceramic tile with silica sand	709	1.88	3.06	2.17	15.30	5.28
3-25	Ceramic tile with windshield glass		2.19	2.18	1.55	10.90	5.64
3-27	Float Glass	217	1.22	7.87	1.71	26.20	10.09
3-28	Float glass with in-house scrap		1.26	7.16	1.55	23.86	9.88

lowest mass per dollar are most often those that have large inputs of human service in their production.

The emergy yield ratio (EYR) expresses the emergy value of a material as a function of the emergy required to make it. The EYR is high when a material has much emergy that resulted from the free work of natural processes. In essence, it relates the net benefit that society receives from a material for a given investment of non-renewable emergy. The higher the ratio, the more benefit society receives. The moderately high EYRs of the materials evaluated (4th column in Table 4-1) are associated with what might be called primary building materials (cement, clay brick, and wood). Even though aluminum requires large inputs of electricity for refining, its large yield suggests that it is an important material and society gains much from its use. Ratios closer to 1 (i.e. ceramic tile and glass) cannot be considered primary building materials, but act more as secondary materials used for aesthetics and fenestration.

When EYRs significantly decrease for materials that include some forms of recycle, it suggests that the recycle pathway may not be economically viable. For instance, there is a significant decline in the EYR for lumber (decreasing nearly 86% from an EYR of 8.74 to 1.23) between the conventional process and recycled post-consumer process.

Emergy of building materials includes all the emergy required to make the material, including the emergies of the environment that were necessary to concentrate the raw material by natural processes. The total required emergy is expressed as emergy per mass (sej/g) in the fifth column of Table 4-1. Materials investigated had emergy per mass values that ranged from 0.88 E+9 sej/g to 13.0 E+9 sej/g. The general pattern is that the more refined the material product, the higher the emergy per gram. Thus steel, aluminum, plastics, and float glass have emergy per mass values that range from 5 E+9 sej/g to 13 E+9 sej/g, while wood, concrete, ceramic tile, and bricks range from 0.8 E+9 to 3 E+9 sej/g.

Emergy theory suggests that quality and versatility of a material are related to emergy per mass. The larger the emergy per mass, the more valuable and versatile the product. The highest emergy per mass values are associated with aluminum (13.0 E+9 sej/g) and float glass (7.9 E+9 sej/g). These materials may be the most versatile and may have the greatest potentials for recycle.

The relationship between emergy per mass of the conventional process and the increase as a percent of the total that is required for recycle suggests the likelihood of recycle becoming a significant aspect of a material's cycle. For instance, it requires only an additional 2.4% emergy input to recycle aluminum while the increase to recycle wood lumber represents an increase of 666% emergy commitment over the conventional process. Steel requires an additional 2.2% emergy input for recycle, while plastic lumber made from recycled post-consumer plastic requires an additional 10% emergy input.

Emprice (emergy-price) is the emergy received for each dollar paid for a material. The sixth column in Table 4-1 gives the emprice for the evaluated materials. The emprice varies for these materials from a high of 18.9 E+12 sej/$ (clay brick) to a low of 1.7 E+12 sej/$ (float glass). The emprice is probably the most telling of the various indices. The emprice is an indicator of the amount of human service that is required in the production process of a material. Very high emprices (13 - 19 E+12 sej/$) are associated with raw resources and primary building materials, which require relatively smaller amount of human service in production, while low emprices (1.0 E+12 sej/$) are indicative of materials having large demands for human service in production.

The seventh column in Table 4-1 lists the ratio of emergy per useful life calculated as the total emergy required to produce a material divided by the material's useful life. This ratio is the only one where smaller is better. Materials with the smallest ratios (clay brick, lumber, and concrete) have the smallest total emergy investment for their useful lives. Materials like plastic, glass, and aluminum have the largest emergy investments for useful life.

The life cycle emergy intensity, given in the last column of Table 4-1, is the total emergy used in the life cycle of a material (expressed as sej/g), including the emergy required to make it and that necessary to collect and dispose of it. The higher the number, the higher the commitment of emergy over the life time of a material. Comparison between the emergy per mass and life cycle emergy for each material indicates the relative portion of the total emergy that is necessary for collection and disposal.

Emergy Costs of Recycled Material Transport

Transport of materials from the site of collection to the point of use may play a major role in determining its recycle-ability. In column a of Table 4-2, recycle emergy intensity which is the emergy required to process used material is given. Landfill emergy intensity, which is the emergy required for collection, landfilling, and landfill operation of 50 years, is given in column b in Table 4-2. It is assumed that different wastes have the same inputs in landfill processes. Table 4-2 lists maximum transport distances for materials based on the savings possible if the materials are not landfilled. The transport

Table 4-2. Transportation distance comparison of landfill and recycling facility (separation).

Figures	Building Materials or separation facilities	(a) Recycle emergy intensity (E+6 sej per g)	(b) Landfill emergy intensity (E+6 sej per g)	(c) Transportation distance ** (miles)
3-2	Cement *			
3-5	Concrete	7	13.4	6
3-8	Clay brick *			
3-11	Steel	3	13.4	10
3-16	Aluminum	5	13.4	8
3-20	Wood lumber	14	13.4	-1
3-23	Plastics (HDPE) lumber	8	13.4	5
3-25	Ceramic tile	5	13.4	8
Table D-7	C&D separation	6.7	13.4	6

* Byproduct use recycle process with no separation facility.

** column (b) - (a) divided by 1.06 E+6 sej/g-mile of truck transportation.

distances are obtained by subtracting the recycle cost from landfilling costs, under the assumption that the difference can be used in transport. The difference between emergy costs of recycle and the emergy costs of landfilling is divided by the emergy costs per mile for truck transport. The result is the number of miles that each recycled material can be transported by truck and still have a net benefit. Of course, if the recycled material is transported by rail, the distances would be greater. In all, this evaluation suggests transport radii from point of collection to point of use for recycled materials are relatively small if the decision criteria is based on net emergy benefit.

Evaluating Material Suitability

The emergy per mass data can be used to evaluate suitability of materials for a given use. Table 4-3 summarizes the use of five materials for interior wall finishing, assuming a 30 year application life. Also given are the dollar costs for comparative purposes. Using minimum dollar costs as the selection criteria, cement plaster is the obvious choice followed by steel, plywood, aluminum, and glass. If on the other hand, the selection criteria were minimum emergy costs, plywood would be the first choice followed by steel, cement plaster, recycled aluminum, glass, and conventional aluminum. This evaluation is not complete, because the wall system supporting each of the wall covering types would probably be different to accommodate the various materials. However, it demonstrates the applicability of emergy per mass data for decision making regarding total resource commitment, as emergy per mass sums all resources on a common basis.

Table 4-3. Application of emergy per useful life as interior finishing for 30 years application life.

	Building components		Emergy per mass (a)	Mass of each material required (b)	Emergy cost for 30 year application life (c)	Dollar cost for 30 yr application life (d)
Note	Interior finishings	Building Materials	(E9 sej/g)	(g)	(E9 sej/yr)	($/sq.ft./yr)
1	Cement plaster	Cement	1.98	1260	83.16	0.005
		Cement with coal fly ash	1.96	1260	82.32	0.005
2	Steel wall panel 28 gauge	Steels (EAF)	4.15	298	41.22	0.026
		Steels (EAF) with post-consumer and byproduct scraps	3.38	298	33.57	0.026
3	Aluminum wall panel 3/16" thick	Aluminum	12.70	1285	543.98	0.130
		Aluminum with post-consumer and byproduct scraps	4.40	1285	188.46	0.130
4	Plywood wall panel 1/2" thick	Plywood	1.21	567	22.87	0.053
		Laminated plywood	1.19	567	22.49	0.053
5	Float glass 1/4" thick	Float Glass	7.87	1510	396.12	0.139
		Float glass with in-house scrap	7.16	1510	360.38	0.139

Footnotes

1. 1 centimeter thick, (0.01*0.3*0.3 cu.m.)(1400000 g/cu.m.) = 1260 g
2. 28 gauge, 0.656 lb/sq.ft., 0.016" thick (SSINA, 1998)
   (0.656 lb)(454 g/lb) = 297.8 g
3. (1/64 cu.ft.)(0.02832 cu./cu.ft.)(2905000 g/cu.m.) = 1285 g
4. (1/24 cu.ft.)(0.02832 cu./cu.ft.)(481000 g/cu.m.) = 567 g
5. (1/48 cu.ft.)(0.02832 cu./cu.ft.)(2560000 g/cu.m.) = 1510 g

(a) Emergy per mass from Table 4-1.
(b) Mass of each material (see footnote 1 to 5).
(c) Emergy cost per year for 30 years application life. [(column a)*(column b)] / 30 years
(d) Ddollar cost per square foot per year. [(column b) / (g/$ from Table 3-15)] / 30 years

Emergy and Recycle

Early in this dissertation, it became apparent that there were several different recycle patterns, involving different material trajectories. It was also apparent, that different criteria would be necessary to evaluate these different trajectories since the way materials were recycled and the objective of each recycle pattern was quite different. After considerable thought, three different recycle patterns were identified and analyzed:

1. material recycle
2. byproduct use, and
3. adaptive reuse

Material recycle is a pattern in which materials are reused as part of the raw material inputs to produce the same or similar product. Examples include paper made from recycled paper, steel from recycled steel, or aluminum from recycled aluminum.

Byproduct use is a recycle pattern in which the byproduct of a process is used in the production of another product. Examples include fly ash from a coal fired power plant used as filler in cement or concrete or the use of oil-contaminated soil in the making of fired bricks.

Adaptive reuse involves the reuse of a post-consumer product as input for a different product. Examples include the use of post-consumer plastic bottles in the making of plastic lumber, or the use of recycled glass in the making of ceramic tiles.

The general principle is the same for each pattern, for example, the recycle of a material should result in a net saving of energy and resources as well as landfill space. Criteria to judge appropriateness is related to whether the recycle of a material requires more energy, resources, and/or service than processing raw material to produce a product. The savings might include less transportation, less non-renewable energy required for refining, and lower landfill costs. Added costs include collection and separation, as well as transportation.

Several recycle indices were developed to evaluate the appropriateness of different recycle systems. The recycle benefit ratio (RBR) is the ratio of the emergy required to provide a material from raw resources over the emergy required to recycle a post-consumer product that is substituted for the raw resource. The recycle yield ratio (RYR) is the ratio of the emergy in a recycled material to emergy used for recycle. The landfill to recycle ratio (LRR) is the ratio of emergy required for landfilling a material to the emergy required for recycle. The recycle efficiency ratio (RER) is the ratio of material and energy of conventional process conserved to the emergy required for recycle when recycled materials are used.

Taken together, the recycle indices provide important information regarding the appropriateness of a particular material recycle system. It is quite apparent that steel and aluminum exhibit high ratios across most of the indices. Primary materials like cement, concrete and clay brick exhibit moderately high values for the ratios across all indices. Wood, on the other hand, exhibits index values less than 1.0, calling into question the potential for large scale recycle of wood lumber.

Individually, the recycle indices provide comparative analysis to evaluate various recycle systems relative to each other. The RBR provides information relative to the potential savings that can result if a material is recycled and substituted for a raw resource. All the materials evaluated in this dissertation, with the exception of wood lumber, had RBRs greater than one. Aluminum and recycled glass in ceramic tile had the highest recycle benefit, reflecting the large emergy savings that result from not processing the raw materials. The RBR for wood was less than 1.0 suggesting that there is little benefit from recycling. Although this value represents an average value. In some cases either where wood is scarce, or the quality of the wood is very high, recycle would probably show positive RBRs.

The recycle yield ratio evaluates the net benefit that society receives for recycling. Aluminum has the highest RYR, while wood has the lowest. Steel, plastics, and recycled glass in ceramic tile have intermediate yield ratios. The RYRs for fly ash recycle in cement and the use of sawdust and oil-contaminated soil in the production of brick have relatively low values although are still positive.

The landfill recycle ratios for all the material recycle systems studied, with the exception of recycled glass for ceramic tile were less than one. It is apparent that landfilling is relatively inexpensive as operated today. Not included in this analysis was the environmental impacts from landfill operations. Those impacts were unknown, but could potentially and significantly increase to landfill costs, by increasing LRRs for materials.

Evaluating recycle patterns and looking for general trends suggests that the highest benefits to society appear to accrue from material recycle systems, followed by adaptive reuse systems, and finally by byproduct reuse systems. Material recycle has the highest overall values for the indices because material reuse substitutes directly for raw resources and refining energy. Adaptive reuse systems vary, depending on the material substitution. Byproduct reuse is often used as a disposal mechanism, and therefore the byproduct incorporated into a new product remains as a small percentage of the total material input. As a result, the byproduct reuse pattern appears to be less efficient than the material recycle pattern.

Comparative Results Comparison of Methodologies

The results of building materials evaluated in this dissertation are similar to results of analysis using other methods. Table 4-4 compares evaluation results of building materials using embodied energy, and life cycle analysis with the results obtained using emergy analysis while the units of measure are vary different (solar emjoules versus joules of heat equivalent). The relative ranking of material using each method is essentially the same. Using embodied energy and life cycle analysis, aluminum has the highest values followed by plastic, steel, and clay brick while float glass is the second highest in emergy analysis method followed by plastics and steel. Concrete and wood lumber have the lowest values which are similar to results obtained using emergy analysis. In all, while the results are similar for ranking materials, these were no studies in the literature that developed recycle indices such as those developed in this dissertation. As a result, no comparisons could be made of recycle systems.

Recommendations for Further Research

The scope of this project was necessarily limited by time and resources available. It was limited to material processes and recycle systems that were operational and had some historical data. By its very nature then, the systems studied had to be more or less successful. Thus conclusions that might be drawn concerning indices and principles

Table 4-4. Comparative results comparison of building materials from different methodologies.

Note	Building Materials	(a) Embodied Energy (E3 J/g)	(b) Life Cycle Analysis (E3 J/g)	(c) Emergy Analysis (E9 sej/g)
1	Cement		9.42	1.98
2	Concrete	2.48	1.51	1.44
3	Clay brick	20.05	32.50	2.22
4	Steel	34.60	44.57	4.15
5	Aluminum	223.76	254.21	12.70
6	Wood lumber	2.29	5.32	0.88
7	Plastics (HDPE) lumber	108.25	112.59	5.75
8	Ceramic tile		18.25	3.06
9	Float glass	8.95 *	17.41	7.87

(a) Data are from Hannon et al. (1977b), (b) Data are from Demkin (1996), and (c) Data are from Table 4-1 (conventional process) in this study.
* Data are from Stein (1977).

Footnotes

1 (b) [(2401 to 4060 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 5565 to 9422 J/g
2 (a) [(1070 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 2487 J/g
(b) [[(1137713 to 2594338 BTU/cu.yd.)*(1054 J/BTU)] / (4000 lb/cu.yd.)] / (454 g/lb) = 664 to 1507 J/g
3 (a) [(3647 to 8643 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 8463 to 20057 J/g
(b) [(4000 to 14000 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 9285 to 32505 J/g
4 (a) [(14905 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 34602 J/g
(b) [(19200 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 44573 J/g
5 (a) [(81919 to 96383 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 190183 to 223764 J/g
(b) [(103500 to 109500 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 240280 to 254214 J/g
6 (a) (17430 BTU/ unit 2"x4"x8'), 2"x4"x8' = 0.44 cu.ft.
[[(17430 BTU/ 0.44 cu.ft.)*(1054 J/BTU)] / (40 lb/cu.ft.)] / (454 g/lb) = 2297 J/g
(b) [[(91618 BTU/cu.ft.)*(1054 J/BTU)] / (40 lb/cu.ft.)] / (454 g/lb) = 5322 J/g
7 (a) [(46630 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 108256 J/g
(b) [(38400 to 48500 BTU/lb)*(1054 J/BTU)] / (454 g/lb) = 89147 to 112598 J/g
8 (b) [[(25161 BTU/sq.ft.)*(1054 J/BTU)] / (3.2 lb/sq.ft.)] / (454 g/lb) = 18255 J/g
9 (a) [[(15430 BTU/sq.ft.)*(1054 J/BTU)] / (4 lb/sq.ft.)] / (454 g/lb) = 8959 J/g
(b) [[(13500000 to 15000000 BTU/ ton)*(1054 J/BTU)] / (2000 lb/ton)] / (454 g/lb) = 15672 to 17412 J/g

regarding patterns that might be unsuccessful were limited. Many more recycle patterns should be studied and indices calculated. Much needed, are evaluations of recycle systems in nature, where energy inputs to a biogeochemical system can be allocated to productive processes and recycle processes to determine trends and develop insight related to general principles of material cycling.

The use of emergy as an indicator of resource intensity has significant benefits since it reduces the various inputs and environmental services required for material cycles to a common denominator. Yet the units are unfamiliar to many, and wide range acceptance of the methodology is still to come. Still, since it includes not only economic inputs, but environmental inputs as well, it is more inclusive than financial analysis.

To evaluate the applicability of a material for a particular use using the emergy criteria, it will be necessary to evaluate building systems. The evaluations in this dissertation were done on a mass of material basis. To apply this information to particular applications, the amount of each alternative material for the application is required. To understand a benefit of building to the society, the next research in this area should focus on building systems and construction processes.

Summary and Conclusions

All systems recycle. The biosphere is a network of continually recycling materials and information in alternating cycles of convergence and divergence. As materials converge or become more concentrated, they gain in quality, increasing their potentials to drive useful work in proportion to their concentrations relative to the environment. As their potentials are used, materials diverge, or become more dispersed in the landscape, only to be concentrated again at another time and place. Fitting the patterns of humanity to these material cycling pathways has become paramount as our numbers and influence on the biosphere increases.

Until very recently, humans gave little thought to the processes of recycle, using the free work of the environment to dispose and dilute byproducts and wastes from an ever expanding conglomeration of technology, infrastructure and culture. However, as humanity enters the 21st century and the limits to both space and resources are felt, efficient use of resources becomes more important, and more attention should be given to recycle and reuse. The evaluations of materials and resource recycle systems in this dissertation provide needed insight into the complex questions facing humanity concerning wise use. Relationships between resource quality and recycle-ability, the total life cycle emergy costs of materials, their useful lives, and their benefits to society were investigated in the hopes of providing perspectives and tools for decision making regarding material selection. The following conclusions regarding materials and material quality were developed:

1. Emergy per mass may be a good indicator of recycle-ability. Based on emergy indices, it appears that materials with high emergy per mass are more recyclable.
2. The emprice (emergy received for money spent) is highest for primary building materials like concrete and clay brick, and lowest for materials that contain more human services.
3. Quality and versatility of a material are related to emergy per mass. The larger the emergy per mass, the more valuable and versatile the product and the greater the potential for recycle.

4. The emergy yield ratio (EYR) may provide important information regarding recycle-ability. When EYRs significantly decrease for materials that include some form of recycle, the recycle pathway may not be economically viable.

5. Price, expressed as mass per dollar is inverse to the amount of human service inputs to a material's production.

Recycle indices were developed that have the potential to provide critical insight regarding material trajectories within recycle patterns. Three recycle patterns were identified that had different material trajectories. Four recycle indices were developed to evaluate recycle patterns as provide needed information on the appropriateness of recycle options. The following conclusions were drawn from the analysis of recycling patterns:

1. Materials that have large refining costs have greatest potential for high recycle benefits, as recycled materials are substituted for raw resources.

2. It appears that materials that require fewer inputs in their refining stages are less likely to exhibit positive recycle benefits.

3. The highest benefits to society appear to accrue from material recycle systems, followed by adaptive reuse systems, and finally by byproduct reuse systems.

4. The landfill recycle ratios for all the material recycle systems studied, with the exception of glass were less than one. This may be the result of inability to evaluate environmental inputs.

5. The yields from recycling some materials (steel, aluminum, plastic, and glass) are high, greater than the yields that society obtains from energy sources

indicating the very important contributions that effective recycling of these materials systems have in the long run.

GLOSSARY

Adaptive reuse	One of recycling patterns which pre- or post-consumer material is used as a main raw material input to another production process (produce different product output). (see Figure 1-1)
Application life	The time interval that a particular material or configuration of materials are required to last under normal use. The application life may be longer or shorter than the useful life.
Available energy	Potential energy capable of doing work and being degraded in the process. It is also termed as exergy. (Odum, 1996, Table 1.1, p.13)
British thermal unit (Btu)	Unit of measure for the amount of energy a given material contains (e.g. energy released as heat during combustion is measured in Btus). Technically, 1 Btu is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit (Lund, 1993, Glossary).
Boundary	A defined scope of interest in an evaluation.
Byproduct	The other product output besides main product. If by product has a marketable value, it is also called co-product. (see co-product)
Byproduct recycle	the process that uses byproduct or waste from another process as part of raw material inputs to produce another product such as cement or concrete with fly ash, particle board with wood chips or sawdust. (see Figure 1-1)
Car-mile (Rail)	The movement of a car the distance of one mile. An empty car-mile is a mile run by a fright car without a load; a loaded car-mile is a mile run be a fright car with a load. In the case of intermodel movements, the car-miles generated will be loaded or empty depending on whether the trailers/containers are moved with or without a waybill, respectively (National, 1997, Glossary).
Composite product	A product output consists more than one major material such as concrete.

Construction wastes	Wastes produced in the course of construction of homes, office buildings, dams, industrial plants, schools, and other structures. The materials usually include used lumber, miscellaneous metal parts, packaging materials, cans, boxes, wire, excess sheet metal, and other materials. Construction and Demolition wastes are usually grouped together (Tchobanoglous et al, 1993, p.906).
Construction and Demolition (C&D) wastes	Wastes produced from construction or demolition activities such as buildings, infrastructures. (see construction waste and demolition waste)
Conventional process	A industry or manufacturing process uses only virgin raw material (without any recycling inputs including materials and energy).
Covering soil	Soil or sand that is used to mix with waste in landfill. Covering soil is about 40 percent of waste input by weight (Personal communication with Alachua County Landfill, 1998).
Cullet	Broken or waste glass used in the manufacture of new glass (Lund, 1993, Glossary).
Curbside collection	The collection of source-separated and mixed wastes from the curbside where they have been placed by the resident (Tchobanoglous et al., 1993).
Demolition wastes	Wastes produced from the demolition of buildings, roads, sidewalks, and other structures. These wastes usually include large, broken pieces of concrete, pope, radiators, duct work, electrical wire, broken-up plaster walls, lighting fixtures, brick, and glass (Tchobanoglous et al, 1993, p.907).
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
Efficiency	The ratio of useful energy and/or material output to total energy and/or material input of a production system.
Energy	A property of all things which can be turned into heat, energy is measured in heat units such as joules (J), British thermal units (Btu), and kilocalories (kcal).
Embodied energy	Energy that required to produce a product. It is various depending on definition of energy and research scale. Total energy expanded during the life cycle, up to and including this stage, expressed in Btus, joules, etc. (Demkin, 1996, Glossary).
Emdollar (em$)	The ratio (sej per sej/$) of the emergy flows or storages of the system divided by emergy per money ratio (sej/$ of that year). The em$ is usually an index for evaluating in region or nation scale. (Odum, 1996, p.57, 288)

Emergy	Available energy of one kind previously used up, directly and indirectly, to make a product or service. Its unit is the emjoule (Odum, 1996, p.7). Emergy refers to "energy memory." (Odum, 1996, p.2).
Emergy exchange ratio	The solar emergy flow of the yield product divided by the solar emergy of the money paid by the buyers. (Odum, 1996, p.61, 84)
Emergy in the product	The sum of the emergy in the raw materials and the emergy inputs for refinering and transforming. For recycling patterns, the emergy in the product is the total emergy excluding recycled inputs. (see Chapter 2)
Emergy intensity	The emergy that is added on to bring the product back to the previous stage. In short, emergy intensity is all emergy inputs excluding material itself. Its unit is solar emjoule per gram (sej/g). Emergy intensity is not transformity or emergy per gram. (see Chapter 2)
Emergy investment ratio (IR)	The feedback emergy from economy divided by emergy inputs from natural resources which are renewable and nonrenewable energy. (Odum 1996, p.83-84)
Emergy per gram	The total emergy required directly and indirectly to produce a product or service, which is transformity, but called emergy per gram since building materials are evaluated by weight unit measurement. (see Chapter 2 and Transformity)
Emergy per mass	Emergy per mass is transformity in units of emergy per gram (sej/g). (see chapter 2 and Transformity)
Emergy per money ratio (se/$)	The ratio (emergy per money) of annual emergy flows or storages of nation or region divided by gross economic product. The emergy per money ratio can be obtained by using gross domestic product. (Odum, 1996, p.57, 288)
Emergy yield ratio (EYR; Y/F)	The emergy inputs from production process divided by the emergy (feedback) from economic sources.
Emprice	The emergy per gram of a product divided by gram per dollar. Its unit is solar emjoules per dollar (sej/$). (see Chapter 2)
Emergy recycle content	A portion of recycled emergy inputs (both materials and energy) in a product. Recycled emergy inputs divided by total emergy inputs.
Environmental loading ratio (ELR)	The emergy of nonrenewable inputs and feedback inputs from economic sources divided by the emergy of renewable inputs. (see Figure 2-5)
EPA	U.S. Environmental Protection Agency
Feedbacks	A pathway(s) from higher hierarchical process to reinforce or control back to its process inputs. It can be positive or negative feedback. (Odum, 1996, p.26)

Fly ash	Small solid particles of ash and soot generated when coal, oil, or solid wastes are burned. Fly ash is a minor portion (about 10 percent) of the total ash produced from combustion and is removed by pollution control equipment. Fly ash can be used for building materials as bricks or in a sanitary landfill (Lund, 1993, Glossary; Tchobanoglous et al., 1993, Glossary). (see ash and bottom ash)
Gross domestic product (GDP)	The total market value of domestic goods and services produced in an economy during a year
Gross national product (GNP)	The total market value of all final goods and services produced in a national economy during a year.
Landfill or Sanitary landfill	An engineered method of disposing of solid wastes on land in a manner that protects human health and the environment. Waste is spread in thin layers, compacted to the smallest practical volume, and covered with soil or other suitable material at the end of each working day (Tchobanoglous et al, 1993, p.911). A large, outdoor area for waste disposal; in sanitary landfills, waste is layered and covered with soil (Lund, 1993, Glossary).
Landfill byproducts	Chemicals and gases that result from the biodegration of waste in a landfill or interaction with rain and environmental conditions Two by-products that must be monitored are leachates and methane gas (Lund, 1993, Glossary).
Landfill linear	Impermeable layers of heavy plastic, clay, and gravel that protect against groundwater contamination. Most sanitary landfills have at lease two plastic liners or layers of plastic and clay (Lund, 1993, Glossary).
Leachate	Liquid that has percolated through solid waste or another medium. Leachate from landfills usually contains extracted, dissolved, and suspended materials, some of which may be harmful (Tchobanoglous, 1993, Glossary).
Life cycle (life-cycle)	The period of time lapsed between the beginning and end of life. All stages of a product's life, beginning with raw materials acquisition, and continuing through processing, materials manufacture, product fabrication, and use, and concluding with waste management, recycling, or reuse programs (Demkin, 1996, Glossary).
Life expectancy	A time period of product or material to serve its function.

Locomotive (Rail)	A self-propelled unit of equipment designed for moving other railroad rolling equipment in revenue service including a self-propelled unit designed to carry freight or passenger traffic, or both, and may consist of one or more operated from singe control (National, 1997, Glossary).
Major input	A main material or energy input in the process.
Market value	The price, assigned a commodity or activity addressing the human services rendered in recovery, production and delivery (such as market supply), and subject to demands of the consumer. It is an assessment of opportunities forgone from using resources in the present and thus lost to future.
Material concentration	An amount of mass (weight) of material per volume. In this dissertation, gram per cubic meter was used.
Material recovery facility (MRF)	The permitted solid waste facilities where solid wastes or recyclable materials are sorted and separated, by hand or machinery, for recycling or composting purposes (Lund, 1993, Glossary).
	A process for removing recyclables and creating a compost like product from the total of full mixed municipal solid waste (MSW) stream. Differs from a "clean" MRF which processes only commingled recyclables (Lund, 1993, Glossary).
Methane (CH4)	An odorless, colorless, and asphyxiating gas that can explode under certain circumstances and that can be produced by solid wastes undergoing anaerobic decomposition (Tchobanoglous et al., 1993, Glossary).
Minor input	A minor material or energy input in the process.
Municipal solid waste (MSW)	Includes nonhazardous waste generated in household and commercial and business establishments and institutions; excludes industrial process wastes, demolition wastes, agricultural wastes, mining wastes, abandoned automobiles, ashes, street sweepings, and sewage sludge (Lund, 1993, Glossary).
	Includes all the wastes generated from residential households and apartment buildings, commercial and business establishments, institutional facilities, construction and demolition activities, municipal services, and treatment plant sites (Tchobanoglous et al., 1993, Glossary).
Nonrenewable resource	Energy and material storages that are used up at rates faster than replacement such as fossil fuels, mineral ores, and soil.

Non-recyclable	Not capable of being recycled or used again (Lund, 1993, Glossary).
Post-consumer	A period of time after being used by consumer(s).
Post-consumer recycling	The reuse of materials generated from residential and commercial waste, excluding recycling of material from industrial processes that has not reached the consumer, such as glass broken in the manufacturing process (Lund, 1993, Glossary).
Primary materials	Virgin or new materials used for manufacturing basic products. such as wood pulp, iron ore, and silica sand (Tchobanoglous et al, 1993, p.910).
Product	Something produced that has an existing value or potential use. A finished building product is in the form in which it will be used, including the packing required for shipment to the building site (Demkin, 1996, Glossary). An outcome or an object; the amount, quantity, or total produced (Lund, 1993, Glossary).
Raw material	Materials (or feedstocks) used in subsequent manufacturing processes. Raw materials can be primary or secondary (e.g., recovered or recycled) (Demkin, 1996, Glossary). Substances still in their natural or original state, before processing or manufacturing; or the starting materials for manufacturing process (Lund, 1993, Glossary).
Recyclability	An ability of material to be reprocessed again. (see recyclable)
Recyclable	Able to be recycled; having certain physical properties that enable a product to be broken down for recycling; often confused with the term recycled, which refers to something that has already gone through the recycling process (Cichonski and Hill, 1993, Glossary). Materials that still have useful physical or chemical properties after serving their original purpose and that can, therefore, be reused or remanufactured into additional products. Waste materials that are collected, separated, and used as raw material (Lund, 1993, Glossary).
Recycle	To separate a given material from waste and process it so that it can be used again in a form similar to its original use; for example, newspapers recycled into newspapers or cardboard (Lund, 1993, Glossary).
Recycle content	A portion of recycled material in a product.

Recycled	Composed of materials that have been processed and used again (Lund, 1993, Glossary).
Recycling	Process by which materials that would otherwise become solid waste are collected, separated, or processed and returned to the economic mainstream to be reused in the form of raw materials or finished goods (Cichonski and Hill, 1993, Glossary). The act of extracting materials from the waste stream and reusing them. Recycling generally includes collection, separation processing, marketing, and the creation of a new product or material from used products or materials. In general usage, recycling refers to the separation of recyclable materials such as newspaper, aluminum, other metals or glass from the waste. This includes recycling of materials form municipal waste, often done through separation by individuals or specially designed materials recovery facilities; industrial in-plant recycling; and recycling by commercial establishments. a. Recycling, primary is remaking the recyclable material into the same materials in a process that can be separated a number of times (e.g., newspaper into newspaper, glass containers into glass containers). b. Recycling, secondary is remaking the recyclable material into a material which has the potential to be recycled again (e.g., newspaper into recycled paperboard). c. Recycling, tertiary is remaking the recyclable material into a product that is unlikely to be recycled again (e.g., glass into asphalt, paper into tissue paper) (Lund, 1993, Glossary). Separating a given waste material from the wastestream and processing it so that it may be used again as a useful material for products which may or may not be similar to the original (Tchobanoglous et al., 1993, Glossary).
Recycling efficiency	The likelihood a recycling program participant will prepare a specific material for recycling (Cichonski and Hill, 1993, Glossary).

Recycling pattern	A recycling alternative which characterized as traditional recycling (same material and product produce), byproduct use (substituted part of raw materials with byproduct or waste from another process), adaptive reuse (substituted raw material with same material from other different products. (see Figure 1-1)
Refuse-derived fuel (RDF)	The material remaining after the selected recyclable and noncombustible materials have been removed from MSW (Tchobanoglous et al., 1993, Glossary). A solid fuel obtain from municipal solid waste as a result of mechanical process or sequence of operations, which improves the physical, mechanical, or combustion characteristics compared to the original unsegregated feed product or unprocessed solid waste. Usually, noncombustibles and recyclables materials are removed. The fuel may be sized for the specific requirements of the furnace were it will be burned, processing a "fluff" or shredded RDF. In some processes, RDF may be compressed into pellets or cubes, producing a densified RDF (d-RDF) (Lund, 1993, Glossary).
Renewable energy	Energy flows, such as sunlight, rainfall, and wind, generally recurring and which ultimately drive the bio-chemical processes of the earth and contribute to geologic processes. Renewable sources are ultimately limited by their flow rates which system cannot draw from these sources any faster than they are delivered.
Renewable resource	Resource that is replenished through natural processes (e.g., surface waters, trees, animals). If renewable resource is depleted faster than it can regenerate resource can be than classified as nonrenewable (Cichonski and Hill, 1993, Glossary).

Reuse	A second, third, etc. use of a material, product, or assembly for the same application (Demkin, 1996, Glossary).
	To use a product repeatedly in the same form (e.g., glass bottles, cloth diapers) (Cichonski and Hill, 1993, Glossary).
	The use of a product more than once in its same form for the same purpose; e.g., a soft-drink bottle is reused when it is refined to the bottling company for refilling; finding new functions for objects and materials which have outgrown their original use; to use again (Lund, 1993, Glossary).
	The use of a waste material or product more than once (Tchobanoglous et al., 1993, Glossary).
Sanitary landfill	(see landfill)
Scale	A scope of interest which includes an interested time and a defined space of the environment in the evaluation.
Scrap	That portion of solid waste which can be economically recycled (Cichonski and Hill, 1993, Glossary).
	Products that have completed their useful life, such as appliances, cars, construction materials, ships, post-consumer products, and new scrap materials that result as byproducts when metals are processed and products are manufactured (Lund, 1993, Glossary).
Separation	To divide wastes into groups of similar materials, such as paper products, glass, food wastes, and metals. Also used to describe the further sorting of materials into more specific categories, such as clear glass and dark glass. Separation may be done manually or mechanically with specialized equipment (Tchobanoglous et al, 1993, p.911).
Solar emergy	The available solar energy used up directly and indirectly through transformations to make a product or service. Its unit is the solar emjoule (sej). (Odum, 1996, p.8)
Solar emjoule (sej)	The measurement unit of solar emergy, abbreviated as sej. (Odum, 1996, p.8)
Solar transformity (sej/J)	The ratio of solar emergy per unit of energy which solar emergy used up in a transformation process divided by the available energy yielded. Its unit is expressed in solar emjoules per joule (sej/J). (Odum, 1996, p.289)

Solid waste	Nonsoluable, discarded solid materials, including sewage sludge, municipal garbage, industrial wastes, agricultural refuse, demolition wastes, and mining residues (Cichonski and Hill, 1993, Glossary).
Sustainable	Sustainability : A concept that subscribes to "meeting the needs of the present without compromising the ability of future generations to meet their own needs." Sustainability principles aim to guide economic growth in an environmentally sound manner, emphasizing appropriate and efficient use of natural resources (Demkin, 1996).
Sustainable use	Resource use that can be continued by society in the long run because the use level and system design allow resources to be renewed by natural or man aided processes (Odum and Arding, 1991. p.114; Odum, 1996, p.289)
Ton	A unit of weight in the U.S. Customary System of Measurement. An avoirdupois unit equals to 2000 pounds. Also called short ton or net ton which equals to 0.907 metric ton (Lund, 1993, Glossary).
Tonne	Metric ton which equals to 1000 kilograms.
Ton-mile	The movement of one ton of freight the distance of one mile. Ton-miles are computed by multiplying the weight in tons of each shipment transported by the distance hauled (National, 1997, Glossary).
Material recycle	A recycle pattern that reuses reuse material as part of the raw material inputs to produce the same product, such as aluminum cans, paper, glass bottles, and steel. (see Figure 1-1)
Train-mile (Rail)	The movement of a train a distance of one mile measured by the distance between terminals and/or stations, and includes yard switching miles, train switching miles, and work train miles. Yard switching miles may be computed on any reasonable, supportable, and verifiable basis. In the event actual mileage is not computable by other means, yard switching miles may be computed at the rate of 6 mph for the time actually engaged in yard switching service (National, 1997, Glossary).
Transformity	The emergy of one type required to make a unit of energy of another type. For example, since 3 coal emjoules (cej) of coal and 1 cej of services are required to generate 1 J of electricity, the coal transformity of electricity is 4 cej/J. Its unit is solar emjoules per joule (sej/J) (Odum, 1996, p.289). (see Emergy per mass)
Transportation	Activities and supporting facilities (systems) to move or bring products or materials from one place to another place.

Transportation distance	A distance of moving products from one area to another by transportation modes (trucks, railroad, and ships).
Transfer station	A place or facility where wastes transferred from smaller collection vehicles into large transportation vehicles for movement to disposal areas, usually landfills. In some transfer operations compaction or separation may be done at the station (Tchobanoglous et al., 1993, Glossary).
Used energy	Energy whose available has been used up in a transformation process according to the second law and no longer able to accomplish useful work.
Useful life	The time interval that a particular material or configuration of material will last under moral use.
Virgin material	Any basic material for industrial processes that as not previously been used, for example, wood-pulp trees, iron ore, silica sand, crude oil and bauxite (Tchobanoglous et al, 1993, p.912). Resource materials extracted from the earth, mined, grown, refined, and /or synthesized (Cichonski and Hill, 1993, Glossary). Term describing raw materials as yet unused (Lund, 1993, Glossary).
Waste	An output with no marketable value that is disposed to the environment. Also any material released to the environment through either air, water, or land, and has no beneficial use (Demkin, 1996, Glossary). Unwanted materials remaining form manufacturing processes, or refuse from humans and animals (Cichonski and Hill, 1993, Glossary). Anything that is discarded, useless, or unwanted: opposite of conserve, as in "to waste." (Lund, 1993, Glossary).
Waste-to-energy incineration	An alternative process to reduction or recover of recyclable materials which are not currently economical (Cichonski and Hill, 1993, Glossary).

APPENDIX A
LIST OF TRANSFORMITIES

Table A-1. List of transformity used in this dissertation.

		Solar Transformity			Reference sources
Note	Item	(sej/g)	(sej/J)	(sej/$)	
Materials					
	Aggregate	1.00E+09			(Odum et al., 1995, p. 4-4, 4-5)
	Bauxite	8.55E+08			(Odum, 1996, p.187)
	Cement rock	1.00E+09			
	Clay	2.00E+09			(Odum, 1996, p.310)
	Coral	1.00E+09			
	Gypsum	1.00E+09			(Brown and McClanahan, 1992, Table 2, p.22)
	Limestone	6.70E+06			(Odum et al., 1995, p. 4-4, 4-5)
		1.00E+09			(Odum, 1996, p. 310)
	Sand	1.00E+09			(Odum, 1996, p.310)
	Shale	1.00E+09			(Odum, 1996, p.310)
	Water		4.80E+04		(Odum, 1996, p.120)
	Zinc or copper	6.80E+10			(Brown et al., 1992, Table A1)
Fuel and energy					
	Coal		4.00E+04		(Odum, 1996, p.310)
	Crude oil *	2.01E+09	5.30E+04		(Odum, 1996, p.186)
	Electricity		1.74E+05		(Odum, 1996, p.305)
	Liquid fuel (waste)		6.60E+04		Using fuel
	LP gas		7.00E+04		(Odum et al., 1983, Table 14.1, p. 276-282)
	Natural gas, Petroleum gas		4.80E+04		(Odum, 1996, p.308)
	Oils, gasoline, fuels		6.60E+04		(Odum, 1996, p.308)
	Oxygen	1.00E+09			
	Steam **		5.02E+04		(This study, Table A-1)
Transportation					
	Trucks	9.65E+11 sej/ton-mile			(This study, Table E-1)
		6.61E+11 sej/tonne-kilometer			(This study, Table E-1)
		7.55E+10	1.20E+06		(McGrane, 1994, p. 24)
	Railroad (class I)	5.07E+10 sej/ton-mile			(This study, Table E-2)
		3.47E+10 sej/tonne-kilometer			(This study, Table E-2)
		4.55E+09	8.70E+06		(McGrane, 1994, p. 40)
		3.07E+10 sej/ton-mile			Updated (Bayley et al., 1977)
	Ships (US domestic)	1.17E+11 sej/ton-mile			(This study, Table E-3)
		7.99E+10 sej/tonne-kilometer			(This study, Table E-3)
		7.55E+10 sej/ton-mile			Updated (Bayley et al., 1977)
Machinery and equipments					
	Machinery	6.70E+09			(Odum et al., 1987b, Table 1, p. 4-5)

Table A-1--continued.

Note	Item	Solar Transformity (sej/g)	(sej/J)	(sej/$)	Reference sources
Products					
	Aluminum ingots	1.63E+10			(Odum et al., 1995, p. B-2; Odum et al., 1983, Table 3.1, p. 40-45)
	Ammonia fertilizer	3.8E+09	1.86E+06		(Odum, 1996, p.310)
	Cement	2.31E+09			updated (Haukoos, 1995, Table A-13, p. 172) w/o service
	Chemical	3.80E+08			(Brown et al., 1992, Table A1)
	Chemical products		3.45E+04		(Odum et al., 1983, Table 11.1, p. 207-215)
	Concrete block	1.35E+09			(Haukoos, 1995, Table A-15, p.177-179) w/ services
	Copper & Zinc alloys (MSW)	6.77E+10			(Odum et al., 1987a, p. 159)
	Explosives (as ammonium nitrate fertilizer)	3.80E+09	1.86E+06		using ammonia fertilizer (Odum, 1996, p.310)
	Ferrous metals (MSW)	9.18E+08			(Odum et al., 1987a, p. 159)
	Fiberboard production (1972)	1.84E+09	1.12E+05		updated (Haukoos, 1995, Table A-7, p.157-158) w/o services
		2.40E+09	1.58E+05		updated (Haukoos, 1995, Table A-7, p.157-158) w/ services
	Flat Glass	4.74E+09			updated (Haukoos, 1995, Table A-16, p.180-182) w/ services
	Food		2.00E+06		(Brown et al., 1992, Table C-7)
	Food waste (MSW)		1.80E+06		(Odum et al., 1987a, p. 159)
	Glass (MSW)	8.44E+08			(Odum et al., 1987a, p. 159)
	Glue and adhesives	3.80E+08			using chemical
	Hardboard production (split products)	1.92E+09	1.27E+05		updated (Haukoos, 1995, Table A-9, p.161-162) w/o services
	Iron ore	8.60E+08			(Odum, 1996, p.186)
	Paper		1.42E+05		(Keller, 1992, p.116)
	Particleboard production (1972)	1.57E+09	1.04E+05		updated (Haukoos, 1995, Table A-6, p.155-156) w/o services
		2.05E+09	1.36E+05		updated (Haukoos, 1995, Table A-6, p.155-156) w/ services
	Plastics (MSW)	3.80E+08			(Odum et al., 1987a, p. 159)
	Potassium fertilizer	1.10E+09	3.00E+06		(Odum, 1996, p.310)
	Rainforest wood, transported and chipped		4.40E+04		(Odum, 1996, p.308)
	Rubber		2.10E+04		(Odum et al., 1983, Table 3.1, p. 40-45)
	Rubber (MSW)	4.30E+09			(Odum et al., 1987a, p. 159)
	Sodium chloride	1.10E+09			using Potassium fertilizer
	Softwood plywood and others (split products)	1.63E+09	1.08E+05		updated (Haukoos, 1995, Table A-4a, p.147-148) w/o services
	Steel	1.78E+09			(Odum, 1996, p.186)
	Textiles (MSW)		3.80E+06		(Odum et al., 1987a, p. 159)
	Tire (waste)		2.10E+04		Using rubber

Table A-1--continued.

Note	Item	Solar Transformity (sej/g)	(sej/J)	(sej/$)	Reference sources
	Wood chips		1.56E+04		(Doherty, 1995, p.145)
	Wood harvested		8.01E+03		(Odum, 1996, p.80)
	Yard-wood trimmings (MSW)		4.30E+03		(Odum et al., 1987a, p. 159)
Services					
	Labor (primitive)		8.10E+04		(Odum, 1996, p.68)
	Labor (1983)			2.40E+12	(Odum, 1996, Table D.1, p.314)
	Labor (1993)			1.37E+12	(Odum, 1996, Table D.1, p.314)

* (53000 sej/J)(6.28E+9 J/bbl)(0.11 gal/lb)/(40 gal/bbl)(454 g/lb)

** Steam Transformity

Calculation based on one hour, one barrel

1 (1 bbl)(6.289E+9 J/bbl)(6.6E+4 sej/J) = 4.15E+14 sej

2 (1 bbl)(6720 lb-hr steam/bbl)(1.23E+6 J/steam lb) = 8.265E+9 J

3 (4.15E+14 sej)/(8.265E+9 J) = 5.0217E+4 sej/J

Table A-2. List of transformity calculated in this dissertation.

Note	Item	Solar Transformity				Reference tables
		with services (sej/g)	without services (sej/g)	with services (sej/J)	without services (sej/J)	
Building Materials						
	Cement with fly ash (byproduct)	2.20E+09	2.19E+09			(Table 3-1)
	Cement without fly ash (conventional)	1.98E+09	1.97E+09			(Table 3-1)
	Ready-mixed Concrete (conventional)	1.44E+09	1.44E+09			(Table 3-2)
	Ready-mixed Concrete with Fly ash (byproduct)	1.55E+09	1.54E+09			(Table 3-2)
	Ready-mixed Concrete with recycled concrete aggregate (material recycle)	1.59E+09	1.59E+09			(Table 3-2)
	Ready-mixed Concrete (1982) wet weight	6.22E+07	6.06E+07			(Table C-2)
	Ready-mixed Concrete (1982) dry weight	1.26E+09	1.23E+09			(Table C-2)
	Crushed Concrete	4.82E+09	4.82E+09			(Table D-8)
	Coal fly ash	1.40E+10				(Table C-1)
	Brick (conventional)	2.22E+09	2.19E+09			(Table 3-3)
	Brick with Sawdust Fuel (byproduct)	2.12E+09	2.04E+09			(Table 3-3)
	Brick with Oil-contaminated Soil and Sawdust Fuel (byproduct)	1.93E+09	1.90E+09			(Table 3-3)
	Brick and Structural Clay Tile (1977)	2.32E+09	2.23E+09			(Table C-13)
	Iron ore (1975)		1.22E+09		8.61E+07	(Table C-4)
	Iron Ore Pellets (1975)		1.48E+09		2.13E+06	(Table C-5)
	Iron Ore Sinter (1975)		1.99E+09		2.86E+06	(Table C-6)
	Pig iron, blast furnace (1996)	2.83E+09	2.65E+09	4.06E+06	3.80E+06	(Table C-3)
	Slag (1996)	7.06E+09	6.61E+09	1.01E+07	9.50E+06	(Table C-3)
	Steel, EAF process (conventional)	4.15E+09	4.10E+09			(Table 3-4)
	Steel, EAF process (material recycle)	4.41E+09	4.37E+09			(Table 3-4)
	Steel, EAF process (material recycle & byproduct)	4.24E+09	4.19E+09	6.09E+06	6.03E+06	(Table 3-4)
	Steel, BOF process (conventional)	5.35E+09	5.31E+09			(Table 3-5)
	Steel, BOF process (material recycle)	5.35E+09	5.31E+09	7.69E+06	7.62E+06	(Table 3-5)

Table A-2--continued.

Note	Item	Solar Transformity				Reference tables
		with services (sej/g)	without services (sej/g)	with services (sej/J)	without services (sej/J)	
	Primary Aluminum (ingots)	1.17E+10	1.14E+10	1.79E+08	1.75E+08	(Table C-7)
	Aluminum billet	6.93E+10	6.77E+10	1.06E+09	1.04E+09	(Table C-7)
	Aluminum Sheet (conventional)	1.27E+10	1.27E+10			(Table 3-6)
	Aluminum Sheet (material recycle)	1.30E+10	1.30E+10			(Table 3-6)
	Aluminum Sheet (material recycle & byproduct)	1.29E+10	1.29E+10	1.98E+08	1.97E+08	(Table 3-6)
	Softwood Plywood	1.21E+09	1.12E+09	5.77E+04	5.33E+04	(Table 3-7)
	Softwood Veneer	1.21E+09	1.12E+09	5.77E+04	5.33E+04	(Table 3-7)
	Hardwood Plywood	1.44E+09	1.25E+09	6.90E+04	6.00E+04	(Table C-16)
	Hardwood Veneer	1.44E+09	1.25E+09	6.90E+04	6.00E+04	(Table C-16)
	Lumbers	8.79E+08	8.33E+08	4.20E+04	3.98E+04	(Table 3-9)
	Wood chips	8.79E+08	8.33E+08	4.20E+04	3.98E+04	(Table 3-9)
	Flooring & sliding	8.79E+08	8.33E+08	4.20E+04	3.98E+04	(Table 3-9)
	Recycled Wood Lumber	6.74E+09	1.77E+09			(Table 3-10)
	Composite Plywood with byproduct wood shaved	1.64E+09	1.49E+09			(Table 3-8)
	Vinyl Floor (PVC)	6.32E+09	6.02E+09	1.94E+05	1.85E+05	(Table 3-11)
	Plastics Lumber (HDPE) (conventional)	5.75E+09	5.04E+09			(Table 3-12)
	Plastics Lumber (HDPE) (adaptive reuse)	6.33E+09	5.61E+09	1.95E+05	1.73E+05	(Table 3-12)
	Plastics (USA)	3.28E+09	3.15E+09	1.01E+05	9.69E+04	(Table C-8)
	Plastics (Europe)		5.76E+09		1.77E+05	(Table C-11)
	High Density Polyethylene (HDPE)		5.27E+09		1.62E+05	(Table C-10)
	Polyvinyl Chloride (PVC)		5.87E+09		1.80E+05	(Table C-9)
	Flat Glass (1987)	1.90E+09	1.60E+09	1.37E+07	1.15E+07	(Table C-12)
	Post-consumer Glass Containers Separation	2.13E+09	2.12E+09	1.53E+07	1.52E+07	(Table D-4)
	Ceramic Tile (conventional)	3.06E+09	2.86E+09			(Table 3-13)
	Ceramic Tile with windshield glass (adaptive reuse)	3.42E+09	3.22E+09			(Table 3-13)
	Ceramic Tile with post-consumer glass bottles (adaptive reuse)	3.38E+09	3.19E+09			(Table 3-13)
	Float Glass (conventional)	7.87E+09	7.68E+09			(Table 3-14)
	Float Glass with recycled in-house New Glass Scrap (material recycle)	7.66E+09	7.47E+09	5.51E+07	5.37E+07	(Table 3-14)

Table A-2--continued.

Note	Item	Solar Transformity				Reference tables
		with services (sej/g)	without services (sej/g)	with services (sej/J)	without services (sej/J)	
	Municipal solid waste (MSW) Recycling Facility (separation) Split pathway					
		5.01E+09	5.00E+09			(Table D-3)
	Construction and Demolition (C&D) Recycling Facility (Split pathway)					
		4.73E+09	4.72E+09			(Table D-7)
	Landfill (with non-separated MSW input)					
		3.88E+09	3.87E+09			(Table D-2)
	Municipal Solid Wastes (MSW) before collection					
			2.79E+09			(Table C-17)
	Demolition	4.70E+09	4.68E+09			(Table D-6)
		5.28E+14	sej/sq.ft.			(Table D-6)
			5.26E+14	sej/sq.ft.		(Table D-6)
		1.85E+16	sej/sq.m.			(Table D-6)
			1.84E+16	sej/sq.m.		(Table D-6)
	Constructed Building	4.58E+09	3.00E+09			(Table D-5)
		1.64E+14	1.07E+14			(Table D-5)
		sej/sq.ft.	sej/sq.ft.			
		1.82E+15	1.19E+15			(Table D-5)
		sej/sq.m.	sej/sq.m.			
	Paint	1.52E+10	1.51E+10			(Table C-14)
	Wood Furniture	4.69E+09	2.89E+09	2.24E+05	1.38E+05	(Table C-15)
	Municipal solid waste (MSW) Combustion Facility (RDF)					
	MSW from curbside collection	4.99E+09	4.95E+09			(Table D-1)

Table A-3. Emergy per gram for processing of recycled materials in separation facilities (excluding major material input).

Note	Item	Emergy per gram with services (sej per gram)	Reference tables
	Post-consumer Glass Containers Separation (excluding glass material)	1.32E+07	(Table D-4)
	Crushed Concrete (excluding concrete material) without transportation	1.66E+07	(Table D-8)
	Recycled Wood Lumber (excluding lumber material)	8.59E+09	(Table 3-10)
	Building demolition (excluding building materials)	4.87E+07	(Table D-6)
	Building construction (excluding building materials)	2.14E+09	(Table D-5)
	Construction and Demolition (C&D) Recycling Facility (excluding C&D waste) without transportation	6.72E+07	(Table D-7)
	Municipal solid waste (MSW) Recycling Facility (separation) (excluding mixed-waste (MSW))	8.24E+06	(Table D-3)
	Curbside collection (MSW) (excluding waste itself)	2.51E+08	(Table D-1)
	Landfill (non-separated MSW input) (excluding waste itself)	1.17E+07	(Table D-2)
	Life time of landfill (50 years)	2.87E+07	(Table D-2)
	Truck transportation (C&D)	2.13E+07	(Table D-7)

APPENDIX B
FOOTNOTES TO EMERGY EVALUATION TABLES

Table B-1. Footnotes to Table 3-1 cement and cement recycling alternatives in Chapter 3.

Footnotes:

1 Limestone (USGS, 1995, Table 5)
(80142000 metric tons/yr)(1000000 g/metric ton)
= 8.0142E+13 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)
6.70E+06 Sej/g (Odum et al, 1995, p. 4-4, 4-5)

2 Cement rock (USGS, 1995, Table 5)
(24164000 metric tons/yr)(1000000 g/metric ton)
= 2.4164E+13 g
Transformity 1.00E+09 Sej/g (Odum et al, 1995, p. 4-4, 4-5)

3 Coral (USGS, 1995, Table 5)
(680000 metric tons/yr)(1000000 g/metric ton)
= 6.8E+11 g
Transformity 1.00E+09 Sej/g

4 Clay (USGS, 1995, Table 5)
(4294000 metric tons/yr)(1000000 g/metric ton)
= 4.294E+12 g
Transformity 2.00E+09 Sej/g (Odum, 1996, p. 310)

5 Shale (USGS, 1995, Table 5)
(4378000 metric ton/yr)(1000000 g/metric ton)
= 4.378E+12 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p. 310)

6 Bauxite (USGS, 1995, Table 5)
(967000 metric tons/yr)(1000000 g/metric ton)
= 9.67E+11 g
Transformity 8.55E+08 Sej/g (Odum, 1996, p.187)

7 Sand and sand stone (USGS, 1995, Table 5)
(2951000 metric tons/yr)(1000000 g/metric ton)
= 2.951E+12 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p. 310)

8 Iron ore (USGS, 1995, Table 5)
(1523000 metric tons/yr)(1000000 g/metric ton)
= 1.523E+12 g
Transformity 1.32E+09 Sej/g (This study, Table C-4)
8.60E+08 Sej/g (Odum, 1996, p. 187)

9 Gypsum (USGS, 1995, Table 5)
(3997000 metric tons/yr)(1000000 g/metric ton)
= 3.997E+12 g
Transformity 1.00E+09 Sej/g (Brown and McClanahan, 1992, Table 2, p. 22)

Table B-1—continued.

10 Coal (USGS, 1995, Table 6)
(10171000 metric tons/yr)(7000000 kcal/ton)(4186 J/kcal)
= 2.9803E+17 J
Transformity 4.00E+04 Sej/J (Odum, 1996, p. 310)

11 Natural gas (USGS, 1995, Table 6)
(1069044000 cu.m./yr)(9077 kcal/cu.m.)(4186 J/kcal)
= 4.062E+16 J
Transformity 4.80E+04 Sej/J (Odum, 1996, p. 308)

12 Oil (USGS, 1995, Table 6)
(41814000 liters/yr)(1/1000 cu.m./l)(6.29 bbl/cu.m.)(6289000000 J/bbl)
= 1.6541E+15 J
Transformity 6.60E+04 Sej/J (Odum, 1996, p. 308)

13 Liquid fuel, waste 700 Btu/cu.ft.(Tchobanoglous et al, 1993, p. 628)
(USGS, 1995, Table 6)
(884586000 liters/yr)(0.03531 cu.ft./l)(700 Btu/cu.ft.)(1054 J/Btu)
= 2.3045E+13 J
Transformity 6.60E+04 Sej/J

14 Tires, waste 10000 BTU/lb (Tchobanoglous et al, 1993, Table 4-5, p. 84)
158000 metric tons/yr (USGS, 1995, Table 6)
(158000 metric tons/yr)(2205 lb/metric ton)(10000 Btu/lb)(1054 J/Btu)
= 3.672E+15 J
Transformity 2.10E+04 Sej/J using rubber (Odum et al, 1983, Table 3.1, p. 40-45)

15 Electricity (USGS, 1995, Table 7)
(11039000000 kWh/yr)(3600000 J/kWh)
= 3.974E+16 J
Transformity 1.74E+05 Sej/J (Odum, 1996, p. 305)

16 Transport (Boat) (USGS, 1995, Table 10)
Plants to terminal (7898000 metric tons/yr)(1.1025 short ton/metric ton)(30 miles)
= 261226350 ton-mile
To consumers (162000 metric tons/yr)(1.1025 short ton/metric ton)(300 miles)
53581500 ton-mile excluding to consumers
Transformity 1.17E+11 sej/ton-mile (This study, Table E-3)

17 Transport (Railroad) (USGS, 1995, Table 10)
Plants to terminal (10388000 metric tons/yr)(1.1025 short ton/metric ton)(30 miles)
= 343583100 J
To consumers (3803000 metric tons/yr)(1.1025 short ton/metric ton)(300 miles)
1257842250 J excluding to consumers
Transformity 5.07E+10 sej/ton-mile (This study, Table E-2)

Table B-1--continued.

18 Transport (Truck) (USGS, 1995, Table 10)
Plants to terminal (2763000 tons/yr)(1.1025 short ton/metric ton)(30 miles)
= 91386225 J
To consumers (72449000 metric tons/yr)(1.1025 short ton/metric ton)(300 miles)
2.3963E+10 J excluding to consumers
Transformity 9.65E+11 sej/ton-mile (This study, Table E-1)

19 Labor 17800 employees/yr 1995 (USGS: Mineral Commodity Summaries, 1997, p.40)
(17800 employees)(2E+10 J/person/yr)
= 3.56E+14 J

666 $/week (Statistical Abstract, 1995, Table 666, p. 424)
(17800 employees)(666 $/week)(52 weeks/yr)
= 616449600 $
Transformity 1.25E+12 Sej/$ for US in 1995 (Projected from Odum, 1996, Table D.1, p. 313-315)

20 Annual Yield of Cement with Fly Ash (USGS, 1995, Table 1)
(76906000 metric tons/yr 1995)(1000000 g/metric ton)
= 7.6906E+13 g
Annual revenue (USGS, 1995, p.40, summaries)
(76906000 metric tons/yr)($68 / metric ton)
= 5229608000 $

21 same as Footnote 1
22 same as Footnote 2
23 same as Footnote 3
24 same as Footnote 4
25 same as Footnote 5
26 same as Footnote 6
27 same as Footnote 7
28 same as Footnote 8
29 same as Footnote 9
30 Fly ash (USGS, 1995, Table 5)
(1396000 metric tons/yr)(1000000 g/metric ton)
= 1.396E+12 g
Transformity 1.40E+10 Sej/g (This study, Table C-1)
31 same as Footnote 10
32 same as Footnote 11
33 same as Footnote 12
34 same as Footnote 13
35 same as Footnote 14
36 same as Footnote 15
37 same as Footnote 16
38 same as Footnote 17
39 same as Footnote 18
40 same as Footnote 19
41 same as Footnote 20

Table B-2. Footnotes to Table 3-2 ready-mixed concrete and ready-mixed concrete recycling alternatives in Chapter 3.

Footnotes:

1 Sand
(1370 lb/cy)(4500 cy/mo)(12 mo/yr)(454 g/lb)
= 33586920000 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)

2 Aggregates
(1750 lb/cy)(4500 cy/mo)(12 mo/yr)(454 g/lb)
= 42903000000 g
Transformity 1.00E+09 Sej/g (Odum et al, 1995, p. 4-4, 4-5)

3 Cement
(540 lb/cy)(4500 cy/mo)(12 mo/yr)(454 g/lb)
= 13238640000 g
Transformity 2.31E+09 Sej/g updated (Haukoos, 1995, Table A-13, p. 172)

4 Water
(300 lb/cy)(4500 cy/mo)(12 mo/yr)(454 g/lb)(4.94 J/g)
= 36332712000 J 7354800000 g
Transformity 48000 Sej/J (Odum, 1996, p.120)

5 Electricity
(800 $/mo)(12 mo/yr)(34.72 kWh/$)(3.6 E+06 J/kWh)
= 1.19992E+12 J 0.0288 $/kWh (Personal communication with Gainesville Regional Utilities (GRU), FL, 1996)
Transformity 174000 Sej/J (Odum, 1996, p. 305)

6 Transport (Truck)
[(3625 lb/cy)(4500 cy/mo)(12 mo/yr)/(2000 lb/short ton)]*(350 miles)
+[(35 lb fly ash/cy)(4500 cy/mo)(12 mo/yr)/(2000 lb/short ton)]*(400 miles)
= 34634250 ton-mile
Transformity 9.65E+11 sej/ton-mile (This study, Table E-1)

7 Machinery
Trucks [(11 trucks)(6600 lb/truck)(454 g/lb)]/(10 yr)
= 3296040 g
Plant (50 tons)(1000000 g/ton)/(20 yr)
= 2500000 g

= 5796040 g
Transformity 6.70E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4)

8 Labor
(1.75 $/cy)(4500 cy/mo)(12 mo/yr)
= 94500 $
Transformity 1.20E+12 Sej/$ for US in 1996 (Projected from Odum, 1996, Table D.1, p. 313-315)

Table B-2--continued.

9 Annual Yield of Ready-mixed Concrete with Coal fly ash

(4500 cy/mo)(12 mo/yr)(3960 lb/cy)(454 g/lb)

= 9.71E+10 g wet weight

8.97E+10 g dry weight

Average $62.50 per cu. yd. (R.S. Means, 1998).

(4500 cy/mo)(12 mo/yr)($62.50/cy)

= 3.38E+06 $

10 same as Footnote 1

11 same as Footnote 2

12 Cement

(505 lb/cy)(4500 cy/mo)(12 mo/yr)(454 g/lb)

= 12380580000 g

Transformity 2.31E+09 Sej/g updated (Haukoos, 1995, Table A-13, p. 172)

13 Fly ash

(35 lb/cy)(4500 cy/mo)(12 mo/yr)(454 g/lb)

= 858060000 g

Transformity 1.40E+10 Sej/g (This study, Table C-1)

14 same as Footnote 4

15 same as Footnote 5

16 same as Footnote 6

17 same as Footnote 7

18 same as Footnote 8

19 same as Footnote 9

20 same as Footnote 1

21 same as Footnote 3

22 Crushed concrete

(1750 lb/cy)(4500 cy/mo)(12 mo/yr)(454 g/lb)

= 42903000000 g

Transformity 1.26E+09 Sej/g using dry weight concrete (This study, Table C-2)

23 Demolition

Emergy (sej) per gram of demolition process (excluding concrete itself)

4.87E+07 sej per gram (This study, Table D-6)

(4.29E+10 g/yr)(4.87E+07 sej per gram)

= 2.07E+18 sej

24 Crushing concrete

Emergy (sej) per gram of crushing process (excluding concrete itself)

1.66E+07 sej per gram (This study, Table D-8)

(4.29E+10 g/yr)(1.66E+07 sej per gram)

= 7.12E+17 sej

25 same as Footnote 4

26 same as Footnote 5

27 same as Footnote 6

28 same as Footnote 7

29 same as Footnote 8

30 same as Footnote 9

Table B-3. Footnotes to Table 3-3 fired clay brick and fired clay brick recycling alternatives in Chapter 3.

Footnotes:

1 Clay 100% of input from on site
(400 million brick/yr)(3.73 lb/brick)(454 g/lb)
= 6.77E+11 g
Transformity 2.00E+09 Sej/g (Odum, 1996, p.310)

2 Water 1 lb per brick, 25% by weight of brick (ERG: Brick and mortar, 1996, p. 22)
(400E+6 bricks/yr)(1 lb of water/brick)(454 g/lb)(4.94 J/g)
= 8.97104E+11 J 1.816E+11 g
Transformity 48000 Sej/J (Odum, 1996, p.120)

3 Natural gas
1700 Btus/lb of brick (ERG: Brick and mortar, 1996, p. 25)
(400 million brick/yr)(3.73 lb/brick)(1700 Btus/lb brick)(1054 J/Btu)
= 2.67E+15 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)

4 Machinery 3 plants use sawdust fuel, 1 plant uses natural gas fuel
machinery is expected for 50 years life
[(4 plants)(1000 tons/plant)(1000000 g/ton)]/(50 yr)
= 8.00E+07 g
Transformity 6.70E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4)

5 Labor 507 $/week (Statistical Abstract, 1995, Table 666, p.424)
(650 employees)(507 $/week)(52 weeks/yr)
= 17136600 $
Transformity 1.15E+12 Sej/$ for US in 1997 (Projected from Odum, 1997, Table D.1, p. 313-315)

6 Annual Yield of Brick with Oil-contaminated Soil
(400 million brick/yr)(3.73 lb/brick)(454 g/lb)
= 6.77368E+11 g

7 same as Footnote 1
8 same as Footnote 2

9 Natural gas 1 plant produces 25% of total brick production
1700 Btus/lb of brick (ERG: Brick and mortar, 1996, p. 25)
(0.25)(400 million brick/yr)(3.73 lb/brick)(1700 Btus/lb brick)(1054 J/Btu)
= 6.68341E+14 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)

Table B-3--continued.

10 Sawdust fuel
3 plants produce 75% of total brick production
1700 Btus/lb of brick (ERG: Brick and mortar, 1996, p. 25)
(0.75)(400 million brick/yr)(3.73 lb/brick)(1700 Btus/lb brick)(1054 J/Btu)
= 2.00502E+15 J
Transformity 1.56E+04 sej/J using wood chips to generate electricity (Doherty, 1995, p.145)

11 same as Footnote 4
12 same as Footnote 5
13 same as Footnote 6

14 Clay
80% of input from on site
(0.8)(400 million brick/yr)(3.73 lb/brick)(454 g/lb)
= 5.41894E+11 g
Transformity 2.00E+09 Sej/g (Odum, 1996, p.310)

15 Oil-contaminated soil
10-30% of input from 30 miles off-site
(0.2)(400 million brick/yr)(3.73 lb/brick)(454 g/lb)
= 1.35474E+11 g 3.0623E+15 J
Transformity 1.00E+09 sej/g

16 same as Footnote 2
17 same as Footnote 9
18 same as Footnote 10

19 Transport (Railroad)
50% by rail of 30 miles distance of Oil-contaminated soil
[(0.5)(0.2)(400 million brick/yr)(3.73 lb/brick)/(2000 lb/short ton)]*(30 miles)
= 2238000 ton-mile
Transformity 5.07E+10 Sej/ton-mile (This study, Table E-2)

20 Transport (Truck)
50% by truck of 30 miles distance of Oil-contaminated soil
[(0.5)(0.2)(400 million brick/yr)(3.73 lb/brick)/(2000 lb/short ton)]*(30 miles)
= 2238000 ton-mile
Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

21 same as Footnote 4
22 same as Footnote 5
23 same as Footnote 6

Table B-4. Footnotes to Table 3-4 steel and steel recycling alternatives products (Electric Arc Furnace (EAF) process) in Chapter 3.

Footnotes: 100 % input from pre- and post-consumer product

1 Pig iron
100% input
[(44.9E+6 tons/yr)+(1%)(44.9E+6 tons/yr)](1000000 g/metric ton)
= 4.53E+13 g
Transformity 2.83E+09 sej/g (This study, Table C-3)

2 Natural gas
60% of 11.18 million Btu/net ton shipped
(0.6)(11.18E+6 Btus/net ton shipped)(44.9E+6 tons/yr)(1054 J/Btu)
= 3.175E+17 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)

3 Other fuels
5.3% of 11.18 million Btu/net ton shipped
(0.053)(11.18E+6 Btus/net ton shipped)(44.9E+6 ton/yr)(1054 J/Btu)
= 2.804E+16 J
Transformity 66000 Sej/J

4 Electricity
34.7% of 11.18 million Btu/net ton shipped
(0.347)(11.18E+6 Btus/net ton shipped)(44.9E+6 ton/yr)(1054 J/Btu)
= 1.836E+17 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

5 Transport (Railroad)
Depending on geographical location of each plant, 400 miles average distance.
About 50% by rail
(0.5)(45.349 million metric tons/yr)(300 miles)(1.102 short ton/metric ton)
= 7.496E+09 ton-mile
Transformity 5.07E+10 Sej/ton-mile (This study, Table E-2)

6 Transport (Truck)
Depending on geographical location of each plant
4-6 hours driven with 400 miles maximum average distance.
(0.5)(45.349 million metric tons/yr)(300 miles)(1.102 short ton/metric ton)
= 7.496E+09 ton-mile
Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

7 Labor
507 $/week (Statistical Abstract, 1995, Table 666, p.424)
(60000 employees)(507 $/week)(52 weeks/yr)
= 1.582E+09 $
Transformity 1.20E+12 Sej/$ for US in 1996 (Projected from Odum, 1996, Table D.1, p. 313-315)

8 Annual Yield of Steel from Electric Arc Furnace process
(44.9 million metric tons/yr 1996)(1000000 g/metric ton)
= 4.49E+13 g $ depends on the final products

9 Post-consumer steels
100% input
[(44.9E+6 tons/yr)+(1%)(44.9E+6 tons/yr)](1000000 g/metric ton)
= 4.53E+13 g
Transformity 2.83E+09 sej/g using pig iron (This study, Table C-3)

Table B-4--continued.

10 Post-consumer steel collection 100% post-consumer steel scrap
Emergy (sej) per gram of steel from curbside collection (excluding steel itself)
2.51E+8 sej per gram (This study, Table D-1)
(4.53E+13 g)(2.51E+8 sej per gram)
= 1.13E+22 sej

11 Post-consumer steel separation 100% post-consumer steel scrap
Emergy (sej) per gram of steel from separation facility (excluding steel itself)
8.24E+6 sej per gram (This study, Table D-3)
(4.53E+13 g)(8.24E+6 sej per gram)
= 3.70E+20 sej
12 same as Footnote 2
13 same as Footnote 3
14 same as Footnote 4
15 same as Footnote 5
16 same as Footnote 6
17 same as Footnote 7
18 same as Footnote 8
100 % input from pre- and post-consumer product
19 Post-consumer steels 30% input from post-consumer product
(0.3)[(44.9E+6 tons/yr)+(1%)(44.9E+6 tons/yr)](1000000 g/metric ton)
= 1.36E+13 g
Transformity 2.83E+09 sej/g using pig iron (This study, Table C-3)

20 Steel scrap or slag 70% input from pre-consumer product
(0.7)[(44.9E+6 tons/yr)+(1%)(44.9E+6 tons/yr)](1000000 g/metric ton)
= 3.174E+13 g
Transformity 2.83E+09 sej/g using pig iron (This study, Table C-3)

21 Post-consumer steel collection 30% post-consumer steel scrap
Emergy (sej) per gram of steel from curbside collection (excluding steel itself)
2.51E+8 sej per gram (This study, Table D-1)
(1.36E+13 g)(2.51E+8 sej per gram)
= 3.4136E+21 sej

22 Post-consumer steel separation 30% post-consumer steel scrap
Emergy (sej) per gram of steel from separation facility (excluding steel itself)
8.24E+6 sej per gram (This study, Table D-3)
(1.36E+13 g)(8.24E+6 sej per gram)
= 1.121E+20 sej
23 same as Footnote 2
24 same as Footnote 3
25 same as Footnote 4
26 same as Footnote 5
27 same as Footnote 6
28 same as Footnote 7
29 same as Footnote 8
300 Btu/lb of ferrous metal (696 J/g) (Tchobanoglous et al, 1993, p.85; Odum et al., 1987b, p.164)

Table B-5. Footnotes to Table 3-5 steel and steel recycling alternatives products (Basic Oxygen Furnace (BOF) process) in Chapter 3.

Footnotes:

1 Pig iron 100 % of input
[(60.4E+6 tons/yr)+(1%)(60.4E+6 tons)](1000000 g/metric ton)
= 6.11E+13 g
Transformity 2.83E+09 sej/g (This study, Table C-3)

2 Water 75000 gal/net ton shipped, 95% recycled for cooling
(0.05)(75000 gal/net ton shipped)(60.4E+6 tons/yr)(8 lb/gal)(454 g/lb)
(4.94 J/g)
= 4.064E+15 J
Transformity 48000 Sej/J (Odum, 1996, p.120)

3 Coal/Coke 58% of 22.26 million Btu/net ton shipped
(0.58)(22.26E+6 Btus/net ton shipped)(60.4E+6 tons/yr)(1054 J/Btu)
= 8.219E+17 J
Transformity 40000 Sej/J (Odum, 1996, p. 310)

4 Natural gas 19.9% of 22.26 million Btu/net ton shipped
(0.199)(22.26E+6 Btus/net ton shipped)(60.4E+6 tons/yr)(1054 J/Btu)
= 2.82E+17 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)

5 Other fuels 16.7% of 22.26 million Btu/net ton shipped
(0.167)(22.26E+6 Btus/net ton shipped)(60.4E+6 tons/yr)(1054 J/Btu)
= 2.367E+17 J
Transformity 66000 Sej/J

6 Electricity 5.4% of 22.26 million Btu/net ton shipped
(0.347)(22.26E+6 Btus/net ton shipped)(60.4E+6 tons/yr)(1054 J/Btu)
= 4.917E+17 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

7 Labor Approximately 4000 employees/plant and 22-25 plants in US
507 $/week (Statistical Abstract, 1995, Table 666, p.424)
(92000 employees)(507 $/week)(52 weeks/yr)
= 2.425E+09 $
Transformity 1.20E+12 Sej/$ for US in 1996 (Projected from Odum, 1996, Table D.1, p. 313-315)

8 Annual Yield of Steel from Basic Oxygen furnace process
(60.4 million tons/yr 1996)(1000000 g/metric ton)
= 6.04E+13 g $ depends on the final products

Table B-5--continued.

9 In-house steel scrap 20-30 % of input (using 25% of input from in plant)
(0.25)[(60.4E+6 tons/yr)+(1%)(60.4E+6 tons)](1000000 g/metric ton)
= 1.525E+13 g
Transformity 2.83E+09 sej/g using pig iron (This study, Table C-3)

10 Pig iron 75 % of input (Iron from Blast furnace)
(0.75)[(60.4E+6 tons/yr)+(1%)(60.4E+6 tons)](1000000 g/metric ton)
= 4.575E+13 g
Transformity 2.83E+09 sej/g (This study, Table C-3)

11 same as Footnote 2
12 same as Footnote 3
13 same as Footnote 4
14 same as Footnote 5
15 same as Footnote 6
16 same as Footnote 7
17 same as Footnote 8
300 Btu/lb of ferrous metal (696 J/g) (Tchobanoglous et al, 1993, p.85; Odum et al., 1987b, p.164)

Table B-6. Footnotes to Table 3-6 aluminum sheets and aluminum sheets recycling alternatives products (electrolytic process) in Chapter 3.

Footnotes:

Total input is 416700 metric ton/yr 1997

1 Primary aluminum (ingot)
100% of input from onsite manufacture
(416700 metric tons/yr)(1000000 g/metric ton)
= 4.17E+11 g
Transformity 1.17E+10 Sej/g (This study, Table C-7)

2 Electricity
(300 MWh/yr)(3.6 E+06 J/kWh)
= 1.08E+15 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

3 Labor 1100 employees with 3 shifts, 24 hr/day
(1100 employees)(2E+10 J/yr)
= 2.2E+13 J

507 $/week (Statistical Abstract, 1995, Table 666, P. 424)
(1100 employees)(507 $/week)(52 weeks/yr)
= 29000400 $
Transformity 1.15E+12 Sej/$ for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)

4 Annual Yield of Aluminum Sheet
(400000 metric tons/yr 1997)(1000000 g/metric ton)
= 4E+11 g

5 Used aluminum can (beverage can)
100% of input with 30 miles distance by truck from Material Recovery Facility
(416700 metric tons/yr)(1000000 g/metric ton)
= 4.17 E+11 g
Transformity 1.17E+10 Sej/g using aluminum ingot (This study, Table C-7)

6 Used Al. can collection
Emergy (sej) per gram of aluminum from curbside collection (excluding aluminum itself)
2.51E+8 sej per gram (This study, Table D-1)
(4.17E+11 g)(2.51E+8 sej per gram)
= 1.046E+20 sej

7 Used Al. can separation
Emergy (sej) per gram of aluminum from separation facility (excluding aluminum itself)
8.24E+6 sej per gram (This study, Table D-3)
(4.17E+11 g)(8.24E+6 sej per gram)
= 3.436E+18 sej

8 same as Footnote 2

Table B-6--continued.

9 Transport (Truck) beverage aluminum cans 30 miles distance
[(416700 metric tons/yr)(1.102 short ton/metric ton)(30 miles)
= 1.38E+7 ton-mile
Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

10 same as Footnote 3
11 same as Footnote 4

12 Used aluminum can (beverage can)
55% of input with 30 miles distance by truck from Material Recovery Facility
(0.55)(416700 metric tons/yr)(1000000 g/metric ton)
= 2.29185E+11 g
Transformity 1.17E+10 Sej/g using aluminum ingot (This study, Table C-7)

13 Primary aluminum (ingot)
30% of input from onsite manufacture
(0.3)(416700 metric tons/yr)(1000000 g/metric ton)
= 1.2501E+11 g
Transformity 1.17E+10 Sej/g (This study, Table C-7)

14 Aluminum scrap 15% of input from other manufactures with 300 miles distance by truck
(0.15)(416700 metric tons/yr)(1000000 g/metric ton)
= 6.25E+10 g
Transformity 1.17E+10 Sej/g using aluminum ingots (This study, Table C-7)

15 Used AL can collection
Emergy (sej) per gram of aluminum from curbside collection (excluding aluminum itself)
2.51E+8 sej per gram (This study, Table D-1)
(2.29E+11 g)(2.51E+8 sej per gram)
= 5.7479E+19 sej
16 Used AL can separation
Emergy (sej) per gram of aluminum from separation facility (excluding aluminum itself)
8.24E+6 sej per gram (This study, Table D-3)
(2.29E+11 g)(8.24E+6 sej per gram)
= 1.88848E+18 sej

17 same as Footnote 2
18 Transport (Truck) beverage aluminum cans 30 miles distance, aluminum scrap 300 miles distance
[(0.55)(416700 metric tons/yr)(1.102 short ton/metric ton)(30 miles)
+(0.15)(416700 metric tons/yr)(1.102 short ton/metric ton)(300 miles)]
= 28241009.1 ton-mile
Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

19 same as Footnote 3
20 same as Footnote 4
*** Aluminum ore (Bauxite) 65.3 J/g (Odum, 1996, p.302)

Table B-7. Footnotes to Table 3-7 conventional process of softwood plywood in Chapter 3.

Footnotes:

1 Hardwood logs (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(100.2 million ft. log scale/yr)(45 lb/cu.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 4.28455E+16 J 2.04709E+12 g
Transformity 8.01E+03 Sej/J (Odum, 1996, p.80)

2 Softwood logs (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(4535.3 million ft. log scale/yr)(35 lb/cu.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 1.50834E+18 J 7.20659E+13 g
Transformity 8.01E+03 Sej/J (Odum, 1996, p.80)

3 Lumbers (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(9.5 million bd.ft./yr)(3 lb/bd.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 2.70813E+14 J 1.29E+10 g
Transformity 4.40E+04 Sej/J (Odum, 1996, p.308)

4 Hardwood veneer (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(224.1 million sq.ft./yr)(0.3 lb/sq.ft. of veneer)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 6.38834E+14 J 3.05E+10 g
Transformity 4.40E+04 Sej/J (Odum, 1996, p.308)

5 Softwood plywood (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(53.9 million sq.ft. 3/8-inch basis)(1.125 lb/sq.ft. 3/8")(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 5.76191E+14 J 2.75E+10 g
Transformity 4.40E+04 Sej/J (Odum, 1996, p.308)

6 Hardboard wood fiber
(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(2.3 million sq.ft. 1/8-inch basis)(0.52 lb/sq.ft. 1/8")(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 1.13647E+13 J 5.43E+08 g
Transformity 1.27E+05 Sej/J updated (Haukoos, 1995, Table A-9, p.161-162)

7 Oil 44.8 million $ (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
1.19 $/gal, 1992 (Statistical Abstract 1997, Table 932, p. 588)
[(44.8 million $/yr)/(1.19 $/gal)](125000 Btu/gal)(1054 J/Btu)
= 4.96E+15 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

Table B-7--continued.

8 **Electricity**
(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
(2669 million kWh/yr)(3.6 E+06 J/kWh)
= 9.6084E+15 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

9 **Labor**
31300 employees(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
(31300 employees)(2E+10 J/yr)
= 6.26E+14 J

827.4 million $ (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
= 827400000 $
Transformity 1.43E+12 Sej/$ for US in 1992 (Odum, 1996, Table D.1, p. 313-315)

10 **Annual Yield of Softwood Plywood and Veneer**
(9.22E+12 g/yr of softwood plywood)+(3.75E+12 g/yr of softwood veneer)
= 1.29862E+13 g
5447 million $(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
2185.9 million $ value added

Annual Yield of Softwood Plywood
(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 6a, p. 24B-19)
(18069.9 million sq.ft. 3/8-inch basis)(1.125 lb/sq.ft. 3/8")(454 g/lb)
= 9.2292E+12 g

Annual Yield of Softwood Veneer
[(449.5 million sq.ft.)(0.3 lb/sq.ft. of veneer)(454 g/lb)]+
[(2713.5 millions sq.ft. 1-inch basis)(3 lb/sq.ft. of 1" veneer)(454 g/lb)]
= 3.75701E+12 g

Table B-8. Footnotes to Table 3-8 byproduct use recycling of laminated plywood in Chapter 3.

Footnotes:

1 Shaved lumber 50% of total weight 76 lb/panel
(0.5)(35000 panels/mo)(12 mo/yr)(76 lb/panel)(454 g/lb)
= 7.246E+09 g
Transformity 8.79E+08 Sej/g using wood chips (This study, Table 3-9)
1.63E+09 Sej/g updated (Haukoos, 1995, Table A-4a, p.147-148)

2 Veneer 40% of total weight 76 lb/panel
(0.4)(35000 panels/mo)(12 mo/yr)(76 lb/panel)(454 g/lb)
= 5.797E+09 g
Transformity 1.21E+09 Sej/g using softwood veneer (This study, Table 3-7)
1.44E+09 Sej/g hardwood veneer (This study, Table C-16)

3 Plastics resin Thermoset plastic resin 10% of total weight 76 lb/panel
(0.1)(35000 panels/mo)(12 mo/yr)(76 lb/panel)(454 g/lb)
= 1.449E+09 g
Transformity 3.28E+09 Sej/g (This study, Table C-8)

4 Water Raw resin contains 40% solid and 60% water
(0.6)(0.1)(35000 panels/mo)(12 mo/yr)(76 lb/panel)(454 g/lb)(4.94 J/g)
= 4.295E+09 J
Transformity 48000 Sej/J (Odum, 1996, p.120)

5 Natural gas 50% of 24 million Btu/hr/mo
(0.5)(24 million Btu/hr)(200 hr/mo)(12 mo/yr)(1054 J/Btu)
= 3.036E+13 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)

6 Oil 50% of 24 million Btu/hr/mo
(0.5)(24 million Btu/hr)(200 hr/mo)(12 mo/yr)(1054 J/Btu)
= 3.036E+13 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

7 Electricity (4000 kWh/mo)(12 mo/yr)(3.6 E+06 J/kWh)
= 1.728E+11 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

8 Labor 507 $/week (Statistical Abstract, 1995, Table 666, p.424)
(70 employees)(507 $/week)(52 week/yr)
= 1845480 $
Transformity 1.15E+12 Sej/$ for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)

9 Annual Yield of Laminated Plywood
(35000 panels/mo)(12 mo/yr)(76 lb/panel)(454 g/lb)
= 1.449E+10 g
(20 $/board*35000 panels/yr) = 700000 $/yr

Table B-9. Footnotes to Table 3-9 conventional process of lumbers in Chapter 3.

Footnotes:

1 Hardwood logs (Census of Manufactures 1992: Sawmills and Planing Mills, Table 7, p. 24A-21)
(4018.4 million ft. log scale/yr)(45 lb/cu.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 1.71827E+18 J 8.20959E+13 g
Transformity 8.01E+03 Sej/J (Odum, 1996, p.80)

2 Softwood logs (Census of Manufactures 1992: Sawmills and Planing Mills, Table 7, p. 24A-21)
(20810.9 million ft. log scale/yr)(35 lb/cu.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 6.92124E+18 J 3.30685E+14 g
Transformity 8.01E+03 Sej/J (Odum, 1996, p.80)

3 Hardwood lumber (Census of Manufactures 1992: Sawmills and Planing Mills, Table 7, p. 24A-21)
(843.3 million bd.ft./yr)(3.3 lb/bd.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 2.64436E+16 J 1.26343E+12 g
Transformity 4.40E+04 Sej/J (Odum, 1996, p.308)
1.51E+05 Sej/J updated (Haukoos, 1995, Table A-3a, p. 143-144)
2.27E+09 Sej/g updated (Haukoos, 1995, Table A-3a, p. 143-144)

4 Softwood lumber (Census of Manufactures 1992: Sawmills and Planing Mills, Table 7, p. 24A-21)
(3243.1 million bd.ft./yr)(2.5 lb/bd.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 7.70416E+16 J 3.68092E+12 g
Transformity 4.40E+04 Sej/J (Odum, 1996, p.308)
1.18E+05 Sej/J updated (Haukoos, 1995, Table A-2a, p. 139-140)
1.77E+09 Sej/g updated (Haukoos, 1995, Table A-2a, p. 139-140)

5 Glue and Adhesives (Census of Manufactures 1992: Sawmills and Planing Mills, Table 7, p. 24A-21)
(114.6 million lb/yr)(454 g/lb)
= 5.20E+10 g
Transformity 3.80E+08 Sej/g using chemical (Brown et al, 1992, Table A1)

6 Oil 125.7 million $ (Census of Manufactures 1992: Sawmills and Planing Mills, Table 3a, p. 24A-11)
1.19 $/gal, 1992 (Statistical Abstract 1997, Table 932, p. 588)
[(125.7 million $/yr)/(1.19 $/gal)](125000 Btu/gal)(1054 J/Btu)
= 1.39168E+16 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

7 Electricity 6763 million kWh (Census of Manufactures 1992: Sawmills and Planing Mills, Table 3a, p. 24A-11)
(6763 million kWh/yr)(3.6 E+06 J/kWh)
= 2.43468E+16 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

Table B-9--continued.

8 Labor (Census of Manufactures 1992: Sawmills and Planing Mills, Table 3a, p. 24A-11)

(138100 employees)(2E+10 J/yr)

= 2.762E+15 J

(Census of Manufactures 1992: Sawmills and Planing Mills, Table 3a, p. 24A-11)

= 3.05E+09 $

Transformity 1.43E+12 Sej/$ for US in 1992 (Odum, 1996, Table D.1, p. 313-315)

9 Total Annual Yield

(4.5E+13 g/yr lumbers)+(4.88E+13 g/yr wood chips)+(8.29E+11 g/yr slidings)

= 9.47006E+13 g

Total Annual Yield of Lumber

(7.48E+12 g/yr of hardwood)+(37.56E+12 g/yr of softwood)

= 4.50434E+13 g

21065.9 million $(Census of Manufactures 1992: Sawmills and Planing Mills, Table 3a, p. 24A-11)

7783.6 million $ value added

Hardwood lumber (Census of Manufactures 1992: Sawmills and Planing Mills, Table 6a, p. 24A-15-16)

(4994.6 million bd.ft./yr)(3.3 lb/bd.ft.)(454 g/lb)

= 7.48291E+12 g

Softwood lumber (Census of Manufactures 1992: Sawmills and Planing Mills, Table 6a, p. 24A-15-16)

(33092.9 million bd.ft./yr)(2.5 lb/bd.ft.)(454 g/lb)

= 3.75604E+13 g

Total Annual Yield of Wood chips (byproduct)

(Census of Manufactures 1992: Sawmills and Planing Mills, Table 6a, p. 24A-15-16)

35.3582E+6 short ton of softwood

18.456E+6 standard units of Wood chip (13.1641E+6 units of softwood, 5.2926E+6 units of hardwood)

hardwood chip	9.61136E+12 g
softwood chip	5.59759E+13 g

[(35.3582E+6 short tons)(907000 g/short ton)] +

[(18.456E+6 standard units)(200 cu.ft./standard unit)(10 lb/cu.ft.)(454 g/lb)]

= 4.88279E+13 g

Total Annual Yield of Flooring, Sliding, and Cut stock (byproduct)

(Census of Manufactures 1992: Sawmills and Planing Mills, Table 6a, p. 24A-15-16)

25.5E+6 bd.ft. of Flooring, 60.2E+6 bd.ft. of Sliding, 645E+6 bd.ft of Cut stock, (mostly softwood)

[(25.5E+6 bd.ft.)+(60.2E+6 bd.ft.)+(645E+6 bd.ft.)]*(2.5 lb/bd.ft.)(454 g/lb)

= 8.29345E+11 g

Table B-10. Footnotes to Table 3-10 material recycling of lumbers in Chapter 3.

Footnotes:

1	Used lumbers	most of labor is used for wood demolition from existing building	
		(20000 sq.ft./mo)(2.7 lb/sq.ft.)(454 g/lb)(12 mo/yr)	
		= 294192000 g	6.15744E+12 J
	Transformity	8.79E+08 sej/g	new lumber (This study, Table 3-9)
2	Propane gas	20 lb cylinder/mo	
		(20 gal/cylinder/mo)(12 mo/yr)(91300 Btu/gal)(1054 J/Btu)	
		= 2.31E+10 J	
	Transformity	4.80E+04 Sej/J	(Odum, 1996, p.311)
3	Oil		
		(200 gal/mo)(125000 Btu/gal)(1054 J/Btu)	
		= 2.635E+10 J	
	Transformity	66000 Sej/J	(Odum, 1996, p. 308)
4	Transport (Truck)	300 miles distance (mostly come to the operating site)	
		[(20000 sq.ft./mo)(2.7 lb/sq.ft.)(12 mo/yr)/(2000 lb/short ton)] *(300 miles)	
		= 97200 ton-mile	
	Transformity	9.65E+11 Sej/ton-mile	(This study, Table E-1)
5	Labor		
		(15 employees)(22 $/hr)(50 hr/week)(52 week/yr)	
		= 858000 $	
	Transformity	1.15E+12 Sej/$	for US in 1997 (Odum, 1996, Table D.1, p. 313-315)
6	Annual Yield of Recycled Lumber		ranges from 12000-15000 sq.ft./mo
		(13500 sq.ft./mo)(2.7 lb/sq.ft.)(454 g/lb)(12 mo/yr)	
		= 198579600 g	

Electricity is generated from byproduct wood chips.

Table B-11. Footnotes to Table 3-11 byproduct use recycling of vinyl floor in Chapter 3.

Footnotes:

1 Plastics (PVC) 100% byproduct from automobile industry (separated waste from industry)
(12480000 lb/yr)(454 g/lb)
= 5.67E+09 g
Transformity 5.87E+09 Sej/g (This study, Table C-9)

2 Electricity
(40000 kWh/mo)(12 mo/yr)(3.6 E+06 J/kWh)
= 1.728E+12 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

3 Transport (Truck)
[(12480000 lb/yr)/(2000 lb/short ton)]*(100 miles)
= 624000 ton-mile
Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

4 Machinery
[(2 extruder machines)(15000 lb/machine)(454 g/lb)]/(15 yr)
= 908000 g
Transformity 6.70E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4)

5 Labor
(55 employees)(2E+10 J/person/yr)
= 1.1E+12 J

507 $/week (Statistical Abstract, 1995, Table 666, p.424)
(55 employees)(507 $/week)(52 weeks/yr)
= 1450020 $
Transformity 1.15E+12 Sej/$ for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)

6 Annual Yield of Vinyl Floor (PVC)
(2000 lb/hr)(24 hr/day)(5 days/week)(52 weeks/yr)(454 g/lb)
= 5665920000 g

*** 14000 Btu/lb (30.84 Btu/g) of energy content of plastics (Tchobanoglous et al, 1993, Table 4-5, p.84)

Table B-12. Footnotes to Table 3-12 plastics lumber (HDPE) and plastic lumber recycling alternatives in Chapter 3.

Footnotes:

1	Wood fiber	15-18% wood fiber	
		(0.15)(1872000 lb/yr)(454 g/lb)(5 kcal/g)(4186 J/kcal)	
		= 2.66822E+12 J	127483200 g
	Transformity	4.20E+04 Sej/J	flooring & sliding (This study, Table 3-9)
2	Plastic resin	80-85% virgin HDPE resin	
		(0.85)(1872000 lb/yr)(454 g/lb)	
		= 722404800 g	
	Transformity	5.27E+09 Sej/g	(This study, Table C-10)
3	Electricity		
		(25000 kWh/mo)(12 mo/yr)(3.6 E+06 J/kWh)	
		= 1.08E+12 J	
	Transformity	174000 Sej/J	(Odum, 1996, p. 305)
4	Transport (Truck)		
		[(1872000 lb/yr)/(2000 lb/short ton)]*(200 miles)	
		= 187200 ton-mile	
	Transformity	9.65E+11 Sej/ton-mile	(This study, Table E-1)
5	Machinery		
		[[(1 extruder machine)(10000 lb/machine)+(2 Heat mold machines)(3000 lb/machine)]*(454 g/lb)]/(15 yr)	
		= 484266.6667 g	
	Transformity	6.70E+09 Sej/g	(Odum et al., 1987b, Table 1, p. 4)
6	Labor		
		507 $/week (Statistical Abstract, 1995, Table 666, p.424)	
		(20 employees)(507 $/week)(52 weeks/yr)	
		= 527280 $	
	Transformity	1.15E+12 Sej/$	for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)
7	Annual Yield of HDPE plastics lumber		
		(300 lb/hr)(24 hr/day)(5 days/week)(52 weeks/yr)(454 g/lb)	
		= 849888000 g	
8	Post-consumer paper	15-18% post-consumer paper	
		(0.15)(1872000 lb/yr)(454 g/lb)(5 kcal/g)(4186 J/kcal)	
		= 2.66822E+12 J	127483200 g
	Transformity	1.42E+05 Sej/J	(Keller, 1992, p.116)
		4.20E+04 Sej/J	flooring & sliding (This study, Table 3-9)

Table B-12--continued.

9 Post-consumer plastic 80-85% post-consumer milk jugs
(0.85)(1872000 lb/yr)(454 g/lb)
= 722404800 g
Transformity 5.27E+09 Sej/g (This study, Table C-10)

10 Collection
Emergy (sej) per gram of paper and plastics from curbside collection (excluding emergy of paper and plastics materials)
2.51E+8 sej per gram (This study, Table D-1)
(1872000 lb/yr)(454 g/lb)(2.51E+8 sej per gram)
= 2.1332E+17 sej

11 Separation (separated wastes from consumers)
Emergy (sej) per gram of paper and plastics from curbside collection (excluding emergy of paper and plastics materials)
8.24E+6 sej per gram (This study, Table D-3)
(1872000 lb/yr)(454 g/lb)(8.24E+6 sej per gram)
= 7.003E+15 sej

12 same as Footnote 3
13 same as Footnote 4
14 same as Footnote 5
15 same as Footnote 6
16 same as Footnote 7
*** 14000 Btu/lb (30.84 Btu/g) of energy content of plastics (Tchobanoglous et al, 1993, Table 4-5, p.84)

Table B-13. Footnotes to Table 3-13 ceramic tile and ceramic tile recycling alternatives in Chapter 3.

Footnotes:

1	Silica sand	20% loss in process	
		[(0.62)(3 millions sq. ft/yr)(3.2 lb/sq. ft)(454 g/lb)]/(0.8)	
		= 3.38E+09 g	
	Transformity	1.00E+09 Sej/g	(Odum, 1996, p.310)
2	Sand	(0.03)(3 millions sq. ft/yr)(3.2 lb/sq. ft)(454 g/lb)	
		= 1.31E+08 g	
	Transformity	1.00E+09 Sej/g	(Odum, 1996, p.310)
3	Clay	(0.25)(3 millions sq. ft/yr)(3.2 lb/sq. ft)(454 g/lb)	
		= 1.09E+09 g	
	Transformity	2.00E+09 Sej/g	(Odum, 1996, p.310)
4	Others	(0.05)(3 millions sq. ft/yr)(3.2 lb/sq. ft)(454 g/lb)	
		= 2.18E+08 g	
	Transformity	1.00E+09 Sej/g	
5	Water	(0.05)(3 millions sq. ft/yr)(3.2 lb/sq. ft)(454 g/lb)(4.94 J/g)	
		= 1.08E+09 J	2.18E+08 g
	Transformity	48000 Sej/J	(Odum, 1996, p.120)
6	Natural gas	25% saved if using cullet	
		[(0.21 therm/sq. ft)(3 millions sq. ft/yr)(105505600 J/Therm)]/(0.75)	
		= 8.85E+13 J	
	Transformity	48000 Sej/J	(Odum, 1996, p. 308)
7	Electricity	25% saved if using cullet	
		[(28000 kWh/mo)(12 mo/yr)(3.6 E+06 J/kWh)]/(0.75)	
		= 1.61E+12 J	
	Transformity	174000 Sej/J	(Odum, 1996, p. 305)
8	Transport (Truck)	54000 lb/truck, 400 miles distance of post-consumer glass	
		(0.62)[(3 millions sq.ft./yr)(3.2 lb/sq.ft.)/(2000 lb/ton)]	
		*(400 miles distance)	
		= 1190400 ton-mile	
	Transformity	9.65E+11 sej/ton-mile	(This study, Table E-1)
9	Machinery	[(3 machines)(450 ton/machine)(907000 g/ton)]/(30 yr)	
		= 40815000 g	
	Transformity	6.70E+09 Sej/g	(Odum et al., 1987b, Table 1, p. 4)
10	Labor	507 \$/week (Statistical Abstract, 1995, Table 666, p.424)	
		(26 people)(507 \$/week)(52 week/yr)	
		= 685464 \$	
	Transformity	1.20E+12 Sej/\$	for US in 1996 (Projected from Odum, 1996, Table D.1, p. 313-315)
11	Annual Yield of Ceramic Tile with Recycled Glass		
		5% of water by weight of product	
		(0.95)(3 millions sq. ft/yr)(3.2 lb/sq. ft)(454 g/lb)	
		= 4.14E+09 g	
	average \$2.50/sq.ft. (R.S. Means, 1998, p.270)		
	(3 millions sq. ft./yr)(\$2.50/sq. ft.) = \$7.5 million/yr		
12	same as Footnote 2		
13	same as Footnote 3		

Table B-13--continued.

14 Post-consumer windshield glass 100% input
(0.62)(3 millions sq. ft/yr)(3.2 lb/sq. ft)(454 g/lb)
= 2.70E+09 g
Transformity 1.90E+09 Sej/g (This study, Table C-12)
15 same as Footnote 4
16 Used windshield glass (collection) 100% windshield input, 300 miles distance of used car
9.65E+11 sej/ton-mile of truck transportation (This study, Table E-)
[(2.7E+9 g)/(907000 g/ton)](300 miles)(9.65E+11 sej/ton-mile)
= 8.61E+17 sej
17 Used windshield glass (separation) 100% windshield input
Emergy (sej) per gram of glass from Recovery Facility (excluding glass itself)
using 8.24E+6 sej per gram (This study, Table D-3)
(2.7E+9 g)(8.24E+6 sej per gram)
= 2.2248E+16 sej
18 same as Footnote 5
19 Natural gas (0.21 therm/sq. ft)(3 millions sq. ft/yr)(105505600 J/Therm)
= 6.6469E+13 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)
20 Electricity (28000 kWh/mo)(12 mo/yr)(3.6 E+06 J/kWh)
= 1.2096E+12 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)
21 same as Footnote 8
22 same as Footnote 9
23 same as Footnote 10
24 same as Footnote 11
25 same as Footnote 2
26 same as Footnote 3
27 Post-consumer glass bottles (0.62)(3 millions sq. ft/yr)(3.2 lb/sq. ft)(454 g/lb)
= 2.70E+09 g 100% input
Transformity 1.90E+09 Sej/g (This study, Table C-12)
28 same as Footnote 4
29 Used glass bottles (collection) Post-consumer 100%
Emergy (sej) per gram of glass from curbside collection (excluding glass itself)
2.51E+8 sej per gram (This study, Table D-1)
(2.7E+9 g)(2.51E+8 sej per gram)
= 6.777E+17 sej
30 Used glass bottles (separation) Post-consumer 100%
Emergy (sej) per gram of glass separation (excluding glass itself)
1.32E+7 sej per gram (This study, Table D-4)
(2.7E+9 g)(1.32E+7 sej per gram)
= 3.564E+16 sej
31 same as Footnote 5
32 same as Footnote 19
33 same as Footnote 20
34 same as Footnote 8
35 same as Footnote 9
36 same as Footnote 10
37 same as Footnote 11
*** 60 Btu/lb (0.132 Btu/g) of energy content of glass (Tchobanoglous et al, 1993, Table 4-5, p.84)

Table B-14. Footnotes to Table 3-14 float glass and float glass recycling alternatives in Chapter 3.

Footnotes:

1 Silica (SiO2) 100% of raw material input, 20% loss in process
(9.18E+10 g of sand)(1.2)+(5.46E+10 g of scrap)(0.95)(1.2)
= 1.72E+11 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)

2 Soda ash (Na2O) 15% of raw material input
(0.15)(385 short ton/day)(907000 g/short ton)(365 days/yr)
= 1.91E+10 g
Transformity 3.80E+08 Sej/g using chemical transformity (Brown et al, 1992, Table A1)

3 Lime (CaO) 10% of raw material input
(0.1)(385 short ton/day)(907000 g/short ton)(365 days/yr)
= 1.27E+10 g
Transformity 6.70E+06 Sej/g (Odum et al, 1995, p. 4-4, 4-5)

4 Magnesium oxide (MgO) 3% of raw material input
(0.03)(385 short ton/day)(907000 g/short ton)(365 days/yr)
= 3.82E+09 g
Transformity 3.80E+08 Sej/g using chemical transformity (Brown et al, 1992, Table A1)

5 Others 2% of raw material input (mostly chemical)
(0.02)(385 short ton/day)(907000 g/short ton)(365 days/yr)
= 2.55E+09 g
Transformity 3.80E+08 Sej/g using chemical transformity (Brown et al, 1992, Table A1)

6 Oil 6.25% increase
[(1300 cu.ft./hr)(7.481 gal/cu.ft.)(125000 Btu/gal)(1054 J/Btu)
(24 hr/day)(365 days/yr)]/(1-0.0625)
= 1.20E+16 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

7 Transport (Railroad)
90% by rail, 10% by truck
Soda ash 15% of 385 short ton/day = 57.75 short ton/day

Raw materials excluding soda ash, 85% of 385 short ton/day = 327.25 short ton/day
90% of 327.25 short ton/day by rail = 294.525 short ton/day

[(57.75 short ton/day)(2000 miles)+(294.525 short ton/day)(200 miles)]
*(365 days/yr)
= 63657825 ton-mile
Transformity 5.07E+10 sej/ton-mile (This study, Table E-2)

Table B-14--continued.

8 Transport (Truck) 10% of 327.25 short ton/day by truck = 32.725 short ton/day
(32.725 short ton/day)(200 miles)(365 days/yr)
= 2388925 ton-mile
Transformity 9.65E+11 sej/ton-mile (This study, Table E-1)

9 Labor 825 employees with 4 shifts/day
(852 employees)(2E+10 J/yr)
= 1.704E+13 J

507 $/week (Statistical Abstract, 1995, Table 666, p.424)
(825 employees)(507 $/week)(52 weeks/yr)
= 21750300 $
Transformity 1.20E+12 Sej/$ for US in 1996 (Projected from Odum, 1996, Table D.1, p. 313-315)

10 Annual Yield of Float Glass
70% of total inputs
(0.7)(550 short ton/day)(907000 g/short ton)(365 days/yr)
= 1.274E+11 g
average $4/sq.ft. of 3/16" and 1/4", $12/sq.ft. of 1/2" float glass (R.S. Means, 1998)
average 4 lb/sq. ft. (Hornbostel, 1978, Table G35, p.352)
Approximately $1 per lb or $0.0022 per gram

550 ton/day of input, 30% in-house scrap, so total raw material input 385 ton/day
11 Silica (SiO2) 72% of raw material input
(0.72)(385 short ton/day)(907000 g/short ton)(365 days/yr)
= 9.18E+10 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)

12 same as Footnote 2
13 same as Footnote 3
14 same as Footnote 4
15 same as Footnote 5

16 Glass scrap 30% of total input
(0.3)(550 short ton/day)(907000 g/short ton)(365 days/yr)
= 5.46E+10 g
Transformity 1.90E+09 sej/g (This study, Table C-12)

17 Oil
(1300 cu.ft./hr)(7.481 gal/cu.ft.)(125000 Btu/gal)(1054 J/Btu)
(24 hr/day)(365 days/yr)
= 1.122E+16 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)
18 same as Footnote 7
19 same as Footnote 8
20 same as Footnote 9
21 same as Footnote 10
*** 60 Btu/lb (0.132 Btu/g) of energy content of glass (Tchobanoglous et al, 1993, Table 4-5, p.84)

APPENDIX C
EMERGY EVALUATION OF PRIMARY MATERIALS

Table C-1. Emergy evaluation of coal fly ash from coal power plant 1996.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+15
1	Coal	J	3.18E+10	4.00E+04	1.27
2	Heat Yield	J	3.18E+10	4.00E+04	1.27
3	Ash Yield (co-product)	g	9.08E+04	1.40E+10	1.27
4	CO2 Yield (co-product)	g	7.22E+05	1.76E+09	1.27

Footnotes:

1 Coal 3.18E+10 J/short ton coal (Odum, 1996, p.299)
(1 short ton of Coal)(3.18E+10 J/short ton)
= 31800000000 J
Transformity 4.00E+04 Sej/J (Odum, 1996, p. 310)

2 Heat Yield
3.18E+10 J/short ton coal (Odum, 1996, p.299)
(1 short ton of Coal)(3.18E+10 J/short ton)
= 31800000000 J

3 Ash Yield 10% (200 lb) ash in coal (Hornbostel, 1978, Table C41, p.195)
190 lb of bottom ash per short ton of coal
10 lb of fly ash per short ton of coal (personal communication with Power Co., Florida, 1997)
(200 lb of ash/s ton coal)(454 g/lb)
= 90800 g

4 CO2 Yield 25 E+6 short ton of CO2 per 1 E+18 J of coal (Johansson et al, 1993, Table 6, p.1129)
(25 E+6 s ton CO2 / 1 E+18 J coal)*(3.18 E+10 J/s ton coal)(2000 lb/s ton)(454 g/lb)
= 7.22E+05 g

Table C-2. Emergy evaluation of ready-mixed concrete in the United States, 1982.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Limestone	g	2.46E+13	1.00E+09	246.45
2	Sand and gravel	g	1.10E+14	1.00E+09	1104.04
3	Stone	g	3.03E+12	1.00E+09	30.30
4	Cement	g	2.75E+13	2.31E+09	635.80
5	Water	J	3.19E+15	4.80E+04	1.53
6	Fuel	J	1.40E+16	6.60E+04	9.24
7	Electricity	J	3.86E+15	1.74E+05	6.72
8	Labor	$	2.24E+09	2.50E+12	56.04
9	Annual Yield (with services)	g	3.36E+15	6.22E+07	2090.13
10	Annual Yield (without services)	g	3.36E+15	6.06E+07	2034.09
11	(dry weight) (with services)	g	1.66E+14	1.26E+09	2090.13
12	(dry weight) (without services)	g	1.66E+14	1.23E+09	2034.09

Footnotes:

1 Limestone (Census of Manufactures, 1982, Table 7, p. 32D-22)
(27172200 short tons/yr 1982)(907000 g/short ton)
= 2.46452E+13 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)
6.70E+06 Sej/g (Odum et al, 1995, p. 4-4, 4-5)

2 Sand and gravel (Census of Manufactures, 1982, Table 7, p. 32D-22)
(121724600 short tons/yr 1982)(907000 g/short ton)
= 1.10404E+14 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)

3 Stone (Census of Manufactures, 1982, Table 7, p. 32D-22)
(3341200 short tons/yr 1982)(907000 g/short ton)
= 3.03047E+12 g
Transformity 1.00E+09 Sej/g

4 Cement (Census of Manufactures, 1982, Table 7, p. 32D-22)
(30346100 short tons/yr 1982)(907000 g/short ton)
= 2.75239E+13 g
Transformity 2.31E+09 Sej/g updated (Haukoos, 1995, Table A-13, p. 172)
7.50E+08 Sej/g (Brown et al, 1992, Table A1 (Mexico))

Table C-2--continued.

5 Water
300 lb/cu.yd. of water in concrete (Hornbostel, 1978;1991, Table C58, p. 210; Walker's, 1992, p.3.126-3.127)
(4744.9E+6 cu.yd./yr)(300 lb/cu.yd.)(454 g/lb)(4.94 J/g)
= 3.1925E+15 J
Transformity 48000 Sej/J (Odum, 1996, p.120)

6 Fuel
130 million $ (Census of Manufactures, 1982, Table 3a, p. 32D-12)
1.244 $/gal, 1982 (Statistical Abstract 1995, Table 770, p. 504; Statistical Abstract 1997, Table 932, p. 588)
[(130E+6 $)/(1.224 $/gal)]*(125000 Btu/gal)(1054 J/Btu)
= 1.39931E+16 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

7 Electricity
(Census of Manufactures, 1982, Table 3d, p. 32D-13)
(1073.1E+6 kWh/yr)(3.6 E+06 J/kWh)
= 3.86316E+15 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

8 Labor
[(81600 employees)+(39000 employees of transportation)]*(2E+10 J/yr)
= 2.412E+15 J (Census of Manufactures, 1982, Table 8, p. 32D-23)

(1481.7E+6 $/yr)+(759.8E+6 $ of transportation/yr)
= 2241500000 $ (Census of Manufactures, 1982, Table 8, p. 32D-23)
Transformity 2.50E+12 Sej/$ for US in 1982 (Odum, 1996, Table D.1, p. 313-315)

9 Annual Yield of Ready-mixed concrete
(Census of Manufactures, 1982, Table 6a, p. 32D-17)
(4744.9E+6 cu.yd./yr 1982)(4000 lb/cu.yd.)(454 g/lb)
= 8.61674E+15 g

Total inputs (limestone, sand and gravel, stone, and cement)
1.66E+14 g dry weight
= 3.36E+15 g wet weight
8199.3 million $/1982 value of shipment (Census of Manufactures, 1982, Table 3a, p. 32D-12)
3295.1 million $/1982 value added (Census of Manufactures, 1982, Table 3a, p. 32D-12)

Table C-3. Emergy evaluation of pig iron from blast furnace process in the United States, 1996.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Iron ore	g	8.62E+11	1.22E+09	10.52
2	Pellets	g	6.49E+13	1.48E+09	960.52
3	Sinter	g	1.16E+13	1.99E+09	230.84
4	Scrap	g	1.70E+12	1.99E+09	33.83
5	Coal/Coke	J	2.98E+17	4.00E+04	119.21
6	Labor	$	7.72E+09	1.20E+12	92.70
7	Annual Yield pig iron (with services)	g	5.12E+13	2.83E+09	1447.61
	Annual Yield pig iron (without services)	g	5.12E+13	2.65E+09	1354.92
8	Annual Yield byproduct slag (with services)	g	2.05E+13	7.06E+09	1447.61
	Annual Yield byproduct slag (without services)	g	2.05E+13	6.61E+09	1354.92

300 Btu/lb of ferrous metal (696 J/g) (Tchobanoglous et al, 1993, p.85; Odum et al., 1987b, p.164)

Footnotes:

1 Iron ore (USGS: Iron and steel, 1996, Table 2)
(862000 metric tons/yr)(1000000 g/metric ton)
= 8.62E+11 g
Transformity 1.22E+09 sej/g using (This study, Table C-4)
3.55E+10 sej/g from sources within US (Odum, 1996, p. 186)
8.60E+08 sej/g imported and outside US (Odum, 1996, p. 186)

2 Pellets (USGS: Iron and steel, 1996, Table 2)
(64900000 metric tons/yr)(1000000 g/metric ton)
= 6.49E+13 g
Transformity 1.48E+09 sej/g (This study, Table C-5)

3 Sinter (USGS: Iron and steel, 1996, Table 2)
(11600000 metric tons/yr)(1000000 g/metric ton)
= 1.16E+13 g
Transformity 1.99E+09 sej/g (This study, Table C-6)

4 Scrap (USGS: Iron and steel, 1996, Table 2)
(1700000 metric tons/yr)(1000000 g/metric ton)
= 1.7E+12 g
Transformity 1.99E+09 sej/g using iron sinter (This study, Table C-6)

Table C-3--continued.

5 Coal/Coke (USGS: Iron and steel, 1996, Table 2)
(20700000 metric tons/yr)(7000000 kcal/ton)(4186 J/kcal)
= 2.98E+17 J
Transformity 40000 Sej/J (Odum, 1996, p. 310)

6 Labor 166000 employees in Blast furnace and steel mills (USGS: Iron and Steel, p.86)
127000 employees in Iron and steel foundries (USGS: Iron and Steel, p.86)
(293000 employees/yr 1996)(2E+10 J/person/yr)
= 5.86E+15 J

507 $/week (Statistical Abstract, 1995, Table 666, p.424)
(293000 employees)(507 $/week)(52 weeks/yr)
= 7.725E+09 $
Transformity 1.20E+12 sej/$ for US in 1996 (Projected from Odum, 1996, Table D.1, p. 313-315)

7 Annual Yield of Pig Iron (USGS: Iron and steel, 1996, Table 2)
(51200000 metric tons/yr 1996)(1000000 g/metric ton)
= 5.12E+13 g $ 73 billion/yr 1996 (USGS: Iron and steel, 1996, p.86)

8 Byproduct Iron and Steel Slag (USGS: Iron and steel slag, 1996, Table 1)
(20500000 metric tons/yr 1996)(1000000 g/metric ton)
= 2.05E+13 g

141 million $/yr 1996 (USGS: Iron and steel slag, 1996, Table 1)
$6.90 /tonne (USGS: Iron and steel slag, 1996, Table 2)
Transported by truck 16500000 tonnes, rail 1000000 tonnes, and waterway 1010000 tonnes(USGS: Iron and steel slag, 1996, Table 7)
220 to 370 kg of slag per tonne of pig iron (USGS: Iron and steel slag, 1996, p.1)

Table C-4. Emergy evaluation of iron ore in the United States, 1975. *

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+14
1	Iron ore rock	g	9.07E+05	1.00E+09	9.07
2	Natural gas	J	1.51E+05	4.80E+04	0.0001
3	Diesel oil	J	2.34E+07	6.60E+04	0.02
4	Gasoline	J	1.32E+06	6.60E+04	0.0009
5	Explosives	J	2.21E+07	1.86E+06	0.41
6	Electricity	J	9.00E+07	1.74E+05	0.16
7	Transport (Boat)	ton-mile	1.15E+03	1.17E+11	1.35
8	Transport (Railroad)	ton-mile	1.75E+02	5.07E+10	0.09
9	Labor	$	0.00E+00	6.00E+12	
10	Iron Ore Yield (without services)	g	9.07E+05	1.22E+09	11.09

* Data from (Oak Ridge, 1980), without services, evaluated based on 1 short ton produced.

*** 14.2 J/g of iron ore (Odum, 1996, p.302)

Footnotes:

1 Iron ore rock 1 short ton of iron ore (Oak Ridge, 1980, Table 8.17, p. 8-20)
(1 short ton)(907000 g/short ton)
= 907000 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p. 310)

2 Natural gas 0.143 cu. ft./ton (Oak Ridge, 1980, Table 8.17, p. 8-20)
(1 short ton)(0.143 cu. ft./ton)(1000 Btu/cu. ft.)(1054 J/Btu)
= 150722 J
Transformity 4.80E+04 Sej/J (Odum, 1996, p. 308)

3 Diesel oil 0.16 gal/ton (Oak Ridge, 1980, Table 8.17, p. 8-20)
(1 short ton)(0.16 gal/ton)(139000 Btu/gal)(1054 J/Btu)
= 23440960 J
Transformity 6.60E+04 Sej/J (Odum, 1996, p. 308)

4 Gasoline 0.01 gal/ton (Oak Ridge, 1980, Table 8.17, p. 8-20)
(1 short ton)(0.01 gal/ton)(125000 Btu/gal)(1054 J/Btu)
= 1317500 J
Transformity 6.60E+04 Sej/J (Odum, 1996, p. 308)

Table C-4--continued.

5	Explosives	0.7 lb/ton, 30000 Btu/lb (Oak Ridge, 1980, Table 8.17, p. 8-20)	
		(1 short ton)(0.7 lb/ton)(30000 Btu/lb)(1054 J/Btu)	
		= 22134000 J	317.8 g
	Transformity	1.86E+06 Sej/J	using ammonia fertilizer (Odum, 1996, p.310)
		3.8E+09 Sej/g	ammonia fertilizer (Odum, 1996, p.310)
6	Electricity	25 kWh/ton (Oak Ridge, 1980, Table 8.17, p. 8-20)	
		(1 short ton)(25 kWh/ton)(3600000 J/kWh)	
		= 90000000 J	
	Transformity	174000 Sej/J	(Odum, 1996, p. 305)
7	Transport (Boat)	1150 ton-mile/ton, 250 Btu/ton-mile (Oak Ridge, 1980, Table 8.17, p. 8-20)	
		(1 short ton)(1150 ton-mile/ton)	
		= 1150 ton-mile	
	Transformity	1.17E+11 Sej/ton-mile	(This study, Table E-3)
8	Transport (Railroad)	175 ton-mile/ton, 670 Btu/ton-mile (Oak Ridge, 1980, Table 8.17, p. 8-20)	
		(1 short ton)(175 ton-mile/ton)	
		= 175 ton-mile	
	Transformity	5.07E+10 Sej/ton-mile	(This study, Table E-2)
9	Labor	no data	
		= $	
	Transformity	6.00E+12 Sej/$	for US in 1975 (Odum, 1996, Table D.1, p. 313-315)
10	Iron Ore Yield	1 short ton of iron ore (Oak Ridge, 1980, Table 8.17, p. 8-20)	
		(1 short ton)(907000 g/short ton)	
		= 907000 g	

Table C-5. Emergy evaluation of iron ore pellets in the United States, 1975. *

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+14
1	Iron ore rock	g	9.07E+05	1.00E+09	9.07
2	Balls, rods, and liners	g	9.08E+03	6.70E+09	0.61
3	Bentonite	J	1.01E+07	3.45E+04	0.0035
4	Natural gas	J	2.90E+08	4.80E+04	0.14
5	Diesel oil	J	9.24E+07	6.60E+04	0.04
6	Gasoline	J	5.14E+06	6.60E+04	0.0034
7	Fuel oil	J	2.37E+08	6.60E+04	0.16
8	Explosives	J	1.11E+08	1.86E+06	2.06
9	Electricity	J	4.30E+08	1.74E+05	0.75
10	Transport (Boat)	ton-mile	1.25E+02	1.17E+11	0.15
11	Transport (Railroad)	ton-mile	9.00E+02	5.07E+10	0.46
12	Labor	$	0.00E+00	6.00E+12	
13	Iron Ore Pellets Yield (without services)	g	9.07E+05	1.48E+09	13.44

* Data from (Oak Ridge, 1980), without services, evaluated based on 1 short ton produced.
300 Btu/lb of ferrous metal (696 J/g) (Tchobanoglous et al, 1993, p.85; Odum et al., 1987b, p.164)

Footnotes:

1 Iron ore rock 1 short ton of iron ore (Oak Ridge, 1980, Table 8.18, p. 8-21)
(1 short ton)(907000 g/short ton)
= 907000 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p. 310)

2 Balls, rods, and liners 20 lb/ton, 17500 Btu/lb (Oak Ridge, 1980, Table 8.18, p. 8-21)
(1 short ton)(20 lb/ton)(454 g/lb)
= 9080 g
Transformity 6.7E+09 Sej/g using machinery (Odum et al., 1987b, Table 1, p. 4)

3 Bentonite 16 lb/ton, 600 Btu/lb (Oak Ridge, 1980, Table 8.18, p. 8-21)
(1 short ton)(16 lb/ton)(600 Btu/lb)(1054 J/Btu)
= 10118400 J
Transformity 3.45E+04 Sej/J using chemical products (Odum et al, 1983, Table 11.1, p. 207-215)

4 Natural gas 275 cu. ft./ton (Oak Ridge, 1980, Table 8.18, p. 8-21)
(1 short ton)(275 cu. ft./ton)(1000 Btu/cu.ft.)(1054 J/Btu)
= 289850000 J
Transformity 4.80E+04 Sej/J (Odum, 1996, p. 308)

Table C-5--continued.

5	Diesel oil	0.631 gal/ton (Oak Ridge, 1980, Table 8.18, p. 8-21)	
		(1 short ton)(0.631 gal/ton)(139000 Btu/gal)(1054 J/Btu)	
		= 92445286 J	
	Transformity	6.60E+04 Sej/J	(Odum, 1996, p. 308)
6	Gasoline	0.039 gal/ton (Oak Ridge, 1980, Table 8.18, p. 8-21)	
		(1 short ton)(0.039 gal/ton)(125000 Btu/gal)(1054 J/Btu)	
		= 5138250 J	
	Transformity	6.60E+04 Sej/J	(Odum, 1996, p. 308)
7	Fuel oil	1.5 gal/ton (Oak Ridge, 1980, Table 8.18, p. 8-21)	
		(1 short ton)(1.5 gal/ton)(150000 Btu/gal)(1054 J/Btu)	
		= 237150000 J	
	Transformity	6.60E+04 Sej/J	(Odum, 1996, p. 308)
8	Explosives	3.5 lb/ton (Oak Ridge, 1980, Table 8.18, p. 8-21)	
		(1 short ton)(3.5 lb/ton)(30000 Btu/lb)(1054 J/Btu)	
		= 110670000 J	
	Transformity	1.86E+06 Sej/J	using ammonia fertilizer (Odum, 1996, p.310)
		3.8E+09 Sej/g	ammonia fertilizer (Odum, 1996, p.310)
9	Electricity	119.56 kWh/ton (Oak Ridge, 1980, Table 8.18, p. 8-21)	
		(1 short ton)(119.56 kWh/ton)(3600000 J/kWh)	
		= 430416000 J	
	Transformity	174000 Sej/J	(Odum, 1996, p. 305)
10	Transport (Boat)	125 ton-mile/ton, 250 Btu/ton-mile (Oak Ridge, 1980, Table 8.18, p. 8-21)	
		(1 short ton)(125 ton-mile/ton)	
		= 125 ton-mile	
	Transformity	1.17E+11 Sej/ton-mile	(This study, Table E-3)
11	Transport (Railroad)	900 ton-mile/ton, 670 Btu/ton-mile (Oak Ridge, 1980, Table 8.18, p. 8-21)	
		(1 short ton)(900 ton-mile/ton)	
		= 900 ton-mile	
	Transformity	5.07E+10 Sej/ton-mile	(This study, Table E-2)
12	Labor	no data	
		= $	
	Transformity	6.00E+12 Sej/$	for US in 1975 (Odum, 1996, Table D.1, p. 313-315)
13	Iron Ore Pellets Yield	1 short ton of iron ore (Oak Ridge, 1980, Table 8.18, p. 8-21)	
		(1 short ton)(907000 g/short ton)	
		= 907000 g	

Table C-6. Emergy evaluation of iron ore sinter in the United States, 1975. *

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+14
1	Iron ore fines	g	5.53E+05	1.00E+09	5.53
2	Returns	g	2.42E+05	1.00E+09	2.42
3	Flue dust and fines	g	1.30E+05	1.00E+09	1.30
4	Mill scale	g	1.11E+05	6.70E+09	7.41
5	Limestone	g	4.44E+04	1.00E+09	0.44
6	Coke breeze	J	1.64E+09	4.00E+04	0.66
7	Natural gas	J	1.58E+08	4.80E+04	0.08
8	Electricity	J	1.08E+08	1.74E+05	0.19
9	Labor	$	0.00E+00	6.00E+12	
10	Iron Ore Sinter Yield (without services)	g	9.07E+05	1.99E+09	18.03

* Data from (Oak Ridge, 1980), without services, evaluated based on 1 short ton produced.
300 Btu/lb of ferrous metal (696 J/g) (Tchobanoglous et al, 1993, p.85; Odum et al., 1987b, p.164)

Footnotes:

1 Iron ore fines 0.61 ton/ton, 440000 Btu/ton (Oak Ridge, 1980, Table 8.19, p. 8-22)
(1 short ton)(0.61 ton/ton)(907000 g/ton)
= 553270 g
Transformity 1.00E+09 Sej/g

2 Returns 0.267 ton/ton (Oak Ridge, 1980, Table 8.19, p. 8-22)
(1 short ton)(0.267 ton/ton)(907000 g/ton)
= 242169 g
Transformity 1.00E+09 Sej/g

3 Flue dust and fines 0.143 ton/ton (Oak Ridge, 1980, Table 8.19, p. 8-22)
(1 short ton)(0.143 ton/ton)(907000 g/ton)
= 129701 g
Transformity 1.00E+09 Sej/g

4 Mill scale 0.122 ton/ton (Oak Ridge, 1980, Table 8.19, p. 8-22)
(1 short ton)(0.122 ton/ton)(907000 g/ton)
= 110654 g
Transformity 6.7E+09 Sej/g using machinery (Odum et al., 1987b, Table 1, p. 4)

Table C-6--continued.

5 Limestone 0.049 ton/ton (Oak Ridge, 1980, Table 8.19, p. 8-22)
(1 short ton)(0.049 ton/ton)(907000 g/ton)
= 44443 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p. 310)

6 Coke breeze 0.074 ton/ton (Oak Ridge, 1980, Table 8.19, p. 8-22)
(1 short ton)(0.074 ton/ton)(21000000 Btu/ton)(1054 J/Btu)
= 1.638E+09 J
Transformity 40000 Sej/J (Odum, 1996, p. 310)

7 Natural gas 150 cu.ft./ton (Oak Ridge, 1980, Table 8.19, p. 8-22)
(1 short ton)(150 cu.ft./ton)(1000 Btu/cu.ft.)(1054 J/Btu)
= 158100000 J
Transformity 4.80E+04 Sej/J (Odum, 1996, p. 308)

8 Electricity 30 kWh/ton (Oak Ridge, 1980, Table 8.19, p. 8-22)
(1 short ton)(30 kWh/ton)(3600000 J/kWh)
= 108000000 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

9 Labor no data

= $
Transformity 6.00E+12 Sej/$ for US in 1975 (Odum, 1996, Table D.1, p. 313-315)

10 Annual Yield of Sinter
(1 short ton)(907000 g/ton)
= 907000 g

Table C-7. Emergy evaluation of primary aluminum in the United States, 1991-92.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Bauxite	g	8.93E+10	8.55E+08	0.76
2	Alumina	g	1.00E+13	8.55E+08	85.68
3	Natural gas	J	2.34E+16	4.80E+04	11.25
4	LP gas	J	1.77E+13	7.00E+04	0.01
5	Fuel	J	7.99E+14	6.60E+04	0.53
6	Electricity	J	2.17E+17	1.74E+05	377.55
7	Labor	$	8.06E+08	1.43E+12	11.52
8	Annual Yield aluminum ingot (with services)	g	4.17E+12	1.17E+10	487.30
	Annual Yield aluminum ingot (without services)	g	4.17E+12	1.14E+10	475.78
9	Yield co-product aluminum billet (with services)	g	7.03E+11	6.93E+10	487.30
	Yield co-product aluminum billet (without services)	g	7.03E+11	6.77E+10	475.78

Aluminum ore (Bauxite) 65.3 J/g (Odum, 1996, p.302)

Footnotes:

1 Bauxite (Census of Manufactures 1992: Smelting and Refining of Nonferrous Metals and Alloys, Table 7, p.33C-20,21,22)
(98500 short tons/yr 1992)(907000 g/short ton)
= 8.934E+10 g
Transformity 8.55E+08 Sej/g (Odum, 1996, p.187)
1.63E+10 Sej/g aluminum ingots (Odum et al, 1983, Table 3.1, p. 40-45)

2 Alumina (Census of Manufactures 1992: Smelting and Refining of Nonferrous Metals and Alloys, Table 7, p.33C-20,21,22)
(11048300 short tons/yr 1992)(907000 g/short ton)
= 1.002E+13 g
Transformity 8.55E+08 Sej/g (Odum, 1996, p.187)

3 Natural gas (DOE: Manufacturing Consumption of Energy, 1991, Table A-38)
(20 billion cu.ft./yr)(1112 Btu/cu.ft.)(1054 J/Btu)
= 2.344E+16 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)

4 LP gas (DOE: Manufacturing Consumption of Energy, 1991, Table A-38)
(42000 bbl/yr)(42 gal/bbl)(2400 kcal/gal)(4186 J/kcal)
= 1.772E+13 J
Transformity 70000 Sej/J (Odum et al, 1983, Table 14.1, p. 276-282)

Table C-7--continued.

5 Fuel (DOE: Manufacturing Consumption of Energy, 1991, Table A-38)
(127000 bbl/yr)(6289000000 J/bbl)
= 7.987E+14 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

6 Electricity (Census of Manufactures 1992: Smelting and Refining of Nonferrous Metals and Alloys, Table 3a, p.33C-10)
(60272.4 million kWh/yr)(3.6 E+06 J/kWh)
= 2.17E+17 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

7 Labor (Census of Manufactures 1992: Smelting and Refining of Nonferrous Metals and Alloys, Table 3a, p.33C-10)
(20400 employees)(2E+10 J/yr)
= 4.08E+14 J

(Census of Manufactures 1992: Smelting and Refining of Nonferrous Metals and Alloys, Table 3a, p.33C-10)
(805.9 million $/yr 1992)
= 805900000 $
Transformity 1.43E+12 Sej/$ for US in 1992 (Odum, 1996, Table D.1, p. 313-315)

8 Annual Yield of Aluminum ingot (Primary production)
(Census of Manufactures 1992: Smelting and Refining of Nonferrous Metals and Alloys, Table 6a-1, p.33C-15)
(4598400 short tons/yr 1994)(907000 g/short ton)
= 4.171E+12 g
(Census of Manufactures 1992: Smelting and Refining of Nonferrous Metals and Alloys, Table 3a, p.33C-10)
5848.9 million $/yr 1992 value of shipments
1609.8 million $/yr 1992 value added

9 Annual Yield of Aluminum extrusion ingot (billet)
(co-product) (Census of Manufactures 1992: Smelting and Refining of Nonferrous Metals and Alloys, Table 6a-1, p.33C-15)
(775200 short tons/yr 1994)(907000 g/short ton)
= 7.031E+11 g

Table C-8. Emergy evaluation of plastics in the United States, 1991-92.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Organic chemicals	g	9.67E+12	3.80E+08	36.73
2	Refined petroleum	J	4.33E+17	6.60E+04	285.67
3	Plastic scrap	g	7.50E+12	5.76E+09	432.00
4	Coal	J	3.42E+16	4.00E+04	13.66
5	Natural gas	J	1.71E+17	4.80E+04	82.14
6	LP gas	J	2.28E+13	7.00E+04	0.02
7	Fuel	J	5.65E+15	6.60E+04	3.73
8	Electricity	J	5.32E+16	1.74E+05	92.58
9	Labor	$	2.67E+09	1.43E+12	38.20
10	Annual Yield plastics (with services)	g	3.01E+13	3.28E+09	984.74
11	Annual Yield plastics (without services)	g	3.01E+13	3.15E+09	946.53

14000 Btu/lb (30.84 Btu/g) of energy content of plastics (Tchobanoglous et al, 1993, Table 4-5, p.84)

Footnotes:

1 Organic chemicals (Census Manufactures: Plastics, 1992, Table 7, p.28B-18)
(21291 million lb/yr)(454 g/lb)
= 9.66611E+12 g
Transformity 3.80E+08 Sej/g using chemical (Brown et al, 1992, Table A1)

2 Refined petroleum (Census Manufactures: Plastics, 1992, Table 7, p.28B-18)
(29333 million lb/yr)(14000 Btu/lb)(1054 J/Btu)
= 4.32838E+17 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

3 Plastic scrap 25% of production is internal plastic scrap (Modern Plastics, 1995, p.A-21)
(0.25)(30E+12 g/yr)
= 7.5E+12 g
Transformity 5.76E+09 Sej/g (This study, Table C-11)

4 Coal (DOE, 1991, Table A36, p. 216)
(1074000 short tons/yr)(3.18E+10 J/short ton)
= 3.41532E+16 J
Transformity 40000 Sej/J (Odum, 1996, p. 310)

5 Natural gas (DOE, 1991, Table A36, p. 216)
(146E+9 cu.ft./yr)(1112 Btu/cu.ft.)(1054 J/Btu)
= 1.71119E+17 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)

Table C-8--continued.

6 LP gas (DOE, 1991, Table A36, p. 216)
(54000 bbls/yr)(42 gal/bbl)(2400 kcal/gal)(4186 J/kcal)
= 2.27852E+13 J
Transformity 70000 Sej/J (Odum et al, 1983, Table 14.1, p. 276-282)

7 Fuel (DOE, 1991, Table A36, p. 216)
(899000 bbls/yr)(6289000000 J/bbl)
= 5.65381E+15 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

8 Electricity (DOE, 1991, Table A36, p. 216)
(14780E+6 kWh/yr)(3.6 E+06 J/kWh)
= 5.32E+16 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

9 Labor 60400 employees/yr 1992 (Census Manufactures: Plastics, 1992, p.28B-3)
(60400 employees)(2E+10 J/yr)
= 1.208E+15 J

2671.6 million $/1992 (Census Manufactures: Plastics, 1992, Table 1a, p.28B-7)
= 2.67E+09 $
Transformity 1.43E+12 Sej/$ for US in 1992 (Odum, 1996, Table D.1, p. 313-315)

10 Annual Yield of Plastics materials and resins
(30.061E+6 metric tons/yr 1992)(1000000 g/metric ton)
= 3.0061E+13 g (Modern Plastics, 1995, p. A-16, A-17)

Table C-9. Emergy evaluation of polyvinyl chloride (PVC) in Europe, 1993.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+10
1	Sand	g	1.20	2.00E+09	0.24
2	Limestone	g	1.60	1.00E+09	0.16
3	Bauxite	g	0.22	8.55E+08	0.02
4	Iron ore	g	0.40	8.60E+08	0.03
5	Sodium chloride	g	690.00	1.10E+09	75.90
6	Water	J	9386.00	4.80E+04	0.05
7	Other fuels	J	32880000.00	4.80E+04	157.82
8	Oil fuels	J	22020000.00	6.60E+04	145.33
9	Electricity	J	11900000.00	1.74E+05	207.06
10	Labor	$	0	1.37E+12	
11	Annual Yield PVC (without services)	g	1000.00	5.87E+09	586.61
12	Byproduct Yield mineral waste	g	66.00	8.89E+10	586.61
13	Byproduct Yield slags & ash	g	47.00	1.25E+11	586.61

* without services, data based on 1 kilogram of plastics produced.

14000 Btu/lb (30.84 Btu/g) of energy content of plastics (Tchobanoglous et al, 1993, Table 4-5, p.84)

Footnotes:

1 Sand 1200 mg (Boustead, 1994, Table 31, p.22)
(1200 mg)(0.001 g/mg)
= 1.2 g
Transformity 2.00E+09 Sej/g (Odum, 1996, p.310)

2 Limestone 1600 mg (Boustead, 1994, Table 31, p.22)
(1600 mg)(0.001 g/mg)
= 1.6 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)

3 Bauxite 220 mg (Boustead, 1994, Table 31, p.22)
(220 mg)(0.001 g/mg)
= 0.22 g
Transformity 8.55E+08 Sej/g (Odum, 1996, p. 187)

4 Iron ore 400 mg (Boustead, 1994, Table 31, p.22)
(400 mg)(0.001 g/mg)
= 0.4 g
Transformity 8.60E+08 sej/g (Odum, 1996, p. 186)

Table C-9--continued.

5	Sodium chloride	690000 mg (Boustead, 1994, Table 31, p.22)
		(690000 mg)(0.001 g/mg)
		= 690 g
	Transformity	1.10E+09 Sej/g using potassium fertilizer (Odum, 1996, p.310)
		3.80E+09 Sej/g ammonia fertilizer (Odum, 1996, p.310)
6	Water	1900000 mg (Boustead, 1994, Table 31, p.22)
		(1900000 mg)(0.001 g/mg)(4.94 J/g)
		= 9386 J
	Transformity	48000 Sej/J (Odum, 1996, p.120)
7	Other fuels	mostly gas 32.88 MJ (12.71 MJ feedstock gas) (Boustead, 1994, Table 30,31, p.22)
		(32.88 MJ)(1000000 J/MJ)
		= 32880000 J
	Transformity	48000 Sej/J (Odum, 1996, p. 308)
8	Oil fuels	22.02 MJ (16.85 MJ feedstock) (Boustead, 1994, Table 30,31, p.22)
		(22.02 MJ)(1000000 J/MJ)
		= 22020000 J
	Transformity	66000 Sej/J (Odum, 1996, p. 308)
9	Electricity	11.9 MJ (Boustead, 1994, Table 30, p.22)
		(11.9 MJ)(1000000 J/MJ)
		= 11900000 J
	Transformity	174000 Sej/J (Odum, 1996, p. 305)
10	Labor	no labor data
		= $
	Transformity	1.37E+12 Sej/$ for US in 1993 (Odum, 1996, Table D.1, p. 313-315)
11	Annual Yield of Polyvinyl Chloride in Europe	
		1 kilogram (Boustead, 1994, Table 31, p.22)
		(1 kg.)(1000 g/kg.)
		= 1000 g
12	Annual Yield of Mineral waste	
	(byproduct)	66000 milligrams (Boustead, 1994, Table 31, p.22)
		(66000 mg.)(0.001 g/mg)
		= 66 g
13	Annual Yield of Slags & ash	
	(byproduct)	47000 milligrams (Boustead, 1994, Table 31, p.22)
		(47000 mg.)(0.001 g/mg)
		= 47 g

Table C-10. Emergy evaluation of high density polyethylene (HDPE) in Europe, 1993.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+10
1	Clay	g	0.02	2.00E+09	0.0004
2	Limestone	g	0.20	1.00E+09	0.02
3	Bauxite	g	0.20	8.55E+08	0.02
4	Iron ore	g	0.30	8.60E+08	0.03
5	Sodium chloride	g	4.00	1.10E+09	0.44
6	Water	J	46930.00	4.80E+04	0.23
7	Other fuels	J	39500000.00	4.80E+04	189.60
8	Oil fuels	J	35690000.00	6.60E+04	235.55
9	Electricity	J	5790000.00	1.74E+05	100.75
10	Labor	$	0	1.37E+12	
11	Annual Yield HDPE (with services)	g	1000.00	5.27E+09	526.63
12	Byproduct Yield mineral waste	g	18.00	2.93E+11	526.63
13	Byproduct Yield slags & ash	g	5.00	1.05E+12	526.63

* without services, data based on 1 kilogram of plastics produced.

14000 Btu/lb (30.84 Btu/g) of energy content of plastics (Tchobanoglous et al, 1993, Table 4-5, p.84)

Footnotes:

1 Clay 20 mg (Boustead, 1993, Table 20, p.13)
(20 mg)(0.001 g/mg)
= 0.02 g
Transformity 2.00E+09 Sej/g (Odum, 1996, p.310)

2 Limestone 200 mg (Boustead, 1993, Table 20, p.13)
(200 mg)(0.001 g/mg)
= 0.2 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)

3 Bauxite 200 mg (Boustead, 1993, Table 20, p.13)
(200 mg)(0.001 g/mg)
= 0.2 g
Transformity 8.55E+08 Sej/g (Odum, 1996, p.187)

4 Iron ore 300 mg (Boustead, 1993, Table 20, p.13)
(300 mg)(0.001 g/mg)
= 0.3 g
Transformity 8.60E+08 sej/g (Odum, 1996, p. 186)

Table C-10--continued.

5 Sodium chloride 4000 mg (Boustead, 1993, Table 20, p.13)
(4000 mg)(0.001 g/mg)
= 4 g
Transformity 1.10E+09 Sej/g using potassium fertilizer (Odum, 1996, p.310)
3.80E+09 Sej/g ammonia fertilizer (Odum, 1996, p.310)

6 Water 9500000 mg (Boustead, 1993, Table 20, p.13)
(9500000 mg)(0.001 g/mg)(4.94 J/g)
= 46930 J
Transformity 48000 Sej/J (Odum, 1996, p.120)

7 Other fuels mostly gas 39.5 MJ (30.48 MJ feedstock gas) (Boustead, 1993, Table 18,20, p.12,13)
(39.5 MJ)(1000000 J/MJ)
= 39500000 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)

8 Oil fuels 35.69 MJ (33.56 MJ feedstock) (Boustead, 1993, Table 18,20, p.12,13)
(35.69 MJ)(1000000 J/MJ)
= 35690000 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

9 Electricity 5.79 MJ (Boustead, 1993, Table 18, p.12)
(5.79 MJ)(1000000 J/MJ)
= 5790000 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

10 Labor no labor data

= $
Transformity 1.37E+12 Sej/$ for US in 1993 (Odum, 1996, Table D.1, p. 313-315)

11 Annual Yield of High Density Polyethylene in Europe
1 kilogram (Boustead, 1993, Table 20, p.13)
(1 kg.)(1000 g/kg.)
= 1000 g

12 Annual Yield of Mineral waste
(byproduct) 18000 milligrams (Boustead, 1993, Table 20, p.13)
(18000 mg.)(0.001 g/mg)
= 18 g

13 Annual Yield of Slags & ash
(byproduct) 5000 milligrams (Boustead, 1993, Table 20, p.13)
(5000 mg.)(0.001 g/mg)
= 5 g

Table C-11. Emergy evaluation of Polyethylene (All Grades) in Europe, 1993. *

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+10
1	Clay	g	0.02	2.00E+09	0.0040
2	Limestone	g	0.15	1.00E+09	0.02
3	Bauxite	g	0.30	8.55E+08	0.03
4	Iron ore	g	0.20	8.60E+08	0.02
5	Sodium chloride	g	7.00	1.10E+09	0.77
6	Water	J	88920.00	4.80E+04	0.43
7	Other fuels	J	42600000.00	4.80E+04	204.48
8	Oil fuels	J	35340000.00	6.60E+04	233.24
9	Electricity	J	7890000.00	1.74E+05	137.29
10	Labor	$	0.00	1.37E+12	
11	Annual Yield (without services)	g	1000.00	5.76E+09	576.27
12	Byproduct Yield (mineral waste) (without services)	g	22.00	2.62E+11	576.27
13	Byproduct Yield (slags & ash) (without services)	g	7.00	8.23E+11	576.27

* without services, data based on 1 kilogram of plastics produced.

14000 Btu/lb (30.84 Btu/g) of energy content of plastics (Tchobanoglous et al, 1993, Table 4-5, p.84)

Footnotes:

1 Clay 20 mg (Boustead, 1993, Table 13, p.9)
(20 mg)(0.001 g/mg)
= 0.02 g
Transformity 2.00E+09 Sej/g (Odum, 1996, p.310)

2 Limestone 150 mg (Boustead, 1993, Table 13, p.9)
(150 mg)(0.001 g/mg)
= 0.15 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)

3 Bauxite 300 mg (Boustead, 1993, Table 13, p.9)
(300 mg)(0.001 g/mg)
= 0.3 g
Transformity 8.55E+08 Sej/g (Odum, 1996, p187)
4 Iron ore 200 mg (Boustead, 1993, Table 13, p.9)
(200 mg)(0.001 g/mg)
= 0.2 g
Transformity 8.60E+08 sej/g (Odum, 1996, p. 186)
1.32E+09 sej/g (This study, Table C-4)

Table C-11--continued.

5 Sodium chloride 7000 mg (Boustead, 1993, Table 13, p.9)
(7000 mg)(0.001 g/mg)
= 7 g
Transformity 1.10E+09 Sej/g using potassium fertilizer (Odum, 1996, p.310)
3.80E+09 Sej/g ammonia fertilizer (Odum, 1996, p.310)

6 Water 18000000 mg (Boustead, 1993, Table 13, p.9)
(18000000 mg)(0.001 g/mg)(4.94 J/g)
= 88920 J
Transformity 48000 Sej/J (Odum, 1996, p.120)

7 Other fuels mostly gas 42.6 MJ (33.59 MJ feedstock gas) (Boustead, 1993, Table 12,13, p.8,9)
(42.6 MJ)(1000000 J/MJ)
= 42600000 J
Transformity 48000 Sej/J (Odum, 1996, p. 308)

8 Oil fuels 35.34 MJ (32.76 MJ feedstock) (Boustead, 1993, Table 12,13, p.8,9)
(35.34 MJ)(1000000 J/MJ)
= 35340000 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

9 Electricity 7.89 MJ (Boustead, 1993, Table 12, p.8)
(7.89 MJ)(1000000 J/MJ)
= 7890000 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

10 Labor no labor data

= $
Transformity 1.37E+12 Sej/$ for US in 1993 (Odum, 1996, Table D.1, p. 313-315)

11 Annual Yield of Polyethylene in Europe
1 kilogram (Boustead, 1993, Table 13, p.9)
(1 kg.)(1000 g/kg.)
= 1000 g

12 Annual Yield of Mineral waste
(byproduct) 22000 milligrams (Boustead, 1993, Table 13, p.9)
(22000 mg.)(0.001 g/mg)
= 22 g

13 Annual Yield of Slags & ash
(byproduct) 7000 milligrams (Boustead, 1993, Table 13, p.9)
(7000 mg.)(0.001 g/mg)
= 7 g

Table C-12. Emergy evaluation of flat glass in the United States, 1987.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Sand	g	2.26E+12	1.00E+09	22.60
2	Soda ash	g	8.14E+11	3.80E+08	3.09
3	Glass	g	9.64E+09	4.74E+09	0.46
4	Fuel	J	1.83E+16	6.60E+04	12.11
5	Electricity	J	5.95E+15	1.74E+05	10.36
6	Labor	$	5.07E+08	1.80E+12	9.12
7	Annual Yield flat glass (with services)	g	3.03E+12	1.90E+09	57.74
8	Annual Yield flat glass (without services)	g	3.03E+12	1.60E+09	48.62

60 Btu/lb (0.132 Btu/g) of energy content of glass (Tchobanoglous et al, 1993, Table 4-5, p.84)

Footnotes:

1 Sand (Census of Manufactures, 1987, Table 7, p.32A-19)
(2491600 short tons/yr)(907000 g/short ton)
= 2.25988E+12 g
Transformity 1.00E+09 Sej/g (Odum, 1996, p.310)

2 Soda ash (Na_2CO_3) (Census of Manufactures, 1987, Table 7, p.32A-19)
(897200 tons/yr)(907000 g/short ton)
= 8.1376E+11 g
Transformity 3.80E+08 Sej/g using chemical transformity (Brown et al, 1992, Table A1)

3 Glass (float, sheet, plate) (Census of Manufactures, 1987, Table 7, p.32A-19)
(129.5 million sq.ft./yr)(1.64 lb/sq.ft. 1/8")(454 g/lb)
= 9642052000 g
Transformity 4.74E+09 Sej/g updated flat glass (Haukoos, 1995, Table A-16, p.180-182)
8.44E+08 Sej/g MSW glass (Odum et al., 1987a, p. 159)

4 Fuel 135.1 million $ (Census of Manufactures 1987: Glass Products, Table 3a, p. 32A-8,9)
0.97 $/gal, 1987 (Statistical Abstract 1997, Table 932, p. 588; Statistical Abstract 1995, Table 770, p.504)
[(135.1E+6 $/yr 1987)/(0.97 $/gal)]*(125000 Btu/gal)(1054 J/Btu)
= 1.83499E+16 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

Table C-12--continued.

5 Electricity (Census of Manufactures 1987: Glass Products, Table 3a, p. 32A-8,9)
(1653.5E+6 kWh/yr 1987)(3.6 E+06 J/kWh)
= 5.95E+15 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

6 Labor (Census of Manufactures 1987: Glass Products, Table 3a, p. 32A-8,9)
(14600 employees)(2E+10 J/person/yr)
= 2.92E+14 J

(Census of Manufactures 1987: Glass Products, Table 3a, p. 32A-8,9)
(506.7 million $/yr 1987)
= 506700000 $
Transformity 1.80E+12 Sej/$ for US in 1987 (Odum, 1996, Table D.1, p. 313-315)

7 Annual Yield of Flat Glass (Census of Manufactures, 1987, Table 6a-2, p. 32A-14)
(4073.9 million sq.ft/yr)(1.64 lb/sq.ft. 1/8")(454 g/lb)
= 3.03326E+12 g
(Census of Manufactures 1987: Glass Products, Table 3a, p. 32A-8,9)
2549.3 million $/yr 1987 value of shipments
1618.4 million $/yr 1987 value of added

Table C-13. Emergy evaluation of brick and structural clay tile in the United States, 1977.*

Note	Item	Unit	Input Resource Energy	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Clay	g	8.98E+12	2.00E+09	179.52
2	Water	J	1.96E+13	4.80E+04	0.01
3	Oil	J	2.32E+16	6.60E+04	15.32
4	Electricity	J	2.81E+15	1.74E+05	4.88
5	Labor	$	1.97E+08	4.40E+12	8.68
6	Annual Yield (with services)	g	8.98E+12	2.32E+09	208.42
7	Annual Yield (without services)	g	8.98E+12	2.23E+09	199.74

Footnotes:

1 Clay
9894400 short tons (Census of Manufactures: Cement and Structural Clay Products, 1977, Table 7, p. 32B-23)
(9894400 short tons/yr)(907200 g/short ton)
= 8.9762E+12 g
19 million $ (Census of Manufactures: Cement and Structural Clay Products, 1977, Table 7, p. 32B-23)
Transformity 2.00E+09 Sej/g (Odum, 1996, p.310)

2 Water
1 lb per brick, 25% by weight of brick (ERG: Brick and mortar, 1996, p. 22)
(8722.4 million bricks)(1 lb/brick)(454 g/lb)(4.94 J/g)
= 1.95622E+13 J
Transformity 48000 Sej/J (Odum, 1996, p.120)

3 Oil
106.6 million $ (Census of Manufactures: Cement and Structural Clay Products, 1977, Table 3a, p. 32B-12)
0.605 $/gal, 1977 (Statistical Abstract 1995, Table 770, p. 504 and Statistical Abstract 1997, Table 932, p. 588)
[(106.6E+6 $)/(0.605 $/gal)]*(125000 Btu/gal)(1054 J/Btu)
= 2.32141E+16 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

4 Electricity
24.4 million $ (Census of Manufactures: Cement and Structural Clay Products, 1977, Table 3a, p. 32B-12)
0.0313 $/kWh (Statistical Abstract 1995, Table 770, p. 504 and Statistical Abstract 1997, Table 932, p. 588)
[(24.4E+6 $)/(0.0313 $/kWh)]*(3.6 E+06 J/kWh)
= 2.80639E+15 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

Table C-13--continued.

5 Labor 20500 employees (Census of Manufactures: Cement and Structural Clay Products, 1977, Table 5a, p. 32B-15)
(20500 employees)(2E+10 J/yr)
= 4.1E+14 J

197.3 million $ (Census of Manufactures: Cement and Structural Clay Products, 1977, Table 5a, p. 32B-15)
= 1.97E+08 $
Transformity 4.40E+12 Sej/$ for US in 1977 (Odum, 1996, Table D.1, p. 313-315)

6 Annual Yield of Brick and Structural Clay Tile 1977
8722.4 million bricks (Census of Manufactures: Cement and Structural Clay Products, 1977, Table 6a, p. 32B-18)
(8722.4 million bricks)(3.73 lb/brick)(454 g/lb)
= 1.47707E+13 g
= 8.9762E+12 g Input equals to output
715.3 million $ (Census of Manufactures: Cement and Structural Clay Products, 1977, Table 6a, p. 32B-15)

Table C-14. Emergy evaluation of paint in the United States, 1996. *

Note	Item	Unit	Input Resource Energy	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
1	Clay	g	2.21E+08	2.00E+09	0.44
2	Plastics	g	2.51E+08	3.28E+09	0.82
3	Zinc oxide	g	2.43E+07	6.80E+10	1.65
4	Titanium dioxide	g	1.94E+08	6.80E+10	13.20
5	Additives	g	4.10E+08	3.80E+08	0.16
6	Water	J	4.58E+07	4.80E+04	0.000002
7	LP gas	J	1.03E+11	4.80E+04	0.0050
8	Electricity	J	6.00E+11	1.74E+05	0.10
9	Transport (Truck)	ton-mile	2.43E+05	9.65E+11	0.23
10	Machinery	g	1.81E+06	6.70E+09	0.01
11	Labor	$	8.74E+04	1.20E+12	0.10
12	Annual Yield (with services)	g	1.10E+09	1.52E+10	16.73
13	Annual Yield (without services)	g	1.10E+09	1.51E+10	16.63

* exterior paint; Acrituf 100% Acrylic Latex Finish House Paint (500 White, 7105 Serious)

Footnotes:

1 Clay
(0.2)(11.68 lb/gal)(208000 gal/yr)(454 g/lb)
= 2.21E+08 g
Transformity 2.00E+09 Sej/g (Odum, 1996, p.310)

2 Plastics Acrylic resin Opaque polymer, and Glycols
(0.228)(11.68 lb/gal)(208000 gal/yr)(454 g/lb)
= 2.51E+08 g
Transformity 3.28E+09 Sej/g (This study, Table C-8)
3.80E+08 Sej/g (Whitfield, 1994, p. 185)

3 Zinc oxide
(0.022)(11.68 lb/gal)(208000 gal/yr)(454 g/lb)
= 2.43E+07 g
Transformity 6.80E+10 Sej/g using zinc from (Brown et al, 1992, Table A1)

4 Titanium dioxide
(0.176)(11.68 lb/gal)(208000 gal/yr)(454 g/lb)
= 1.94E+08 g
Transformity 6.80E+10 Sej/g using zinc from (Brown et al, 1992, Table A1)

Table C-14--continued.

5 Additives

(0.372)(11.68 lb/gal)(208000 gal/yr)(454 g/lb)

= 4.10E+08 g

Transformity 3.80E+08 Sej/g using chemicals from (Brown et al, 1992, Table A1)

6 Water

[(200 \$/mo)(12 mo/yr)/(0.94 \$/gal)]*(8 lb/gal)(454 g/lb)(4.94 J/g)

= 4.58E+07 J 9273191.489 g

Transformity 48000 Sej/J (Odum, 1996, p.120)

7 LP gas LP gas = 90800 Btu/gal (Davis and McFarlin, 1996, Table B.1, p. B-2)

(3 tank/mo)(12 mo/yr)(30 gal/tank)(90800 Btu/gal)(1054 J/Btu)

= 1.0336E+11 J

Transformity 48000 Sej/J (Odum, 1996, p. 308)

8 Electricity 0.0288 \$/kWh (Personal communication with Gainesville Regional Utilities (GRU), FL, 1996)

(400 \$/mo)(12 mo/yr)(34.72 kWh/\$)(3.6 E+06 J/kWh)

= 5.9996E+11 J

Transformity 174000 Sej/J (Odum, 1996, p. 305)

9 Transport (Truck) 200 miles distance of inputs, 208000 gal of paint/yr, 11.68 lb/gal

[(208000 gal/yr)(11.68 lb/gal)/(2000 lb/short ton)]*(200 miles)

= 242944 ton-mile

Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

10 Machinery

[(3 machines)(20 ton/machine)(907000 g/ton)]/(30 yr)

= 1814000 g

Transformity 6.70E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4)

11 Labor

(60 hr/day)(7 \$/hr)(4 days/week)(52 weeks/yr)

= 87360 \$

Transformity 1.20E+12 Sej/\$ for US in 1996 (Projected from Odum, 1996, Table D.1, p. 313-315)

12 Annual Yield of Exterior Paint

(1000 gal/day)(4 days/week)(52 weeks/yr)(11.68 lb/gal)(454 g/lb)

= 1.10E+09 g

Table C-15. Emergy evaluation of wood furniture in the United States, 1992. *

Note	Item	Unit	Input Resource Energy	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Lumber	g	1.08E+12	1.85E+09	20.06
2	Fiberboard (MDF)	g	6.40E+11	2.40E+09	15.36
3	Oil	J	2.98E+15	6.60E+04	1.97
4	Electricity	J	7.14E+15	1.74E+05	12.43
5	Labor	$	2.17E+09	1.43E+12	31.08
6	Annual Yield (with services)	g	1.72E+12	4.69E+09	80.89
7	Annual Yield (without services)	g	1.72E+12	2.89E+09	49.81

Footnotes:

1 Lumber (Census of Manufactures 1992: Household Furniture, Table 7, p. 25A-24)
[(853.9 million bd.ft.)/(0.35 bd.ft./lb)](454 g/lb)
= 1.0843E+12 g
Transformity 1.85E+09 Sej/g (This study, Table 3-9)
1.40E+09 Sej/g (Haukoos, 1995, Table A-2a, p. 139-140)

2 Fiberboard (MDF) (Census of Manufactures 1992: Household Furniture, Table 7, p. 25A-24)
[(451.1 million sq.ft. 3/4")/(0.32 sq.ft./lb)]*(454 g/lb)
= 6.4E+11 g
Transformity 2.40E+09 Sej/g updated (Haukoos, 1995, Table A-7, p. 157-158)
1.58E+05 Sej/J updated (Haukoos, 1995, Table A-7, p. 157-158)

3 Oil 26.9 million $ (Census of Manufactures 1992: Household Furniture, Table 3a, p. 25A-12)
1.19 $/gal, 1992 (Statistical Abstract 1997, Table 932, p. 588)
[(26.9 million $/yr)/(1.19 $/gal)](125000 Btu/gal)(1054 J/Btu)
= 2.9782E+15 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

4 Electricity 1983.8 million kWh (Census of Manufactures 1992: Household Furniture, Table 3a, p. 25A-13)
(1983.8E+6 kWh/yr)(3.6 E+06 J/kWh)
= 7.1417E+15 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

Table C-15--continued.

5 Labor 121100 employees (Census of Manufactures 1992: Household Furniture, Table 2, p. 25A-10)
(121100 employees)(2E+10 J/yr)
= 2.422E+15 J

2173.5E+6 \$/yr (Census of Manufactures 1992: Household Furniture, Table 2, p. 25A-10)
= 2.17E+09 \$
Transformity 1.43E+12 Sej/\$ for US in 1992 (Odum, 1996, Table D.1, p. 313-315)

6 Annual Yield of Wood Furniture
[(853.9 million bd.ft.)/(0.35 bd.ft./lb)+(451.1 million sq.ft. 3/4")/
(0.32 sq.ft./lb)](454 g/lb)
= 1.7243E+12 g
31104500 units/yr (Census of Manufactures 1992: Household Furniture, Table 6a, p. 25A-18,19)
7976.4 million \$/yr (Census of Manufactures 1992: Household Furniture, Table 6a, p. 25A-18)

Table C-16. Emergy evaluation of hardwood veneer and plywood in the United States, 1992.

Note	Item	Unit	Input Resource Energy	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Hardwood logs	J	1.84E+17	8.01E+03	14.73
2	Softwood logs	J	5.17E+16	8.01E+03	4.14
3	Lumbers	J	3.65E+14	4.40E+04	0.16
4	Hardwood veneer	J	7.36E+15	4.40E+04	3.24
5	Softwood Veneer	J	2.47E+16	4.40E+04	10.89
6	Particleboard (wood)	J	5.24E+15	1.04E+05	5.45
7	MDF	J	3.12E+15	1.12E+05	3.50
8	Oil	J	1.15E+15	6.60E+04	0.76
9	Electricity	J	2.01E+15	1.74E+05	3.50
10	Labor	$	4.91E+08	1.43E+12	7.02
11	Annual Yield * (with services)	g	3.69E+12	1.44E+09	53.38
12	Annual Yield * (without services)	g	3.69E+12	1.25E+09	46.36

* Split pathway

Footnotes:

1 Hardwood logs (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(430 million ft. log scale/yr)(45 lb/cu.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 1.83868E+17 J 8.7849E+12 g
Transformity 8.01E+03 Sej/J (Odum, 1996, p.80)

2 Softwood logs (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(155.5 million ft. log scale/yr)(35 lb/cu.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 5.17158E+16 J 2.4709E+12 g
Transformity 8.01E+03 Sej/J (Odum, 1996, p.80)

3 Lumbers (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(12.8 million bd.ft./yr)(3 lb/bd.ft.)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 3.64885E+14 J 1.74E+10 g
Transformity 4.40E+04 Sej/J (Odum, 1996, p.308)

4 Hardwood veneer (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(2583.3 million sq.ft./yr)(0.3 lb/sq.ft. of veneer)(454 g/lb)(5 kcal/g)(4186 J/kcal)
= 7.36413E+15 J 3.51845E+11 g
Transformity 4.40E+04 Sej/J (Odum, 1996, p.308)

Table C-16--continued.

5 Softwood Veneer (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(867.9 million sq.ft. 1-inch basis/yr)(3 lb/sq.ft. of 1" veneer)(454 g/lb)
(5 kcal/g)(4186 J/kcal)
= 2.47409E+16 J 1.18208E+12 g
Transformity 4.40E+04 Sej/J (Odum, 1996, p.308)

6 Particleboard (wood) (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(183.9 million sq.ft. 3/4-inch basis/yr)(3 lb/sq.ft.)(454 g/lb)(5 kcal/g)
(4186 J/kcal)
= 5.24237E+15 J 2.50472E+11 g
Transformity 1.04E+05 Sej/J updated (Haukoos, 1995, Table A-6, p.155-156)

7 MDF Medium density fiberboard
(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 7, p. 24B-24)
(109.5 million sq.ft. 3/4-inch basis/yr)(3 lb/sq.ft.)(454 g/lb)(5 kcal/g)
(4186 J/kcal)
= 3.12148E+15 J 1.49139E+11 g
Transformity 1.12E+05 Sej/J updated (Haukoos, 1995, Table A-7, p.157-158)

8 Oil 10.4 million $ (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
1.19 $/gal, 1992 (Statistical Abstract 1997, Table 932, p. 588)
[(10.4 million $/yr)/(1.19 $/gal)](125000 Btu/gal)(1054 J/Btu)
= 1.15143E+15 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

9 Electricity (Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
(558.3 million kWh/yr)(3.6 E+06 J/kWh)
= 2.00988E+15 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

10 Labor 20100 employees(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
(20100 employees)(2E+10 J/yr)
= 4.02E+14 J

490.9 million $(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
= 490900000 $
Transformity 1.43E+12 Sej/$ for US in 1992 (Odum, 1996, Table D.1, p. 313-315)

Table C-16--continued.

11 **Annual Yield of Hardwood Veneer and Plywood**

(3.14E+12)+(5.48E+12)
= 3.69481E+12 g
2247.5 million $(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 3a, p. 24B-12)
856.8 million $ value added

Annual Yield of Hardwood Plywood

(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 6a, p. 24B-19)
(2310.1 million sq.ft.)(3 lb/sq.ft.)(454 g/lb)
= 3.14636E+12 g

Annual Yield of Hardwood Veneer

(Census of Manufactures 1992: Millwork, Plywood, and Structural Wood Members, Table 6a, p. 24B-19)
(4026.8 million sq.ft.)(0.3 lb/sq.ft.)(454 g/lb)
= 5.4845E+11 g

Table C-17. Emergy evaluation of municipal solid wastes (MSW) before collection in the United States, 1994.

Note	Item	Unit	Input Resource Energy	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
1	Paper & paperboard	J	1.54E+18	1.42E+05	2191.57
2	Glass	g	1.21E+13	1.90E+09	229.20
3	Ferrous metals	g	1.04E+13	6.28E+09	655.04
4	Aluminum	g	2.81E+12	1.17E+10	328.97
5	Other nonferrous metals	g	1.09E+12	2.83E+09	30.80
6	Plastics	g	1.80E+13	3.28E+09	589.04
7	Rubber and leather	g	5.80E+12	4.30E+09	249.61
8	Textiles	J	1.25E+17	5.00E+05	626.46
9	Wood	J	2.77E+17	8.01E+03	22.20
10	Other materials	g	3.27E+12	1.00E+09	32.65
11	Food wastes	J	2.68E+17	1.00E+05	267.67
12	Yard trimmings	J	5.81E+17	8.01E+03	46.53
13	Inorganic wastes	g	2.81E+12	1.00E+09	28.12
14	Annual Yield mixed MSW (without services)	g	1.90E+14	2.79E+09	5297.85

Footnotes:

1 Paper & paperboard (EPA, 1995, Table ES-1, p. 6)
38.9% of MSW generated, 35.3% recovery (28.7 million tons)
(81.3 million tons/yr 1994)(907000 g/ton)(5 kcal/g)(4186 J/kcal)
= 1.54E+18 J
Transformity 1.42E+05 sej/J (Keller, 1992, p.116)

2 Glass (EPA, 1995, Table ES-1, p. 6)
6.3% of MSW generated, 23.4% recovery (3.1 million tons)
(13.3 million tons/yr 1994)(907000 g/ton)
= 1.20631E+13 g
Transformity 1.90E+09 sej/g using flat glass (This study, Table C-12)
8.44E+08 sej/g glass (Odum et al., 1987a, p. 159)
1.97E+09 sej/g updated flat glass (Haukoos, 1995, Table A-16, p.180-182)

Table C-17--continued.

3	Ferrous metals	(EPA, 1995, Table ES-1, p. 6)	
		32.3% recovery (3.7 million tons)	
		(11.5 million tons/yr 1994)(907000 g/ton)	
		= 1.04305E+13 g	
	Transformity	6.28E+09 sej/g	average of EAF and BOF steel (about 50% each in market (USGS: Iron and Steel, 1997, p.86))
		7.21E+09 sej/g	steel (EAF) (This study, Table 3-4)
		5.35E+09 sej/g	steel (BOF) (This study, Table 3-5)
		1.78E+09 sej/g	iron/steel (Odum, 1996, p.186)
		2.64E+09 sej/g	iron/steel (Brown et al, 1992, Table A1)
4	Aluminum	(EPA, 1995, Table ES-1, p. 6)	
		37.6% recovery (1.2 million tons)	
		(3.1 million tons/yr 1994)(907000 g/ton)	
		= 2.8117E+12 g	
	Transformity	1.17E+10 sej/g	using primary aluminum (This study, Table C-7)
		1.63E+10 sej/g	(Odum et al., 1987a, p. 159)
5	Other nonferrous metals	(EPA, 1995, Table ES-1, p. 6)	
		66.1% recovery (0.8 million tons)	
		(1.2 million tons/yr 1994)(907000 g/ton)	
		= 1.0884E+12 g	
	Transformity	2.83E+09 sej/g	using steels (This study, Table C-3)
		9.18E+08 sej/g	metals wastes (Odum et al., 1987a, p. 159)
		6.80E+10 sej/g	copper and zinc (Brown et al, 1992, Table A1)
6	Plastics	(EPA, 1995, Table ES-1, p. 6)	
		9.5% of MSW generated, 4.7% recovery (0.9 million tons)	
		(19.8 million tons/yr 1994)(907000 g/ton)	
		= 1.79586E+13 g	
	Transformity	3.28E+09 Sej/g	(This study, Table C-8)
		3.80E+08 sej/g	(Odum et al., 1987a, p. 159)
7	Rubber and leather	(EPA, 1995, Table ES-1, p. 6)	
		7.1% recovery (0.5 million tons)	
		(6.4 million tons/yr 1994)(907000 g/ton)	
		= 5.8048E+12 g	
	Transformity	4.30E+09 sej/g	(Odum et al., 1987a, p. 159)
		2.10E+04 sej/J	rubber (Odum et al, 1983, Table 3.1, p. 40-45)

Table C-17--continued.

8	Textiles	(EPA, 1995, Table ES-1, p. 6)	
		11.7% recovery (0.8 million tons)	
		(6.6 million tons/yr 1994)(907000 g/ton)(5 kcal/g)(4186 J/kcal)	
		= 1.25291E+17 J	
	Transformity	5.00E+05 sej/J	estimated
		3.80E+06 sej/J	textiles (Odum et al., 1987a, p. 159)
		1.42E+05 sej/J	paper (Keller, 1992, p.116)
9	Wood	(EPA, 1995, Table ES-1, p. 6)	
		7.0% of MSW generated, 9.8% recovery (1.4 million tons)	
		(14.6 million tons/yr 1994)(907000 g/ton)(5 kcal/g)(4186 J/kcal)	
		= 2.77159E+17 J	
	Transformity	8.01E+03 Sej/J	(Odum, 1996, p.80)
10	Other materials	(EPA, 1995, Table ES-1, p. 6)	
		20.9% recovery (0.8 million tons)	
		(3.6 million tons/yr 1994)(907000 g/ton)	
		= 3.2652E+12 g	
	Transformity	1.00E+09 sej/g	
		1.79E+09 sej/g	(Odum et al., 1987a, p. 159)
11	Food wastes	(EPA, 1995, Table ES-1, p. 6)	
		6.7% of MSW generated, 3.4% recovery (0.5 million tons)	
		(14.1 million tons/yr 1994)(907000 g/ton)(5 kcal/g)(4186 J/kcal)	
		= 2.67667E+17 J	
	Transformity	1.00E+05 sej/J	estimated
		1.80E+06 sej/J	(Odum et al., 1987a, p. 159)
		8.50E+04 sej/J	(Brown et al, 1992, Table A1)
		2.00E+06 sej/J	(Brown et al, 1992, Table C-7)
12	Yard trimmings	(EPA, 1995, Table ES-1, p. 6)	
		14.6% of MSW generated, 22.9% recovery (7.0 million tons)	
		(30.6 million tons/yr 1994)(907000 g/ton)(5 kcal/g)(4186 J/kcal)	
		= 5.80895E+17 J	
	Transformity	8.01E+03 Sej/J	(Odum, 1996, p.80)
		4.30E+03 Sej/J	(Odum et al., 1987a, p. 159)
13	Inorganic wastes	(EPA, 1995, Table ES-1, p. 6)	
		(3.1 million tons/yr 1994)(907000 g/ton)	
		= 2.8117E+12 g	
	Transformity	1.00E+09 sej/g	
		1.79E+09 sej/g	(Odum et al., 1987a, p. 159)

Table C-17--continued.

14 Annual Yield 209.1 million tons in 1994 (EPA, 1995, p. 2)
(209.1 million tons)(907000 g/short ton)
= 1.89654E+14 g

Annual Yield of MSW to landfills (EPA, 1995, Figure ES-3, p. 9)
(127.3 million tons/yr 1994)(907000 g/ton)
= 1.15461E+14 g

Annual Yield of MSW to Recovery (EPA, 1995, Figure ES-3, p. 9)
49.3 million ton - 0.5 million ton composition = 48.8 million ton recycling
(48.8 million tons/yr 1994)(907000 g/ton)
= 4.42616E+13 g (recycling and composting)

Annual Yield of MSW to Composting
(500000 tons/yr 1994)(907000 g/ton)
= 4.535E+11 g

Annual Yield of MSW to Combustion (EPA, 1995, Figure ES-3, p. 9)
(32.5 million tons/yr 1994)(907000 g/ton)
= 2.94775E+13 g (RDF and heat recovery system)

APPENDIX D
EMERGY EVALUATION OF WASTE RECOVERY AND LANDFILL

Table D-1. Emergy evaluation of curbside collection 1997.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
Wastes					
1	Paper waste	J	4.61E+14	1.42E+05	65.43
2	Yard trimming waste	J	1.73E+14	8.01E+03	1.39
3	Plastics waste	g	5.38E+09	3.28E+09	17.64
4	Metals waste	g	4.30E+09	2.83E+09	12.17
5	Wood waste	J	8.29E+13	8.01E+03	0.66
6	Food waste	J	7.94E+13	2.00E+06	158.73
7	Glass waste	g	3.57E+09	1.90E+09	6.77
8	Other wastes	g	5.32E+09	1.00E+09	5.32
Process inputs					
9	Transport (Truck)	ton-mile	1.25E+07	9.65E+11	12.04
10	Labor	$	1.87E+06	1.15E+12	2.15
11	Annual Yield of mixed waste	g	5.66E+10	4.99E+09	282.31

Emergy (sej) per gram of MSW in processes (excluding MSW itself)

5.66E+10 Total MSW in grams
1.42E+19 Total sej from process inputs (truck and labor)
2.51E+08 sej per gram of MSW in processes (excluding MSW itself)

Footnotes:

1 Paper waste 38.9% of paper (EPA, 1995, Figure ES-1, p. 5)
(0.389)(200 short tons/day)(907000 g/short ton)(5 kcal/g)(4186 J/kcal)
(6 day/week)(52 week/yr)
= 4.608E+14 J
Transformity 1.42E+05 sej/J (Keller, 1992, p.116)

2 Yard trimming waste 14.6% of yard trimmings (EPA, 1995, Figure ES-1, p. 5)
(0.146)(200 short tons/day)(907000 g/short ton)(5 kcal/g)(4186 J/kcal)
(6 day/week)(52 week/yr)
= 1.729E+14 J
Transformity 8.01E+03 Sej/J (Odum, 1996, p.80)

3 Plastics waste 9.5% of plastics (EPA, 1995, Figure ES-1, p. 5)
(0.095)(200 short tons/day)(907000 g/short ton)(6 day/week)(52 week/yr)
= 5.377E+09 g
Transformity 3.28E+09 Sej/g using (This study, Table C-8)
3.80E+08 sej/g (Odum et al., 1987a, p. 159)

Table D-1--continued.

4 Metals waste
7.6% of metals (EPA, 1995, Figure ES-1, p. 5)
(0.076)(200 short tons/day)(907000 g/short ton)(6 day/week)(52 week/yr)
= 4.301E+09 g

Transformity		
	2.83E+09 sej/g	using steel (This study, Table C-3)
	9.18E+08 sej/g	metals wastes (Odum et al., 1987a, p. 159)
	6.80E+10 sej/g	copper and zinc (Brown et al, 1992, Table A1)

5 Wood waste
7% of wood (EPA, 1995, Figure ES-1, p. 5)
(0.07)(200 short tons/day)(907000 g/short ton)(5 kcal/g)(4186 J/kcal)
(6 day/week)(52 week/yr)
= 8.292E+13 J

Transformity		
	8.01E+03 Sej/J	(Odum, 1996, p.80)

6 Food waste
6.7% of food (EPA, 1995, Figure ES-1, p. 5)
(0.067)(200 short tons/day)(907000 g/short ton)(5 kcal/g)(4186 J/kcal)
(6 day/week)(52 week/yr)
= 7.937E+13 J

Transformity		
	2.00E+06 sej/J	using (Brown et al, 1992, Table C-7)
	1.80E+06 sej/J	(Odum et al., 1987a, p. 159)
	8.50E+04 sej/J	(Brown et al, 1992, Table A1)

7 Glass waste
6.3% of glass (EPA, 1995, Figure ES-1, p. 5)
(0.063)(200 short tons/day)(907000 g/short ton)(6 day/week)(52 week/yr)
= 3.566E+09 g

Transformity		
	1.90E+09 sej/g	using flat glass (This study, Table C-12)
	8.44E+08 sej/g	glass (Odum et al., 1987a, p. 159)
	1.97E+09 sej/g	updated flat glass (Haukoos, 1995, Table A-16, p.180-182)

8 Other wastes
9.4% others (EPA, 1995, Figure ES-1, p. 5)
(0.094)(200 short tons/day)(907000 g/short ton)(6 day/week)(52 week/yr)
= 5.32E+09 g

Transformity 1.00E+09 sej/g

9 Transport (Truck)
30 trucks, 40 cu.yd./truck, 10 hr/day, 200 miles/truck/day
(200 short ton/day)(6 days/week)(52 week/yr)(200 miles)
= 1.25E+07 ton-mile

Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

10 Labor
(60 employees)(12 $/hr)(50 hr/week)(52 weeks/yr)
= 1872000 $

Transformity 1.15E+12 Sej/$ for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)

11 Annual Yield of Solid Waste
(200 short tons/day)(907000 g/short ton)(6 day/week)(52 week/yr)
= 5.66E+10 g
500 lb/cu.yd. of MSW waste in compactor truck (Tchobanoglous et al, 1993, Table 4-1, p.70)

Table D-2. Emergy evaluation of landfill with non-separated MSW inputs.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
1	Sunlight	J	7.45E+14	1.00E+00	0.0007
2	MSW input without MRF	g	1.70E+11	4.97E+09	843.86
3	Gravel (drainage system)	g	7.49E+08	1.00E+09	0.75
4	Plastics (liners)	g	2.93E+08	3.28E+09	0.96
5	Plastics (pipes)	g	2.00E+07	3.28E+09	0.07
6	Fuel	J	8.70E+12	6.60E+04	0.57
7	Electricity	J	4.84E+11	1.74E+05	0.08
8	Transport (Truck)	ton-mile	8.42E+06	9.65E+11	8.13
9	Machinery	g	6.00E+07	6.70E+09	0.40
10	Labor	$	6.03E+05	1.15E+12	0.69
11	Annual Yield (Y) landfill (with services)	g	2.38E+11	3.88E+09	923.43

Emergy (sej) per gram of landfill in processes (excluding MSW itself)

2.38E+11 Total MSW in grams
2.78E+18 Total sej from process inputs (plastics, fuels, electricity, machinery, and labor)
1.17E+07 sej per gram of landfill in processes (excluding MSW itself)

Emergy (sej) per gram of operating landfill, assuming 50 years life (Tchobanoglous et al., 1993)

2.38E+12 Total MSW in grams (assuming 10 years MSW input before fill up)
4.05E+18 Total sej from process inputs (sunlight, electricity), see footnote 12
1.70E+06 sej per gram of landfill in processes

Total emergy per gram for life time landfill processes, 1.17+0.17 = 1.34 E+07 sej per gram

Footnotes:

1 Sunlight
(40 acres)(4047 sq.m./acre)(110 kcal/sq.cm./yr)
(10000 sq.cm./sq.m.)(4186 J/kcal)
= 7.45393E+14 J
Transformity 1 Sej/J (Odum, 1996, p.187)

2 MSW input without MRF 600 short ton/day
(600 short ton/day)(6 days/week)(52 weeks/yr)(907000 g/short ton)
= 1.6979E+11 g
Transformity 4.97E+09 Sej/g curbside collection
(This study, Table D-1)

3 Gravels (drainage system) 1114688 lb/acre (Tchobanoglous et al, 1993, p.403,408-409,412-413)
(1114688 lb/acre)(37 acres)(454 g/lb)/(25 yr)
= 7.49E+08 g
Transformity 1.00E+09 Sej/g

4 Plastics (liners) 10 lb/sq.ft. (Tchobanoglous et al, 1993, p.434-435,438)
(10 lb/sq.ft.)(37 acres)(43560 sq.ft./acre)(454 g/lb)/(25 yr)
= 2.93E+08 g
Transformity 3.28E+09 Sej/g (This study, Table C-8)

Table D-2--continued.

5	Plastics (pipes)		29700 lb/acre (Tchobanoglous et al, 1993, p.403,408-409,412-413)
			(29700 lb/acre)(37 acres)(454 g/lb)/(25 yr)
		=	2.00E+07 g
	Transformity		3.28E+09 Sej/g (This study, Table C-8)
6	Fuel		6000 $/mo
			[(6000 $/mo)/(1.09 $/gal)]*(12 mo/yr)(125000 Btu/gal)(1054 J/Btu)
		=	8.70275E+12 J
	Transformity		66000 Sej/J (Odum, 1996, p. 308)
7	Electricity		Office 400 kWh/mo, Landfills 600 $/mo
			0.0555 $/kWh (Personal communication with Gainesville Regional Utilities (GRU), FL, 1998)
			[(600 $/mo)/(0.0555 $/kWh)+(400 kWh/mo)]*(12 mo/yr)
			(3.6 E+06 J/kWh)
		=	4.84307E+11 J
	Transformity		174000 Sej/J (Odum, 1996, p. 305)
8	Transport (Truck)		45 miles distance from transfer station to landfill
			(600 short ton/day)(6 day/week)(52 week/yr)(45 miles)
		=	8.42E+06 ton-mile
	Transformity		9.65E+11 Sej/ton-mile (This study, Table E-1)
9	Machinery		50000 lb/scraper, 15000 lb/loader, 15000 lb/dozer, 50000 lb/compactor, 50000 lb/caterpillar, 3500 lb/4x4 truck, 50000 lb/truck in average (Deere, 1997)
			[(50000 lb/machine)(11 machines)+(15000 lb/loader-dozer)(2 machines)
			+(70000 lb/15' tractor)+(3 trucks)(3500 lb/4x4 truck)]
			*(454 g/lb)/(5 yr)
		=	6.00E+07 g
	Transformity		6.70E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4)
10	Labor		(29 employees)(400 $/week)(52 weeks/yr)
		=	603200 $
	Transformity		1.15E+12 Sej/$ for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)
11	Annual Yield of MSW in landfill		
			[(600 MSW short ton/day)+(240 soil short ton/day)]
			*(907000 g/short ton)(6 days/week)(52 week/yr)
		=	2.37707E+11 g
	Revenue		($25/short ton)(600 short ton/day)(6 days/week)(52 weeks/yr)
		=	4680000 $
	Covering soil (mostly sand)		40% of MSW input
	Annual Yield of Leachate (byproduct)		24000 gal/day
			(24000 gal/day)(365 day/yr)(8 lb/gal)(454 g/lb)
		=	3.18E+10 g
12	Electricity		Landfills 600 $/mo
			0.0555 $/kWh (GRU Gainesville, FL, 1998)
			[(600 $/mo)/(0.0555 $/kWh)]*(12 mo/yr)(3.6 E+06 J/kWh)(50 yr)
		=	2.33E+13 J
	Transformity		174000 Sej/J (Odum, 1996, p. 305)
			(2.33E+13 J per 50 yr)(1.74E+5 sej/J)
		=	4.05E+18 sej per 50 yr

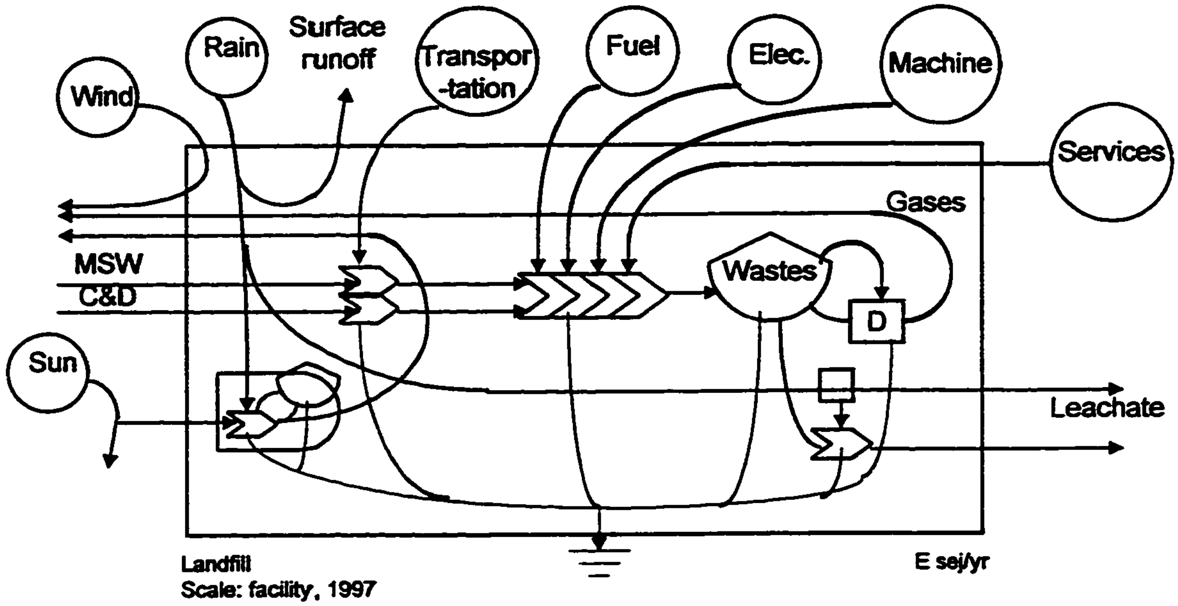


Figure D-1. Emergy evaluation of landfill showing long term flows of environment energies maintaining vegetation cover and the flow of wastes and purchased energy.

Table D-3. Emergy evaluation of materials recovery facility (MRF) separation processes (1997).

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
1	MSW wastes	g	9.94E+11	4.97E+09	4941.47
2	Fuel	J	3.85E+13	6.60E+04	2.54
3	Electricity	J	6.57E+12	1.74E+05	1.14
4	Transport (Truck)	ton-mile	3.29E+07	9.65E+11	31.70
5	Machinery	g	2.90E+07	6.70E+09	0.19
6	Labor	$	3.74E+06	1.15E+12	4.31
7	Annual Yield separated MSW	g	9.94E+11	5.01E+09	4981.35

Emergy (sej) per gram of MSW in processes (excluding MSW itself)

9.94E+11 Total MSW in grams

8.18E+18 Total sej from process inputs (fuel, electricity, machinery, and labor)

8.24E+06 sej per gram of MSW in processes (excluding MSW itself)

Footnotes:

1 MSW wastes 3000 short ton/day, 365 day/yr

(3000 short ton/day)(365 day/yr)(2000 lb/short ton)(454 g/lb)

= 9.943E+11 g

Transformity 4.97E+09 sej/g curbside collection (This study, Table D-1)

2 Fuel 800 gal/day

(800 gal/day)(365 day/yr)(125000 Btu/gal)(1054 J/Btu)

= 3.847E+13 J

Transformity 66000 Sej/J (Odum, 1996, p. 308)

3 Electricity 2 turbines (40 MWh/day each), 5 MWh/day used in this facility (15 MWh/day total used in both recycling and RDF facility)

(5 MWh/day)(1000 kWh/MWh)(365 day/yr)(860 kcal/kWh)(4186 J/kcal)

= 6.57E+12 J

Transformity 174000 Sej/J (Odum, 1996, p. 305)

4 Transport (Truck) 30 miles from transfer station

(3000 short ton/day)(365 day/yr)(30 miles)

= 32850000 ton-mile

Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

Table D-3--continued.

5	Machinery	5 shredders (100 short ton each), 6 trommels (50 short ton each) [(5*100 short ton/shredder)+(6*50 short ton/trommel)]*(907000 g/short ton)/(25 yr) = 29024000 G	
	Transformity	6.7E+09 Sej/g	(Odum et al., 1987b, Table 1, p. 4)
6	Labor	operate 24 hr/day with 3 shifts/day, 15 $/hr in average, total 200 people (80 people work in recycling facility) (80 employees)(15 $/hr)(60 hr/week)(52 weeks/yr) = 3744000 $	
	Transformity	1.15E+12 Sej/$	for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)
7	Annual Yield	(3000 short ton/day)(365 day/yr)(2000 lb/short ton)(454 g/lb) = 9.94E+11 g	
	Revenue	($45/short ton)(3000 short ton/day)(365 days/yr) = 49275000 $	
Split pathway			
	Annual Yield of Combustible MSW	10% incombustible MSW [(0.9)(3000 short ton/day)(365 days/yr)-(30000 short ton of Fe/yr)-(600 short ton of non-Fe/yr)]*(907000 g/short ton) = 8.661E+11 g	
	Annual Yield of Ferrous metal (byproduct)	(30000 short ton/yr)(907000 g/short ton) = 2.721E+10 g	transported by rail with 400 miles distance by rail
	Annual Yield of Non-ferrous metal (byproduct)	(600 short ton/yr of non-ferrous metals)(907000 g/short ton) = 5.44E+08 g	transported by rail with 20 miles distance by truck
	Annual Yield of incombustible MSW waste (byproduct)	About 10 % of input is incombustible MSW (such as glass) goes to on-site landfill. (300 ton/day of incombustible MSW)(365 days/yr)(907000 g/short ton) = 9.932E+10 g	

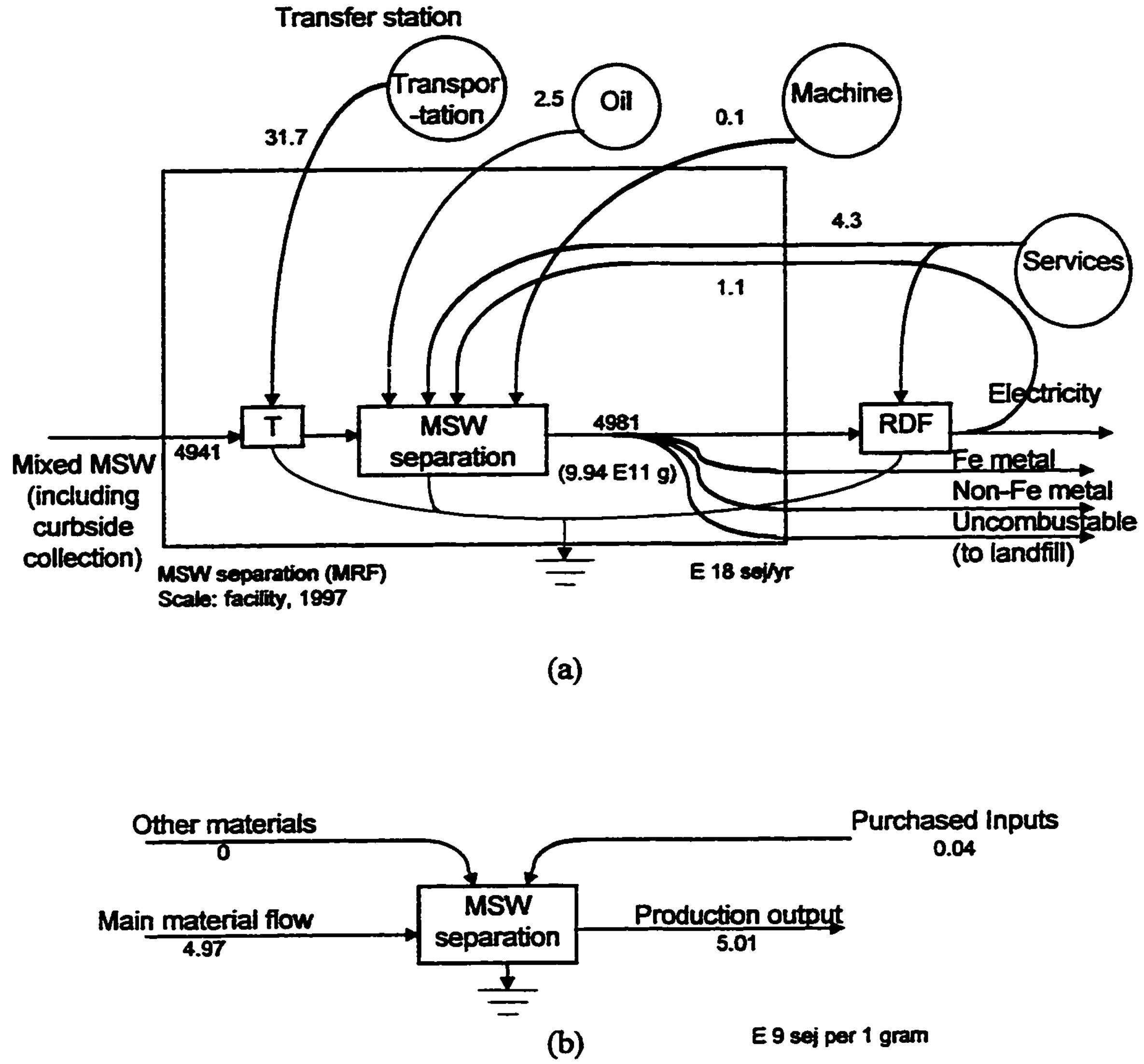


Figure D-2. Emergy systems diagram materials recovery facility (MRF) separation processes (a) and summary diagram (b). Data are form Table D-3.

Table D-4. Emergy evaluation of post-consumer glass containers separation in the United States, 1997.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
1	Green glass	g	7.07E+09	1.90E+09	13.44
2	Brown glass	g	2.12E+10	1.90E+09	40.33
3	Clear glass	g	7.07E+09	1.90E+09	13.44
4	Electricity	J	8.64E+11	1.74E+05	0.15
5	Transport (Truck)	ton-mile	7.80E+06	9.65E+11	7.53
6	Machinery	g	1.81E+06	6.70E+09	0.01
7	Labor	$	2.64E+05	1.15E+12	0.30
8	Annual Yield separated glasses (with services)	g	3.54E+10	2.13E+09	75.20
9	Annual Yield separated glasses (without services)	g	3.54E+10	2.12E+09	74.90

60 Btu/lb (0.132 Btu/g) of energy content of glass (Tchobanoglous et al, 1993, Table 4-5, p.84)

Emergy (sej) per gram of glass from separation facility (excluding glass itself)
3.54E+10 Total glass waste in grams
7.99E+18 Total sej from process inputs (electricity, truck, machinery, and labor)
2.26E+08 sej per gram of glass in processes (excluding glass itself)

Emergy (sej) per gram of glass from separation facility (excluding glass itself)
3.54E+10 Total glass waste in grams
4.66E+17 Total sej from process inputs (electricity, machinery, and labor) excluding truck
1.32E+07 sej per gram of glass in processes (excluding glass itself)

Footnotes:

1 Green glass 20% of input
(0.2)(750 tons/week)(52 weeks/yr)(907000 g/ton)
= 7074600000 g
Transformity 1.90E+09 sej/g (This study, Table C-12)
4.74E+09 Sej/g updated flat glass (Haukoos, 1995, Table A-16, p.180-182)
8.44E+08 Sej/g MSW glass (Odum et al., 1987a, p. 159)

2 Brown glass 60% of input
(0.6)(750 tons/week)(52 weeks/yr)(907000 g/ton)
= 21223800000 g
Transformity 1.90E+09 sej/g (This study, Table C-12)
4.74E+09 Sej/g updated flat glass (Haukoos, 1995, Table A-16, p.180-182)
8.44E+08 Sej/g MSW glass (Odum et al., 1987a, p. 159)

Table D-4--continued.

3	Clear glass	20% of input	
		(0.2)(750 tons/week)(52 weeks/yr)(907000 g/ton)	
		= 7074600000 g	
	Transformity	1.90E+09 sej/g	(This study, Table C-12)
		4.74E+09 Sej/g	updated flat glass (Haukoos, 1995, Table A-16, p.180-182)
		8.44E+08 Sej/g	MSW glass (Odum et al., 1987a, p. 159)
4	Electricity		
		(20000 kWh/mo)(12 mo/yr)(3.6 E+06 J/kWh)	
		= 8.64E+11 J	
	Transformity	174000 Sej/J	(Odum, 1996, p. 305)
5	Transport (Truck)	10,000 lbs truck	
		12.2 gal/mile (Davis and McFarlin, 1996, Table 3.24, p.3-28)	
		(750 tons/week)(52 weeks/yr)(200 miles)	
		= 7800000 ton-mile	
	Transformity	9.65E+11 sej/ton-mile	(This study, Table E-1)
6	Machinery		
		(50 short ton)(907000 g/short ton)/(25 yr)	
		= 1814000 g	
	Transformity	6.70E+09 Sej/g	(Odum et al., 1987b, Table 1, p. 4)
7	Labor	work 16 hr/day, 5 days/week	
		(10 employees/line)(2E+10 J/yr)	
		= 2E+11 J	
		507 $/week (Statistical Abstract, 1995, Table 666, p.424)	
		(10 employees)(507 $/week)(52 weeks/yr)	
		= 263640 $	
	Transformity	1.15E+12 Sej/$	for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)
8	Annual Yield of Post-consumer Glass Separation		
		(750 tons/week)(907000 g/ton)(52 weeks/yr)	
		= 35373000000 g	
		500-1000 tons/week	
		$ 0.01/lb = (750*2205)*52*0.01) = 8.59E+5 $/yr	

Table D-5. Emergy evaluation of building construction of office building (University of Florida Campus) 1996-97.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+16
1	Cement	g	3.65E+07	2.20E+09	8.02
2	Concrete	g	2.76E+07	6.22E+07	0.17
3	Masonry, 8" CMU	g	9.11E+07	1.35E+09	12.29
4	Masonry, 4" tile brick	g	2.92E+07	2.32E+09	6.77
5	Structural steel	g	1.39E+07	1.78E+09	2.47
6	Other metals	g	3.35E+07	1.78E+09	5.97
7	Glass	g	8.10E+05	1.90E+09	0.15
8	Drywall	g	9.94E+07	2.05E+09	20.37
9	Vinyl tile and carpet	g	1.24E+07	5.87E+09	7.26
10	Paint	g	4.46E+06	1.52E+10	6.79
11	Electrical system	g	1.48E+06	6.70E+09	0.99
12	Elevators	g	5.63E+06	6.70E+09	3.77
13	HVAC	g	1.36E+07	6.70E+09	9.14
14	Fire system	g	4.41E+06	6.70E+09	2.96
15	Plumbing system	g	3.27E+06	6.70E+09	2.19
16	Furnishings/furnitures	g	1.31E+07	4.69E+09	6.12
17	Water	J	4.84E+08	4.80E+04	0.0023
18	Fuel	J	5.86E+11	6.60E+04	3.87
19	Electricity	J	4.64E+11	1.74E+05	8.07
20	Machinery	g	1.45E+07	6.70E+09	9.68
21	Labor	$	5.15E+05	1.20E+12	61.83
22	Yield (g) (15 months)	g	3.90E+08	4.58E+09	178.88
23	Yield (sq.ft.) (15 months)	sq.ft.	1.09E+04	1.64E+14	178.88
24	Yield (sq.m.) (15 months)	sq.m.	9.81E+02	1.82E+15	178.88

Emergy (sej) per gram of construction materials in processes (excluding material itself)

3.90E+08	Total construction materials in grams
8.34E+17	Total sej from process inputs (water, fuels, electricity, machinery, and labor)
2.14E+09	sej per gram of construction materials in processes (excluding material itself)

Table D-5--continued.

Footnotes:

1	Cement	(4015 sq.ft.)(20 lb/sq.ft.)(454 g/lb)	
		= 36456200 g	
	Transformity	2.20E+09 Sej/g	cement with fly ash (This study, Table 3-1)
		1.98E+09 Sej/g	cement without fly ash (This study, Table 3-1)
		2.31E+09 Sej/g	updated (Haukoos, 1995, Table A-13, p.172)
2	Concrete	(405 cu.yd.)(150 lb/cu.yd.)(454 g/lb)	
		= 27580500 g	
	Transformity	6.22E+07 Sej/g	(This study, Table C-2)
		8.76E+08 Sej/g	(Haukoos, 1995, Table A-14, p.175-176)
3	Masonry, 8" CMU	(4015 sq.ft.)(50 lb/sq.ft.)(454 g/lb)	
		= 91140500 g	
	Transformity	1.35E+09 Sej/g	updated (Haukoos, 1995, Table A-15, p.177-179)
4	Masonry, 4" tile brick	(4015 sq.ft.)(16 lb/sq.ft.)(454 g/lb)	
		= 29164960 g	
	Transformity	2.32E+09 Sej/g	(This study, Table C-13)
5	Structural steel	(30560 lb)(454 g/lb)	
		= 13874240 g	
	Transformity	1.78E+09 Sej/g	(Odum, 1996, p.186)
6	Other metals	[(65664 lb stud)(454 g/lb)]+[(8153 lb metals)(454 g/lb)]	
		= 33512918 g	
	Transformity	1.78E+09 Sej/g	using steel (Odum, 1996, p.186)
7	Glass	(1088 sq.ft.)(1.64 lb/sq.ft 1/8")(454 g/lb)	
		= 810081.28 g	
	Transformity	1.90E+09 Sej/g	(This study, Table C-12)
		4.26E+09 Sej/g	(Haukoos, 1995, Table A-16, p.180)
8	Drywall	(2 sides)(10 lb/sq.ft.)(10944 sq.ft)(454 g/lb)	
		= 99371520 g	
	Transformity	2.05E+09 Sej/g	using updated particleboard (Haukoos, 1995, Table A-6, p.155-156)

Table D-5--continued.

9 Vinyl tile and carpet
(10900 sq.ft)(2.5 lb/sq.ft.)(454 g/lb)
= 12371500 g
Transformity 5.87E+09 Sej/g using PVC (This study, Table C-9)
6.32E+09 Sej/g vinyl floor (This study, Table 3-11)

10 Paint
(2 sides)(10944 sq.ft.)(1 gal/26 sq.ft.)(11.68 lb/gal)(454 g/lb)
= 4464074.4 g
Transformity 1.52E+10 Sej/g (This study, Table C-14)

11 Electrical system
(3252 lb)(454 g/lb)
= 1476408 g
Transformity 6.7E+09 Sej/g using machinery (Odum et al., 1987b, Table 1, p. 4)

12 Elevators
(12400 lb)(454 g/lb)
= 5629600 g
Transformity 6.7E+09 Sej/g using machinery (Odum et al., 1987b, Table 1, p. 4)

13 HVAC
[(3660 lb)+(13380 lb)+(7*1860 lb)](454 g/lb)
= 13647240 g
Transformity 6.7E+09 Sej/g using machinery (Odum et al., 1987b, Table 1, p. 4)

14 Fire system
(9720 lb)(454 g/lb)
= 4412880 g
Transformity 6.7E+09 Sej/g using machinery (Odum et al., 1987b, Table 1, p. 4)

15 Plumbing system
(7200 lb)(454 g/lb)
= 3268800 g
Transformity 6.7E+09 Sej/g using machinery (Odum et al., 1987a, Table 1, p. 4)

16 Furnishings/furnitures
(28750 lb)(454 g/lb)
= 13052500 g
Transformity 4.69E+09 Sej/g (This study, Table C-15)

17 Water
(1800 gal/mo)(15 mo)(8 lb/gal)(454 g/lb)(4.94 J/g)
= 484436160 J
Transformity 48000 Sej/J (Odum, 1996, p.120)

Table D-5--continued.

18 Fuel

(4447.4 gal)(125000 Btu/gal)(1054 J/Btu)

= 5.859E+11 J

Transformity 66000 Sej/J (Odum, 1996, p. 308)

19 Electricity

[(15 mo)*(419 kWh/mo site office trailer)+(14 mo)*(7700 kWh/mo building)
+(14700 kWh last mo)](3.6 E+06 J/kWh)

= 4.636E+11 J

Transformity 174000 Sej/J (Odum, 1996, p. 305)

20 Machinery Average age of machinery is 4.3 years (Moore, 1998)
Assume life expectancy of machinery is 5 years
50000 lb/crane/12 mo, 3*15000 lb/backhoe/2 mo, 20000 lb/loader/mo
2*15000 lb/forklifts/12 mo, 3*20000 lb/truck/12 mo,
5*6000 lb/platform/12 mo
10000+1500+333+6000+8000+6000 = 31833 lb

(31833 lb)(454 g/lb)

= 14452182 g

Transformity 6.7E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4)

21 Labor

(515252 $/15 mo)

= 515252 $

Transformity 1.20E+12 Sej/$ for US in 1996 (Projected from Odum, 1996,
Table D.1, p. 313-315)

22 Yield of Commercial Building (g)

(390233922 g of 15 mo)

= 390233922 g

35801.277 g per sq.ft. 397791.9691 g per sq.m.

23 Yield of Commercial Building (sq.ft.)

(10900 sq.ft)

= 10900 sq.ft.

24 Yield of Commercial Building (sq.m.)

(10900 sq.ft)(0.09 sq.m./sq.ft.)

= 981 sq.m.

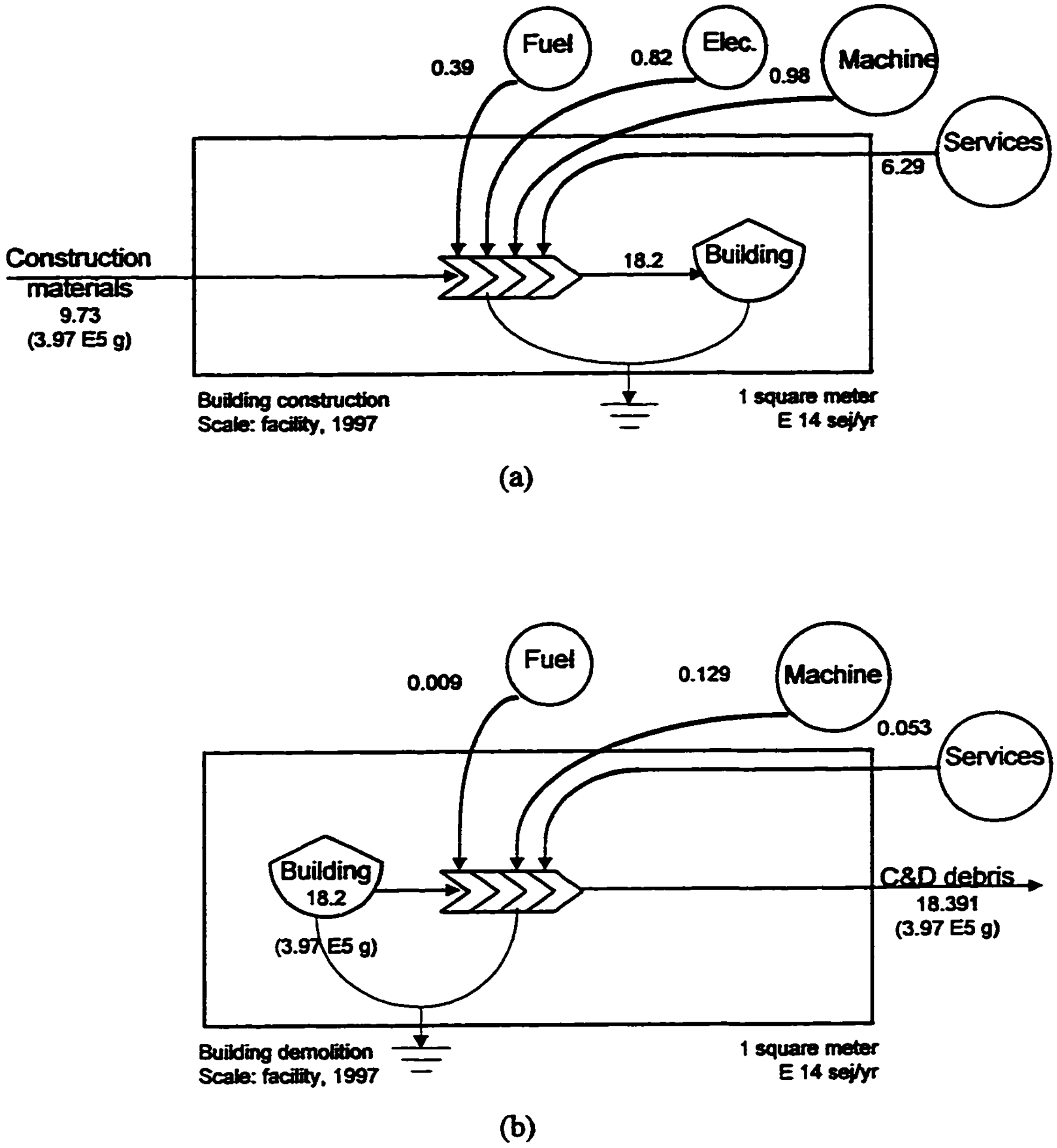


Figure D-3. Emergy evaluation of building construction. Data are from Table D-5.

Table D-6. Emergy evaluation of building demolition (University of Florida) 1997.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
1	Materials in building	g	3.25E+09	4.58E+09	14.90
2	Fuel	J	1.18E+11	6.60E+04	0.0078
3	Transport (Truck)	ton-mile	7.17E+04	9.65E+11	0.07
4	Machinery	g	1.58E+07	6.70E+09	0.11
5	Labor	$	3.80E+04	1.15E+12	0.04
6	Yield C&D debris	g	3.22E+09	4.70E+09	15.13
7	Yield C&D (sq.ft.)	sq.ft.	2.87E+04	5.28E+14	15.13
8	Yield C&D (sq.m.)	sq.m.	8.19E+02	1.85E+16	15.13

Emergy (sej) per gram of demolished building materials in processes (excluding material itself)

3.22E+09	Total building materials in grams
1.57E+17	Total sej from process inputs (fuels, machinery, and labor), excluding transportation.
4.87E+07	sej per gram of demolished building materials in processes (excluding material itself)

Footnotes:

1 Materials in building

(250 lb/sq.ft.)(28664 sq.ft. of building)(454 g/lb)

= 3.253E+09 g

Transformity 4.58E+09 Sej/g (This study, Table D-5)

2 Fuel 3 gal/hr concrete saw, 3.3 gal/hr excavator (John Deere Co., 1998)

2.9 gal/hr loader, and 7.6 gal/hr off-road dump truck (John Deere Co., 1998)

[(3 gal/hr saw)(50 hr)+(3.3 gal/hr excavator)(120 hr)+(2.9 gal/hr)(120 hr)]

*125000 Btu/gal)(1054 J/Btu)

= 1.178E+11 J

Transformity 66000 Sej/J (Odum, 1996, p. 308)

Table D-6--continued.

3 Transport (Truck) 20 miles to landfill (40 miles round trip), approximately 190 loads
[(250 lb/sq.ft.)(28664 sq.ft. of building)/(2000 lb/short ton)]*(20 miles)
= 71660 ton-mile
Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

4 Machinery 2 large concrete saws for 5 days
1/220 Truck excavator and operator with driver for 12 days
1/250 Loader and operator with driver for 12 days
3 dump trucks with drivers for 12 days

50000 lb/ concrete saw, 50000 lb/ excavator (John Deere, 1997; Construction Equipment On-Line, 1997)
30000 lb/ loader, 30000 lb/ dump truck (John Deere, 1997; Construction Equipment On-Line, 1997)
Average age of machinery is 4.3 years (Moore, 1998)

[(2 units)(50000 lb/concrete saw)(5/365 days*5 yr)](454 g/lb)+[(50000 lb excavator + 30000 lb loader + 3*30000 lb dump truck)(12/365 days*5 yr)] *(454 g/lb)
= 15796712 g
Transformity 6.7E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4)

5 Labor
(176 man-hours*5 days)+(136 man-hours*12 days)+(6 man-hours*12 days)
= 2584 man-hours
14.69 $/hr (Statistical Abstract, 1995, Table 666, p.424)
(2584 man-hours)(14.69 $/hr)
= 37958.96 $
Transformity 1.15E+12 Sej/$ for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)

6 Yield of Demolition debris
2081 lb/cu.yd. (Lund, 1993, p.6.31-6.32 and Tchobanoglous et al, 1993, p.70-71)
[(92000 cu.ft./project)/(27 cu.ft./cu.yd.)](2081 lb/cu.yd.)(454 g/lb)
= 3.219E+09 g

7 Yield of Demolition building area
(28664 sq.ft./project)
= 28664 sq.ft.

8 Yield of Demolition building area
(28664 sq.ft./project)/(35 cu.ft./cu.m.)
= 818.97 sq.m.

Table D-7. Emergy evaluation of construction and demolition (C&D) separation processes (1997).

Note	**Item**	**Unit**	**Input Resource**	**Solar emergy per unit (sej/unit)**	**Emergy (sej) 1.00E+18**
Waste					
1	Concrete	g	1.16E+11	4.70E+09	545.31
2	Dirt	g	4.39E+10	4.70E+09	206.15
3	Wood	g	3.54E+10	4.70E+09	166.25
4	Steels	g	2.83E+09	4.70E+09	13.30
5	Fuel	J	8.22E+12	6.60E+04	0.54
6	Electricity	J	5.18E+11	1.74E+05	0.09
7	Transport (Truck)	ton-mile	4.37E+06	9.65E+11	4.22
8	Machinery	g	3.63E+06	6.70E+09	0.02
9	Labor	$	5.93E+05	1.15E+12	0.68
10	Annual Yield (Y) separated C&D wastes	g	1.98E+11	4.73E+09	936.57

Emergy (sej) per gram of C&D in processes (excluding C&D itself)

1.98E+11 Total C&D waste in grams
1.33E+18 Total sej from process inputs (fuel, electricity, machinery, and labor)
6.71E+06 sej per gram of C&D in processes (excluding C&D itself)

Emergy (sej) per gram of C&D truck transportation (excluding C&D itself)

1.98E+11 Total C&D waste in grams
4.22E+18 Total sej from truck transportation
2.13E+07 sej per gram of C&D in processes (excluding C&D itself)

Footnotes:

1 Concrete — Total input 700 ton/day, 6 days/week, 410 ton/day of concrete
(410 short tons/day)(312 days/yr)(907000 g/short ton)
= 1.16E+11 g
Transformity — 4.70E+09 Sej/g — demolition (This study, Table D-6)

2 Dirt — Total input 700 ton/day, 6 days/week, 155 ton/day of dirt
(155 short tons/day)(312 days/yr)(907000 g/short ton)
= 4.386E+10 g
Transformity — 4.70E+09 Sej/g — demolition (This study, Table D-6)

3 Wood — Total input 700 ton/day, 6 days/week, 125 ton/day of wood
(125 short tons/day)(312 days/yr)(907000 g/short ton)
= 3.537E+10 g
Transformity — 4.70E+09 Sej/g — demolition (This study, Table D-6)

4 Steels — Total input 700 ton/day, 6 days/week, 10 ton/day of steels
(10 short tons/day)(312 days/yr)(907000 g/short ton)
= 2.83E+09 g
Transformity — 4.70E+09 Sej/g — demolition (This study, Table D-6)

Table D-7--continued.

5 Fuel 200 gal/day for main crusher, 300 gal/day for trucks
(200 gal/day)(312 days/yr)(125000 Btu/gal)(1054 J/Btu)
= 8.221E+12 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

6 Electricity
(12000 kWh/mo)(12 mo/yr)(3.6 E+06 J/kWh)
= 5.184E+11 J
Transformity 174000 Sej/J (Odum, 1996, p. 305)

7 Transport (Truck) 20 miles distance of inputs, using 40 cu.yd. hauling trucks.
(700 ton/day*20 miles)*(312 days/yr)
= 4368000 ton-mile
Transformity 9.65E+11 Sej/ton-mile (This study, Table E-1)

8 Machinery 40 tons for main crusher, Total machinery 100 tons, expected 25 years of life
[(100 tons)(907000 g/short ton)]/(25 yr)
= 3628000 g
Transformity 6.7E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4)

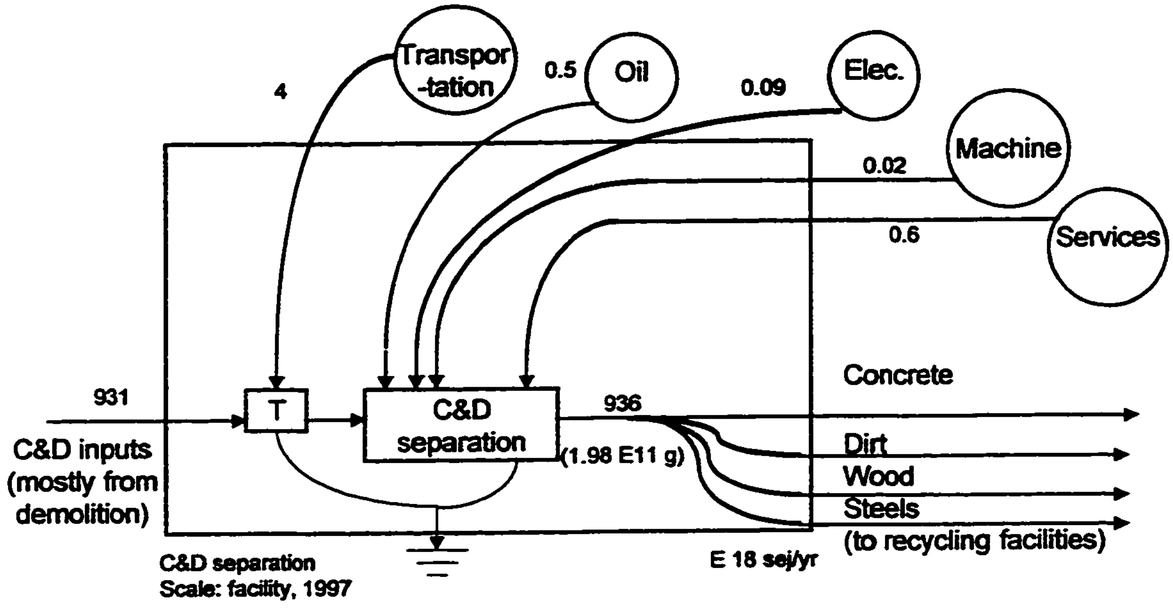
9 Labor 10 employees in operation, 10 employees of truck drivers
(20 employees)(2E+10 J/yr)
= 4E+11 J

570 $/week/employees (Statistical Abstract 1995, Table 666, p.424)
(20 employees)(570 $/week)(52 weeks/yr)
= 592800 $
Transformity 1.15E+12 Sej/$ for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)

10 Annual Yield of Construction and Demolition outputs
(700 short tons/day)(312 days/yr)(907000 g/short ton)
= 1.981E+11 g

Split pathway
Yield of Concrete (410 tons/day)(312 days/yr)(907000 g/short ton)
= 1.16E+11 g
Yield of Dirt (155 tons/day)(312 days/yr)(907000 g/short ton)
= 4.386E+10 g
Yield of Wood (125 tons/day)(312 days/yr)(907000 g/short ton)
= 3.537E+10 g
Yield of Steels (10 tons/day)(312 days/yr)(907000 g/short ton)
= 2.83E+08 g

Costs
250 $/load input (40 cu.yd, 38 tons), 3 $/ton output
Total revenue is [(250 $/load)(700 ton/day)/(38 ton/load)+(3 $/ton)(700 ton/day)]*(300 day/yr)
= 2011578.9 $ 1381578.947 $ of input/yr
630000 $ of output/yr



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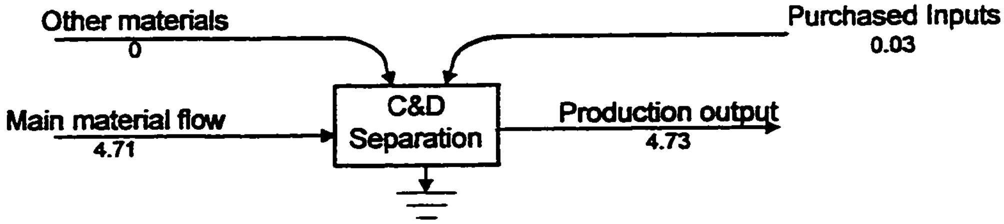

(b)

Figure D-4. Emergy systems diagram construction and demolition (C&D) separation processes (a) and summary diagram (b). Data are from Table D-7.

Table D-8. Emergy evaluation of crushed concrete aggregate 1997.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+18
1	Concrete (waste)	g	7.95E+10	4.70E+09	373.43
2	Oil	J	2.37E+12	6.60E+04	0.16
3	Electricity	J	2.89E+11	1.74E+05	0.05
4	Transport (Truck)	ton-mile	8.76E+06	9.65E+11	8.45
5	Machinery	g	1.25E+08	6.70E+09	0.84
6	Labor	$	2.37E+05	1.15E+12	0.27
7	Annual Yield crushed concrete (with services)	g	7.95E+10	4.81E+09	382.50
8	Annual Yield crushed concrete (without services)	g	7.95E+10	4.82E+09	383.20

Emergy (sej) per gram of crushed concrete from separation facility (excluding concrete itself)

7.95E+10 Total concrete waste in grams
9.77E+18 Total sej from process inputs (fuel, electricity, truck, machinery, and labor)
1.23E+08 sej per gram of concrete in processes (excluding concrete itself)

Emergy (sej) per gram of crushed concrete from separation facility (excluding concrete itself)

7.95E+10 Total concrete waste in grams
1.32E+18 Total sej from process inputs (fuel, electricity, machinery, and labor) excluding truck
1.66E+07 sej per gram of concrete in processes (excluding concrete itself)

Footnotes:

1 Concrete (waste)
(292 tons/day)(25 days/mo)(12 mo/yr)(907000 g/ton)
= 79453200000 g
Transformity 4.70E+09 Sej/g using demolition (This study, Table D-6)

2 Oil
(1500 gal/mo)(12 mo/yr)(125000 Btu/gal)(1054 J/Btu)
= 2.3715E+12 J
Transformity 6.60E+04 Sej/J (Odum, 1996, p. 308)

3 Electricity
(6700 kWh/mo)(12 mo/yr)(3.6 E+06 J/kWh)
= 2.8944E+11 J
Transformity 1.74E+05 Sej/J (Odum, 1996, p. 305)

4 Transport (Truck) 10 ton/truck (22000 lb/truck), 100 miles maximum distance
(292 tons/day)(25 days/mo)(12 mo/yr)(100 miles)
= 8760000 ton-mile
Transformity 9.65E+11 sej/ton-mile (This study, Table E-1)

Table D-8--continued.

5 Machinery

[(23 machines)(150 ton/machine)(907000 g/ton)]/(25 yr)
= 125166000 g
Transformity 6.70E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4)

6 Labor

(8 employees)(2E+10 J/yr)
= 1.6E+11 J

570 $/week/employees (Statistical Abstract 1995, Table 666, p.424)
(8 employees)(570 $/week)(52 weeks/yr)
= 237120 $
Transformity 1.15E+13 Sej/$ for US in 1997 (Projected from Odum, 1996, Table D.1, p. 313-315)

7 Annual Yield of Crushed Concrete aggregates

(292 tons/day)(300 days/yr)(907000 g/ton)
= 79453200000 g
(17 $/cu.yd)(550-600 cu.yd/day) = 3.06E+6 $/yr

APPENDIX E
EMERGY EVALUATION OF TRANSPORTATION

Transportation is one effective factor to recycling evaluation. Trucks, class I railroad, and domestic ships were evaluated. Transformities of transportation modes were calculated in solar emergy per ton-mile (sej/ton-mile) which means to transport one ton of goods for one mile distance. The transformities of trucks, class I railroad, and domestic ships are 9.65 E+11, 5.07 E+10, and 1.17 E+11 sej per ton-mile respectively. Transformity of class I railroad is lower than domestic ships which correspond to those transformities in 1975; 3.07 E+10 sej per ton-mile for train and 7.55 E+10 sej per ton-mile for ships (updated data from Bayley et al., 1977). In 1977, the actual energy used by train was 522.6 Btu per ton-mile, and by ships was 1029.3 Btu per ton-mile (Bayley et al., 1977, Table 8, p.69 and Table 5, p.54). In 1994, the actual energy used by train was 388 Btu per ton-mile, and by ships was 369 Btu per ton-mile (Davis and McFarlin, 1996, Table 6.9, p.6-10 and Table 6.5, p.6-6). Transportation distance for trucks is usually 4 to 6 hours which is approximately 300 to 400 miles.

Table E-1. Emergy evaluation of trucks transportation in the United States 1994.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
	Truck materials				
1	Conventional steel	g	4.88E+12	1.78E+09	86.92
2	High-strength steel	g	9.74E+11	1.78E+09	17.34
3	Stainless steel	g	1.57E+11	1.78E+09	2.79
4	Other steels	g	1.57E+11	1.78E+09	2.79
5	Iron	g	1.39E+12	1.78E+09	24.72
6	Aluminum	g	6.50E+11	1.63E+10	105.88
7	Rubber	g	4.70E+11	4.30E+09	20.23
8	Plastics/composite	g	8.62E+11	3.28E+09	28.29
9	Glass	g	3.25E+11	4.26E+09	13.84
10	Copper	g	1.57E+11	6.77E+10	106.15
11	Zinc die castings	g	5.60E+10	6.77E+10	37.91
12	Power metal parts	g	1.01E+11	6.70E+09	6.75
13	Other materials	g	3.58E+11	1.00E+09	3.58
	Highway construction				
14	Cement	g	4.42E+13	2.20E+09	971.80
15	Bitumen	g	1.89E+14	3.80E+08	719.07
16	Aggregates ***	g	0.00E+00	1.00E+09	
17	Steels	g	7.83E+12	1.78E+09	139.36
18	Concrete pipe	g	6.82E+12	1.20E+09	81.89
19	Lumber	J	7.47E+14	4.40E+04	0.33
20	Fuel	J	2.25E+16	6.60E+04	14.87
21	Aluminum culvert	g	3.20E+09	1.63E+10	0.52
	Fuel use				
22	Petroleum gas	J	2.39E+16	4.80E+04	11.48
23	Diesel fuel	J	3.54E+18	6.60E+04	2335.89
24	Gasoline	J	5.35E+18	6.60E+04	3529.54
	Services				
25	Human services (construction)	$	3.56E+09	1.31E+12	46.66
26	Human services (drivers)	$	1.28E+09	1.31E+12	16.78
27	Other human services (profit)	$	3.31E+10	1.31E+12	433.24
28	Annual Yield of Trucks (with services)	ton-mile	9.08E+11	9.65E+11	8758.65
29	(with services)	tonne-kilometer	1.33E+12	6.61E+11	8758.65

*** Excluded to avoid double counting.

Table E-1--continued.

Footnotes:

63445000 trucks of 1994, 839537 million miles/yr 1994 (DOT:NTS, 1997, Table 4-8)
57141000 Class 1 and 2 trucks of 1994 (Davis and McFarlin, 1996, Table 3.22, p. 3-25)
1626000 Class 6 trucks (Davis and McFarlin, 1996, Table 3.26, p. 3-29)
4678000 Class 8 trucks of 1994 (Davis and McFarlin, 1996, Table 3.23, p. 3-26)

Body weight truck (Woods et al, 1960, Table 23-6, p.23-18)
[(57141000 class 1 and 2 trucks)(3500 lb/truck)+(1626000 class 6 trucks)(6000 lb/truck)
+(4678000 class 8 trucks)(8000 lb/truck)](454 g/lb)
= 1.12217E+14 g

1 Conventional steel
43.6% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.436)(1.12E+14 g of trucks 1994)/(10 yr)
= 4.8832E+12 g
Transformity 1.78E+09 Sej/g (Odum, 1996, p.186)

2 High-strength steel
8.7% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.087)(1.12E+14 g of trucks 1994)/(10 yr)
= 9.744E+11 g
Transformity 1.78E+09 Sej/g (Odum, 1996, p.186)

3 Stainless steel
1.4% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.014)(1.12E+14 g of trucks 1994)/(10 yr)
= 1.568E+11 g
Transformity 1.78E+09 Sej/g (Odum, 1996, p.186)

4 Other steels
1.4% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.014)(1.12E+14 g of trucks 1994)/(10 yr)
= 1.568E+11 g
Transformity 1.78E+09 Sej/g (Odum, 1996, p.186)

5 Iron
12.4% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.124)(1.12E+14 g of trucks 1994)/(10 yr)
= 1.3888E+12 g
Transformity 1.78E+09 Sej/g (Odum, 1996, p.186)

6 Aluminum
5.8% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.058)(1.12E+14 g of trucks 1994)/(10 yr)
= 6.496E+11 g
Transformity 1.63E+10 Sej/g (Odum et al., 1995, p. B-2)

7 Rubber
4.2% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.042)(1.12E+14 g of trucks 1994)/(10 yr)
= 4.704E+11 g
Transformity 4.30E+09 Sej/g (Odum et al., 1987a, p. 159)

Table E-1--continued.

8 Plastics/composite 7.7% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.077)(1.12E+14 g of trucks 1994)/(10 yr)
= 8.624E+11 g
Transformity 3.28E+09 Sej/g (This study, Table C-8)

9 Glass 2.9% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.029)(1.12E+14 g of trucks 1994)/(10 yr)
= 3.248E+11 g
Transformity 4.26E+09 Sej/g (Haukoos, 1995, Table A-16, p.180)

10 Copper 1.4% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.014)(1.12E+14 g of trucks 1994)/(10 yr)
= 1.568E+11 g
Transformity 6.77E+10 Sej/g (Odum et al., 1987a, p. 159)

11 Zinc die castings 0.5% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.005)(1.12E+14 g of trucks 1994)/(10 yr)
= 56000000000 g
Transformity 6.77E+10 Sej/g (Odum et al., 1987a, p. 159)

12 Power metal parts 0.9% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.009)(1.12E+14 g of trucks 1994)/(10 yr)
= 1.008E+11 g
Transformity 6.70E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4-5)

13 Other materials 3.2% by weight (Davis and McFarlin, 1996, Table 3.12, p. 3-14)
(0.032)(1.12E+14 g of trucks 1994)/(10 yr)
= 3.584E+11 g
Transformity 1.00E+09 Sej/g

Highway construction
(133.93 million cars*3000 lb/car) (Davis and McFarlin, 1996, Table 3.10, p. 3-12)
= 4.0179E+11 lb of cars
(86638 buses/yr 1994* 25000 lb/bus) (Davis and McFarlin, 1996, Table 3.31, p. 3-33)
12 people per bus in average (Davis and McFarlin, 1996, Table 3.31, p. 3-33)
(547718 school buses/yr 1994* 15000 lb/school bus) (Davis and McFarlin, 1996, Table 3.31, p. 3-33)
30 students per school bus in average
[(86638*25000)+(547718*15000)]
= 1.04E+10 lb of buses
(Davis and McFarlin, 1996, Table 3.22-3.23, p. 3-25,3-26)
(57141000 Class 1 & 2 trucks*6000 lb/truck)+(4678000 Class 6 trucks*23000 lb/truck)
+(1625000 class 8 trucks*33000 lb/truck)
= 5.04065E+11 lb of trucks

9.16237E+11 total lb of cars, buses, and trucks
= 55.01 percent of trucks in 1994

Table E-1--continued.

Total length of highway 3907000 miles in 1994 (Statistical Abstract, 1997, Table 1023, p.636)
Highway construction of five year average is 1.9 million $/mile.
(3907000 miles in 1994)(1.9 million $/mile) = 7423300 million $

14	Cement	835 short tons/million $ of construction cost in average from 1972-1995 (DOT: Federal Highway 1993-94-95, 1996, p.2) 71 years life expectancy (Woods et al, 1960, p.19-21) (0.55)(7423300 million $)(835 tons/million $ cost)(907000 g/ton)/(70 yr)	
		= 4.41729E+13 g	
	Transformity	2.20E+09 Sej/g	Updated (Haukoos, 1995)
15	Bitumen	511 short tons/million $ of construction cost in average from 1972-1995 (DOT: Federal Highway 1993-94-95, 1996, p.2) (0.55)(7423300 million $)(511 tons/million $ cost)(907000 g/ton) /(10 yr)	
		= 1.89229E+14 g	
	Transformity	3.80E+08 Sej/g	(Odum et al., 1987a, p. 159)
16	Aggregates ***	26955 short tons/million $ of construction cost in average from 1972-1995 (DOT: Federal Highway 1993-94-95, 1996, p.2) 100 years life expectancy (Woods et al, 1960, p.3-11) 5000 yr (one-forth) life of rock (Odum, 1996, Table 3.6, p.50) (0.55)(7423300 million $)(26955 tons/million $ cost) (907000 g/ton)/(5000 yr)	
		= 1.99635E+13 g	
	Transformity	1.00E+09 Sej/g	
17	Steels	148 short tons/million $ of construction cost in average from 1972-1995 (DOT: Federal Highway 1993-94-95, 1996, p.2) 71 years life expectancy (Woods et al, 1960, p.19-21) (0.55)(7423300 million $)(148 tons/million $ cost)(907000 g/ton) /(70 yr)	
		= 7.82944E+12 g	
	Transformity	1.78E+09 Sej/g	(Odum, 1996, p.186)
18	Concrete pipe	129 short tons/million $ of construction cost in average from 1972-1995 (DOT: Federal Highway 1993-94-95, 1996, p.2) 71 years life expectancy (Woods et al, 1960, p.19-21) (0.55)(7423300 million $)(129 tons/million $ cost)(907000 g/ton) /(70 yr)	
		= 6.82431E+12 g	
	Transformity	1.20E+09 Sej/g	(Haukoos, 1995, Table A-13, p.172)
19	Lumber	8909 bd.ft./million $ of construction cost in average from 1972-1995 (DOT: Federal Highway 1993-94-95, 1996, p.2) (0.55)(6418 million $/yr 1994)(8909 bd.ft./million $ cost) (2.5 lb/bd.ft.) *(454 g/lb)(5 kcal/g)(4186 J/kcal)/(1 yr)	
		= 7.47062E+14 J	35693342779 g
	Transformity	4.40E+04 Sej/J	(Odum, 1996, p.308)

Table E-1--continued.

20	Fuel	48454 gal/million $ of construction cost in average from 1972-1995 (DOT: Federal Highway 1993-94-95, 1996, p.2) 25979 gal/million $ of construction cost (DOT: Highway Statistics 1995, p.IV-51) (0.55)(6418 million $/yr 1994)(48454 gal/million $ cost)(125000 Btu/gal)(1054 J/Btu)/(1 yr) = 2.25342E+16 J
	Transformity	66000 Sej/J (Odum, 1996, p. 308)
21	Aluminum culvert	121 lb/million $ of construction cost (DOT: Highway Statistics 1995, p.IV-51) (0.55)(7423300 million $)(121 lb/million $ cost)(454 g/lb)/(70 yr) = 3204076560 g
	Transformity	1.63E+10 Sej/g (Odum et al., 1995, p. B-2)
	Fuel use	
22	Petroleum gas	(Davis and McFarlin, 1996, Table 2.10, p. 2-11) (22.7 trillion Btu/yr)(1054 J/Btu) = 2.39258E+16 J
	Transformity	48000 Sej/J (Odum, 1996, p. 308)
23	Diesel fuel	(Davis and McFarlin, 1996, Table 2.10, p. 2-11) (3357.9 trillion Btu/yr)(1054 J/Btu) = 3.53923E+18 J
	Transformity	66000 Sej/J (Odum, 1996, p. 308)
24	Gasoline	(Davis and McFarlin, 1996, Table 2.10, p. 2-11) (5073.8 trillion Btu/yr)(1054 J/Btu) = 5.34779E+18 J
	Transformity	66000 Sej/J (Odum, 1996, p. 308)
	Services	
25	Human services (construction)	257000 employees/yr 1994 (Statistical Abstract 1997, Table 1176, p. 713) 81272000 labor hr in 1994, 15.76 $/hr (DOT: Highway Statistics 1995, p.IV-52) (257000 employees/yr 1994)(2E+10 J/person/yr) = 5.14E+15 J 6418 million $/yr 1994 value of construction (DOT: Highway Statistics 1995, p.IV-52) 55.5% of construction cost is overhead, profit, and wages (DOT: Highway Statistics 1995, p.IV-50) (0.555)(6418 million $/yr 1994) = 3.56E+09 $
	Transformity	1.31E+12 Sej/$ for US in 1994 (Projected from Odum, 1996, Table D.1, p. 313-315)

37671 million $/yr 1994 value of new construction (Statistical Abstract 1997, Table 1180, p. 715)

15711 million $/yr value added (Statistical Abstract 1997, Table 1176, p. 713)

Table E-1--continued.

26	Human services (drivers)	2565000 employees/yr 1994 (Statistical Abstract 1997, Table 646, p. 413)	
		(2565000 employees/yr 1994)(2E+10 J/person/yr)	
		= 5.13E+16 J	
		15.76 \$/hour 1994, 81272000 labor hours/1994 (DOT: Highway Statistics 1995, p.IV-52)	
		(15.76 \$/hour 1994)(81272000 hours/yr)	
		= 1.28E+09 \$	
	Transformity	1.31E+12 Sej/\$	for US in 1994 (Projected from Odum, 1996, Table D.1, p. 313-315)
27	Other human services (profit)	Annual revenue 330716 million \$/yr 1994 (Statistical Abstract 1997, Table 989, p. 617)	
		10% as a profit	
		(0.1)(330716 million \$ in 1994)	
		= 3.31E+10 \$	
	Transformity	1.31E+12 Sej/\$	for US in 1994 (Projected from Odum, 1996, Table D.1, p. 313-315)
28	Annual Yield of Trucks		
		908000 million ton-miles of freight trucks 1994 (DOT:NTS, 1997, Table 1-9)	
		= 9.08E+11 ton-mile	
		tonne = metric ton	
		1325655 million tonne-kilometers of trucks 1994 (DOT:NTS, 1997, Table 1-9M)	
		= 1.32566E+12 tonne-kilometer	

Table E-2. Emergy evaluation of class I railroad transportation in the United States 1994.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
	Locomotive and car				
1	Steel and Iron	g	1.13E+11	1.78E+09	2.02
2	Engine	g	1.01E+10	6.70E+09	0.68
3	Lubricants	g	3.02E+11	6.70E+09	20.26
4	Steel (fright car)	g	1.56E+12	1.78E+09	27.79
	Fuel use				
5	Diesel fuel (use)	J	4.91E+17	6.60E+04	323.75
	Railroad construction				
6	Tee rail (steel)	g	1.33E+12	1.78E+09	23.74
7	Gravels ***	g	0.00E+00	1.00E+09	
8	Tie (wood)	J	5.06E+14	4.10E+04	0.21
	Services				
9	Human services (construction)	$	1.84E+09	1.31E+12	24.06
10	Human services (operation)	$	8.90E+09	1.31E+12	116.65
11	Other human services (profit)	$	5.30E+09	1.31E+12	69.40
12	Annual Yield of Railroad (with services)	ton-mile	1.20E+12	5.07E+10	608.57
13	(with services)	tonne-kilometer	1.75E+12	3.47E+10	608.57

*** Excluded to avoid double counting.

Footnotes:

1 Steel and Iron
90% by weight locomotive (Lawson and Cook, 1981, Table 2 and A-2)
18505 locomotives and 590930 cars/yr 1994 (National, 1997, table 4-11)
(0.9)[(450000 lb/locomotive)(18505 locomotives)(454 g/lb)/(30 yr)
= 1.13417E+11 g
Transformity 1.78E+09 Sej/g (Odum, 1996, p.186)

2 Engine
8% by weight locomotive (Lawson and Cook, 1981, Table 2 and A-2)
(0.08)[(450000 lb/locomotive)(18505 locomotives)(454 g/lb)/(30 yr)
= 10081524000 g
Transformity 6.70E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4-5)

3 Lubricants
2% by weight locomotive (Lawson and Cook, 1981, Table 2 and A-2)
(0.02)[(450000 lb/locomotive)(18505 locomotives)(454 g/lb)/(0.25 yr)
= 3.02446E+11 g
Transformity 6.70E+09 Sej/g

Table E-2--continued.

4	Steel (fright car)	590930 cars/yr 1994 (National, 1997, Table 4-11) 87300 lb/car (DOT: Truck Design, 1981, Table A-1, p. A-2) (590930 cars/yr 1994)(87300 lb/car)(454 g/lb)/(15 yr) = 1.5614E+12 g	
	Transformity	1.78E+09 Sej/g	(Odum, 1996, p.186)
	Fuel use		
5	Diesel fuel (use)	465.4 trillion Btu/yr 1994 (Davis and McFarlin, 1996, Table 2.10, p. 2-11) (465.4E+12 Btu/yr)(1054 J/Btu) = 4.90532E+17 J	
	Transformity	66000 Sej/J	(Odum, 1996, p. 308)
	Railroad construction		
6	Tee rail (steel)	110 lb/yard (Railroad Construction, 1970, Fig.5-1, p.5-1 and Table 5-1, p.5-2) approximately 50% is double track (Railroad Construction, 1970) 354000 miles/yr 1994 (Statistical Abstract, 1997, Table 1039, p.643) (1.5)(2 sides)(110 lb/yard)(1760 yard/mile)(354000 miles/yr 1994)(454 g/lb)/(70 yr) = 1.33E+12 g	
	Transformity	1.78E+09 Sej/g	(Odum, 1996, p.186)
7	Gravels ***	846 cu.yd./1000 ft track (Railroad Construction, 1970, Fig.5-1, p.5-1 and Table 5-1, p.5-2) = 2.538 cu.yd./yard of track 5000 yr (one-forth) life of rock (Odum, 1996, Table 3.6, p.50) 3000 lb/cu.yd. (Hornbostel, 1978, p.371) (2.538 cu.yd./yard)(3000 lb/cu.yd.)(1760 yard/mile)(354000 miles/yr 1994)(454 g/lb)/(5000 yr) = 4.31E+11 g	
	Transformity	1.00E+09 Sej/g	
8	Tie (wood)	1 Tie/yard (Railroad Construction, 1970, Fig.4-18, p.4-22) 6"x7"x8' = 2.33 cu.ft. (Railroad Construction, 1970, Fig.4-32, p.4-30 and p.B-4) add 10% for bridges, switches, etc. (1.10)(2.33 cu.ft./Tie)(1 Tie/yard)(1760 yards/mile)(354000 miles/yr 1994)(454 g/lb)(5 kcal/g)(4186 J/kcal)/(30 yr) = 5.06E+14 J	
	Transformity	4.10E+04 Sej/J	
	Services		
9	Human services (construction)	3340 million $/yr 1994 (Statistical Abstract, 1997, Table 1180, p.715) 55% is profit, overhead, and wages (0.55)(3340 million $/yr 1994) = 1837000000 $	
	Transformity	1.31E+12 Sej/$	for US in 1994 (Projected from Odum, 1996, Table D.1, p. 313-315)

Table E-2--continued.

10 Human services (operation)

190000 employees/yr 1994 (Statistical Abstract, 1997, Table 1039, p.643)

(190000 employees/yr 1994)(2E+10 J/person/yr)

= 2.306E+15 J

8874 million \$/yr 1994 (Statistical Abstract, 1997, Table 1039, p.643)

120.5 man-hours/yr per locomotive maintenance (Lawson and Cook, 1981, Table 4, p. 22)

13.88 \$/hr, 554 \$/week 1994 (Statistical Abstract, 1995, Table 666, p. 424)

[(8874 million \$/yr 1994)]+[(120.5 man-hours/locomotive/yr)(18505 locomotive)(13.88 \$/hr 1994)]

= 8904950353 \$

Transformity 1.31E+12 Sej/\$ for US in 1994 (Projected from Odum, 1996, Table D.1, p. 313-315)

11 Other human services (profit)

5298 million \$/yr 1994 operating net revenue (~17%) (Statistical Abstract, 1997, Table 1039, p.643)

= 5.30E+09 \$

Transformity 1.31E+12 Sej/\$ for US in 1994 (Projected from Odum, 1996, Table D.1, p. 313-315)

12 Annual Yield of Class I Railroad

441 million train-miles of Class I Railroad 1994 (DOT:NTS, 1997, Table 1-8)

28485 million car-miles of Class I Railroad 1994 (DOT:NTS, 1997, Table 1-8)

1200701 million ton-miles of Class I Railroad 1994 (DOT:NTS, 1997, Table 1-9)

= 1.2007E+12 ton-mile

710 million train-kilometers of Class I Railroad 1994 (DOT:NTS, 1997, Table 1-8M)

45842 million car-kilometers of Class I Railroad 1994 (DOT:NTS, 1997, Table 1-8M)

1752990 million tonne-kilometers of Class I Railroad 1994 (DOT:NTS, 1997, Table 1-9M)

= 1.75299E+12 tonne-kilometer

2815000000 ton/yr 1994 (Davis and McFarlin, 1996, Table 6.9, P. 6-10)

= 2815000000 ton

23179000 carloads/yr 1994 (Statistical Abstract, 1996, Table 1034, p.640)

33121 million \$/yr 1994 revenue (Statistical Abstract, 1997, Table 989, p. 617)

30809 million \$/yr 1994 operating revenues (Statistical Abstract, 1997, Table 1039, p.643)

25511 million \$/yr 1994 operating expenses (Statistical Abstract, 1997, Table 1039, p.643)

Table E-3. Emergy evaluation of domestic water freight (ship) transportation in the United States 1994.

Note	Item	Unit	Input Resource	Solar emergy per unit (sej/unit)	Emergy (sej) 1.00E+20
	Ships				
1	Steel	g	1.64E+13	1.78E+09	292.04
2	Engine	g	4.69E+12	6.70E+09	314.07
3	Others	g	4.69E+12	1.00E+09	46.88
	Fuel use				
4	Diesel fuel	J	2.96E+17	6.60E+04	195.54
	Services				
5	Labor (repairing)	$	2.97E+09	1.31E+12	38.91
6	Labor (operation)	$	4.78E+09	1.31E+12	62.65
7	Annual Yield of Ships (with services)	ton-mile	8.15E+11	1.17E+11	950.09
9	(with services)	tonne-kilometer	1.19E+12	7.99E+10	950.09

Footnotes:

1 Steel
39064 vessels/yr 1994 (Davis and McFarlin, 1996, Table 6.5, p. 6-6)
Average body weight 30000 ton/vessel, 70% steel of vessel
(http://www.shipinformationcenter.com, January 15, 1998)
(0.7)(30000 ton/vessel)(1000000 g/ton)(39064 vessels/yr 1994)/50 yr
= 1.64069E+13 g
Transformity 1.78E+09 Sej/g (Odum, 1996, p.186)

2 Engine
20% of vessel (http://www.shipinformationcenter.com, January 15, 1998)
(0.2)(30000 ton/vessel)(1000000 g/ton)(39064 vessels)/50 yr
= 4.68768E+12 g
Transformity 6.70E+09 Sej/g (Odum et al., 1987b, Table 1, p. 4-5)

3 Others
10% of vessel (http://www.shipinformationcenter.com, January 15, 1998)
(0.1)(30000 ton/vessel)(1000000 g/ton)(39064 vessels)/25 yr
= 4.68768E+12 g
Transformity 1.00E+09 Sej/g

4 Diesel fuel
281.1 trillion (E12) Btu per yr 1994 of Diesel fuel (Davis and McFarlin, 1996, Table 2.10, p. 2-11; Table 6.5, p.6-6)
(281.1E+12 Btu/yr)(1054 J/Btu)
= 2.96279E+17 J
Transformity 66000 Sej/J (Odum, 1996, p. 308)

Table E-3--continued.

5 Labor (repairing) (SIC 3731)
revenue 9896 million $/yr 1994 (Statistical Abstract, 1995, Table 1466, p. 897)
14 $/hr, 560 $/week/employee, 102000 employees/yr 1994 (Statistical Abstract, 1995, Table 1466, p. 897)
(102000 employee)(560 $/week)(52 week/yr)
= 2970240000 $
Transformity 1.31E+12 Sej/$ for US in 1994 (Projected from Odum, 1996, Table D.1, p. 313-315)

6 Labor (operation) (Statistical Abstract, 1995, Table no. 668, p. 428)
(166000 employees/yr 1994)(2E+10 J/person/yr)
= 3.32E+15 J

554 $/week 1994 (Statistical Abstract, 1995, Table no. 668, p. 428)
(554 $/week)(52 weeks/yr)(166000 employees/yr 1994)
= 4782128000 $
Transformity 1.31E+12 Sej/$ for US in 1994 (Projected from Odum, 1996, Table D.1, p. 313-315)

7 Annual Yield of Water Freight
40 foot standard box has 75 cu.m. with maximum 26.5 tons
(http://www.hohenstein-line.com/specs.htm, January 15, 1998)
Deadload 30000 tons with 80000 cu.m. capacity
(http://www.shipinformationcenter.com, January 15, 1998)
698+31910+7033 vessels/yr 1994 (Transportation, 1997, Table 1, p. 3)

497 billion ton-miles/yr 1993 (Statistical Abstract, 1997, Table 992, p.619)
814919 million ton-miles of Domestic Water Transport 1994 (DOT:NTS, 1997, Table 1-9)
= 8.14919E+11 ton-mile
1189759 million tonne-kilometers of Domestic Water Transport 1994 (DOT:NTS, 1997, Table 1-9M)
= 1.18976E+12 tonne-kilometer
1099 million tons shipped/yr 1994 (Davis and McFarlin, 1996, Table 6.5, p. 6-6)
= 1099000000 ton
value added in average 57-61% of value of work done (Statistical Abstract, 1997, Table 1073, p.659)

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BIOGRAPHICAL SKETCH

Vorasun Buranakarn was born in 1967, Bangkok, Thailand. In 1986 he entered the five-year architectural degree program at Chulalongkorn University in Bangkok, Thailand. He graduated in 1991 with the highest score of bachelor thesis. In the same year, he continued his master's studies at the University of Colorado at Denver with computer graphics and real estate majors. After graduation in 1992, he went back to Thailand. He worked as a tenure lecturer at Faculty of Architecture, Chulalongkorn University, as well as in private architect and consultant companies. In August 1995, he entered the Doctor of Philosophy program in the College of Architecture, University of Florida, under a scholarship from the Royal Thai Government. He finished program course work and the qualifying examination in September 1997.

After graduation in 1998, he can be reached at Faculty of Architecture, Chulalongkorn University, Pathumwan, Bangkok 10330, Thailand.

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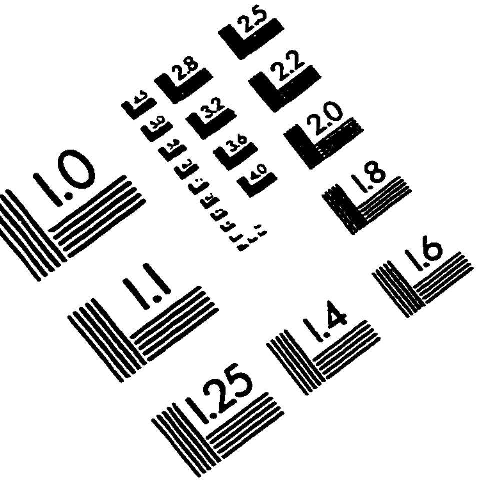

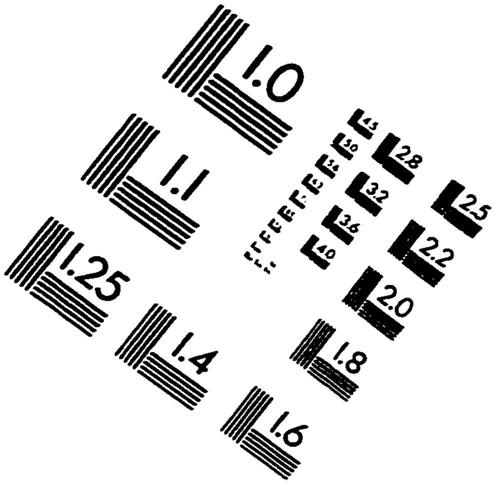

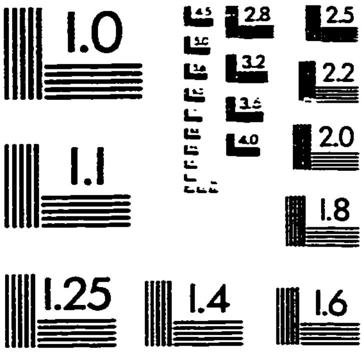

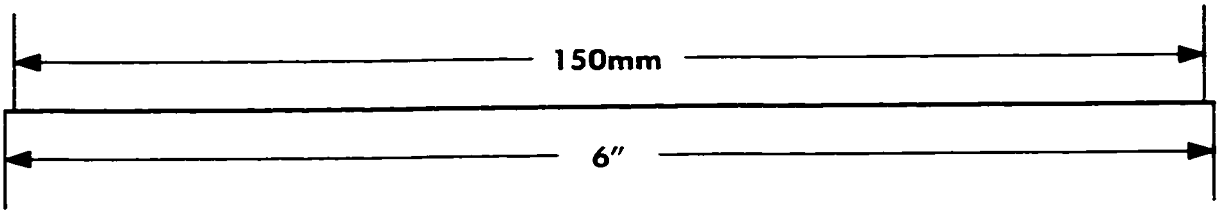

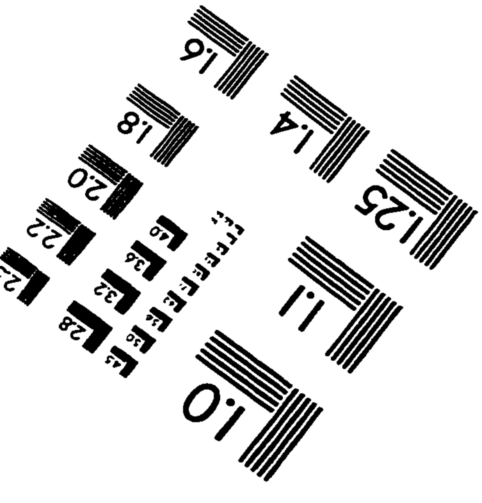

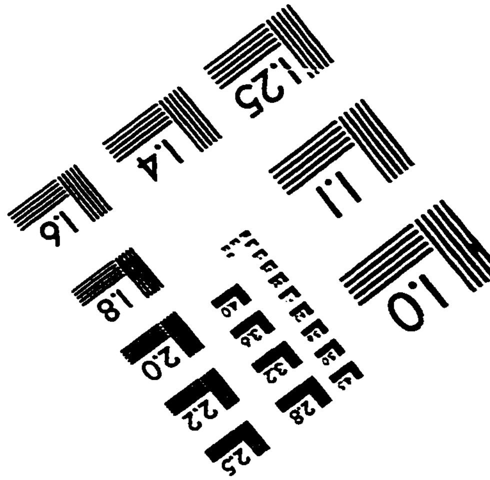

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