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Office of Applied Economics
Building and Fire Research Laboratory
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BEES 1.0

Building for Environmental and Economic Sustainability Technical Manual and User Guide

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Sponsored by:
National Institute of Standards and Technology
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Abstract

The BEES (**B**uilding for **E**nvironmental and **E**conomic **S**ustainability) version 1.0 software implements a rational, systematic technique for selecting environmentally and economically balanced building products. The technique is based on consensus standards and designed to be practical, flexible, and transparent. The Windows-based decision support software, aimed at designers, builders, and product manufacturers, includes actual environmental and economic performance data for 22 building products across a range of functional applications. BEES measures the environmental performance of building products using the environmental life-cycle assessment approach specified in the latest versions of ISO 14000 draft standards. All stages in the life of a product are analyzed: raw material acquisition, manufacture, transportation, installation, use, and waste management. Economic performance is measured using the American Society for Testing and Materials (ASTM) standard life-cycle cost method, which covers the costs of initial investment, replacement, operation, maintenance and repair, and disposal. Environmental and economic performance are combined into an overall performance measure using the ASTM standard for Multiattribute Decision Analysis. For the entire BEES analysis, building products are defined and classified based on the ASTM standard classification for building elements known as UNIFORMAT II.

Key words: Building products, economic performance, environmental performance, green buildings, life cycle assessment, life-cycle costing, multiattribute decision analysis, sustainable development

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Getting Started

System Requirements

BEES runs on a Windows 95 personal computer with a 486 or higher microprocessor, 32 Megabytes or more of RAM, at least 10 Megabytes of available disk space, and a 3.5 inch floppy diskette drive. A printer is preferred but not required.

Installing BEES

Install BEES by inserting Disk 1 into any floppy drive (e.g., drive A) and running the BEES setup program as follows:

In Windows 95, Select Start/Run, then type A:Setup and press Ok.

Running BEES

First-time BEES users may find it useful to read the BEES Tutorial, found in section 4 of this report. The BEES Tutorial is a printed version of the BEES on-line help system, with step-by-step instructions for running the software. The tutorial also includes illustrations of the screen displays. Alternatively, first-time users may choose to double-click on the help icon installed in the BEES program group at installation for an electronic version of the help system.

While running the BEES software, context-sensitive help is often available from the BEES Main Menu. Context-sensitive help is also available through Help buttons on many of the BEES windows.

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1. Background and Introduction

Buildings significantly alter the environment. According to Worldwatch Institute, [1] building construction consumes 40 percent of the raw stone, gravel, and sand used globally each year, and 25 percent of the virgin wood. Buildings also account for 40 percent of the energy and 16 percent of the water used annually worldwide. In the United States, about as much construction and demolition waste is produced as municipal garbage. Unhealthy indoor air is found in 30 percent of new and renovated buildings worldwide.

Negative environmental impacts arise from building construction and renovation. For example, raw materials extraction can lead to resource depletion and biological diversity losses. Building product manufacture and transport consumes energy, generating emissions linked to global warming, acid rain, and smog. Landfill problems may arise from waste generation. Poor indoor air quality may lower worker productivity and adversely affect human health.

Selecting environmentally preferable building products is one way to reduce these negative environmental impacts. However, while 93 percent of U.S. consumers worry about their home's environmental impact, only 18 percent are willing to pay more to reduce the impact, according to a survey of 3,600 consumers in 9 U.S. metropolitan areas.[2] Thus, environmental performance must be balanced against economic performance. Even the most environmentally conscious building product manufacturer or designer will ultimately weigh environmental benefits against economic costs. To satisfy their customers, manufacturers and designers need to develop and select building products with an attractive balance of environmental and economic performance.

Identifying environmentally and economically balanced building products is no easy task. Today, the green building decisionmaking process is based on little structure and even less credible, scientific data. There is a great deal of interesting green building information available, so that in many respects we know what to *say* about green buildings. However, we still do not know how to synthesize the available information so that we know what to *do* in a way that is transparent, defensible, and truly environmentally sound.

In this spirit, the U.S. National Institute of Standards and Technology (NIST) Green Buildings Program began the **B**uilding for **E**nvironmental and **E**conomic **S**ustainability (BEES) project in 1994. The purpose of the BEES project is to develop and implement a

[1] D.M. Roodman and N. Lenssen, *A Building Revolution: How Ecology and Health Concerns are Transforming Construction,* Worldwatch Paper 124, Worldwatch Institute, Washington, DC, March 1995.

[2] 1995 Home Shoppers survey cited in Minneapolis Star Tribune, 11/16/96, p H4 (article by Jim Buchta). According to another survey, Japanese consumers are willing to pay up to 25 percent more for environmentally friendly products (Maurice Strong, Chairman, Earth Council Institute, "Closing Day Keynote Address," *Engineering and Construction for Sustainable Development in the 21st Century,* Washington, DC, February 4-8, 1996, p 54)

systematic methodology for selecting building products that achieve the most appropriate balance between environmental and economic performance based on the decision maker's values. The methodology is based on consensus standards and is designed to be practical, flexible, and transparent. The BEES model is implemented in publicly available decision-support software, complete with actual environmental and economic performance data for a number of building products. The intended result is a cost-effective reduction in building-related contributions to environmental problems.

In 1997, the U.S. Environmental Protection Agency's (EPA) Environmentally Preferable Purchasing (EPP) Program also began supporting the development of BEES. The EPP program is charged with carrying out Executive Order 12873 (10/93), "Federal Acquisition, Recycling, and Waste Prevention," which directs Executive agencies to reduce the environmental burdens associated with the $200 billion in products and services they purchase each year, including building products. Over the next several years, BEES will be further developed as a tool to assist the Federal procurement community in carrying out the mandate of Executive Order 12873.

2. The BEES Model

The BEES methodology takes a multidimensional, life-cycle approach. That is, it considers multiple environmental and economic impacts over the entire life of the building product. Considering multiple impacts and life-cycle stages is necessary because product selection decisions based on single impacts or stages could obscure others that might cause equal or greater damage. In other words, a multidimensional, life-cycle approach is necessary for a comprehensive, balanced analysis.

It is relatively straightforward to select products based on minimum life-cycle economic impacts because building products are bought and sold in the marketplace. But how do we include life-cycle environmental impacts in our purchase decisions? Environmental impacts such as global warming, water pollution, and resource depletion are for the most part economic externalities. That is, their costs are not reflected in the market prices of the products that generated the impacts. Moreover, even if there were a mandate today to include environmental "costs" in market prices, it would be nearly impossible to do so due to difficulties in assessing these impacts in economic terms. How do you put a price on clean air and clean water? What is the value of human life? Economists have debated these questions for decades, and consensus does not appear likely in the near future.

While environmental performance cannot be measured on a monetary scale, it can be quantified using the evolving, multi-disciplinary approach known as environmental life-cycle assessment (LCA). The BEES methodology measures environmental performance using an LCA approach, following guidance in the International Standards Organization 14040 series of draft standards for LCA.[3] Economic performance is separately measured using the American Society for Testing and Materials (ASTM) standard life-cycle cost (LCC) approach. These two performance measures are then synthesized into an overall performance measure using the ASTM standard for Multiattribute Decision Analysis.[4] For the entire BEES analysis, building products are defined and classified based on UNIFORMAT II, the ASTM standard classification for building elements.[5]

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[3] International Standards Organization, *Environmental Management--Life-Cycle Assessment--Principles and Framework,* Draft International Standard 14040, 1996; ISO *Environmental Management--Life-Cycle Assessment—Goal and Scope Definition and Inventory Anslysis,* Committee Draft International Standard 14041.2, 1996; and ISO *Environmental Management--Life-Cycle Assessment—Life Cycle Impact Assessment,* Committee Draft International Standard 14042.1, 1997; and ISO *Environmental Management--Life-Cycle Assessment—Life Cycle Interpretation,* Committee Draft International Standard 14043.1, 1996.

[4] American Society for Testing and Materials, *Standard Practice for Applying the Analytic Hierarchy Process to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems,* ASTM Designation E 1765-95, West Conshohocken, PA, 1995.

[5] American Society for Testing and Materials, *Standard Classification for Building Elements and Related Sitework--UNIFORMAT II,* ASTM Designation E 1557-96, West Conshohocken, PA, September 1996.

2.1 Environmental Performance

Environmental life-cycle assessment is a "cradle-to-grave," systems approach for measuring environmental performance. The approach is based on the belief that all stages in the life of a product generate environmental impacts and must therefore be analyzed, including raw materials acquisition, product manufacture, transportation, installation, operation and maintenance, and ultimately recycling and waste management. An analysis that excludes any of these stages is limited because it ignores the full range of upstream and downstream impacts of stage-specific processes.

The strength of environmental life-cycle assessment is its comprehensive, multi-dimensional scope. Many green building claims and strategies are now based on a single life-cycle stage or a single environmental impact. A product is claimed to be green simply because it has recycled content, or claimed not to be green because it emits volatile organic compounds (VOCs) during its installation and use. These single-attribute claims may be misleading because they ignore the possibility that other life-cycle stages, or other environmental impacts, may yield offsetting impacts. For example, the recycled content product may have a high embodied energy content, leading to resource depletion, global warming, and acid rain impacts during the raw materials acquisition, manufacturing, and transportation life-cycle stages. LCA thus broadens the environmental discussion by accounting for shifts of environmental problems from one life-cycle stage to another, or one environmental medium (land, air, water) to another. The benefit of the LCA approach is in implementing a trade-off analysis to achieve a genuine reduction in overall environmental impact, rather than a simple shift of impact.

The general LCA methodology involves four steps.[6] The *goal and scope definition* step spells out the purpose of the study and its breadth and depth. The *inventory analysis* step identifies and quantifies the environmental inputs and outputs associated with a product over its entire life-cycle. Environmental inputs include water, energy, land, and other resources; outputs include releases to air, land, and water. However, it is not these inputs and outputs, or *inventory flows,* that are of interest. We are more interested in their consequences, or impacts on the environment. Thus, the next LCA step, *impact assessment,* characterizes these inventory flows in relation to a set of environmental impacts. For example, the impact assessment step might relate carbon dioxide emissions, a *flow*, to global warming, an *impact*. Finally, the *interpretation* step combines the environmental impacts in accordance with the goals of the LCA study.

2.1.1 Goal and Scope Definition

The goal of the BEES LCA is to generate relative environmental performance scores for building product alternatives based on U.S. average data. These will be combined with relative, U.S. average economic scores to help the building community select environmentally and economically balanced building products.

[6] International Standards Organization, *Environmental Management--Life-Cycle Assessment--Principles and Framework,* Draft International Standard 14040, 1996.

The scoping phase of any LCA involves defining the boundaries of the product system under study. The manufacture of any product involves a number of unit processes (e.g., ethylene production for input to the manufacture of the styrene-butadiene bonding agent for stucco walls). Each unit process involves many inventory flows, some of which themselves involve other, subsidiary unit processes. The first product system boundary determines which unit processes are included in the LCA. In the BEES system, the boundary-setting rule consists of a set of three decision criteria. For each candidate unit process, mass and energy contributions to the product system are the primary decision criteria. In some cases, cost contribution is used as a third criterion.[7] Together, these criteria provide a robust screening process, as illustrated in figure 2.1, showing how five ancillary materials (e.g., limestone used in portland cement manufacturing) are selected from a list of nine candidate materials for inclusion in the LCA. A material must have a large contribution for at least one decision criterion to be selected. The weight criterion selects materials A, B, and C; the energy criterion adds material E; and cost flags material I. As a result, the unit processes for producing ancillary materials A, B, C, E, and I are included in the system boundaries.

Ancillary Material	***Weight***	***Energy***	*Cost (as a flag when necessary)*	***Included in system boundaries***
A				Yes
B				Yes
C				Yes
D				No
E				Yes
F				No
G				No
H				No
I				Yes

	negligible contribution
	small contribution
	large contribution

Figure 2.1 Decision Criteria for Setting Product System Boundaries

The second product system boundary determines which inventory flows are tracked for in-bounds unit processes. Quantification of *all* inventory flows is not practical for the following reasons:

[7] While a large cost contribution does not directly indicate a significant environmental impact, it may indicate scarce natural resources or numerous subsidiary unit processes potentially involving high energy consumption.

- An ever expanding number of inventory flows can be tracked. For instance, including the U.S. Environmental Protection Agency's Toxic Release Inventory (TRI) data would result in tracking approximately 200 inventory flows arising from polypropylene production alone. Similarly, including radionucleide emissions generated from electricity production would result in tracking more than 150 flows. Managing such large inventory flow lists adds to the complexity, and thus the cost, of carrying out and interpreting the LCA.
- Attention should be given in the inventory analysis step to collecting data that will be useful in the next LCA step, impact assessment. By restricting the inventory data collection to the flows actually needed in the subsequent impact assessment, a more focused, higher quality LCA can be carried out.

Therefore, in the BEES model, a focused, cost-effective set of inventory flows is tracked, reflecting flows that will actually be needed in the subsequent impact assessment step.

Defining the unit of comparison is another important task in the goal and scoping phase of LCA. The basis for all units of comparison is the *functional unit*, defined so that the products compared are true substitutes for one another. In the BEES model, the functional unit for most building products is 0.09 square meters (1 square foot) of product service for 50 years.[8,9] Therefore, for example, the functional unit for the BEES roof covering alternatives is *covering 0.09 square meters (1 square foot) of roof surface for 50 years.* The functional unit provides the critical reference point to which all inventory flows are scaled.

Scoping also involves setting data requirements. Data requirements for the BEES study include:

- Geographic coverage: The data are U.S. average data.
- Time period covered: The data are a combination of data collected specifically for BEES within the last 2 years, and data from the well-known Ecobalance LCA database created in 1990.[10] Most of the Ecobalance data are updated annually. No data older than 1990 are used.
- Technology covered: When possible, the most representative technology is studied. Where data for the most representative technology are not available, an aggregated result is used based on the U.S. average technology for that industry.

2.1.2 Inventory Analysis

Inventory analysis entails quantifying the inventory flows for a product system. Inventory flows include inputs of water, energy, and raw materials, and releases to air, land, and water. Data categories are used to group inventory flows in LCAs. For example, in the BEES model, flows such as aldehydes, ammonia, and sulfur oxides are grouped under the

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[8] All product alternatives are assumed to meet minimum technical performance requirements (e.g., acoustic and fire performance).

[9] The functional unit for concrete products except driveways and sidewalks is 0.76 cubic meters (1 cubic yard) of product service for 50 years.

[10] Ecobalance, Inc., *DEAM™: Data for Environmental Analysis and Management,* Rockville, MD, 1997.

air emissions data category. Figure 2.2 shows the categories under which data are grouped in the BEES system. Refer to the BEES environmental performance data files, accessible through the BEES software, for a detailed listing of approximately 100 inventory flow items included in BEES.

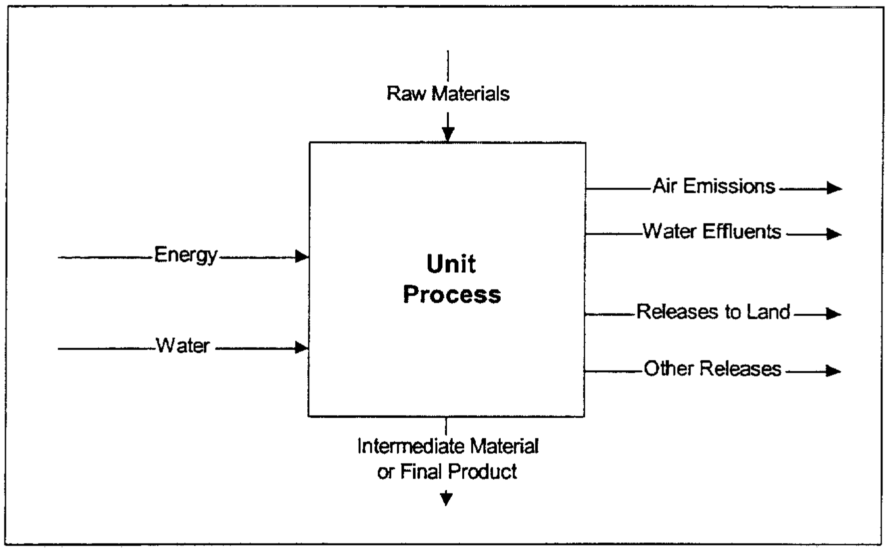

Figure 2.2 BEES Inventory Data Categories

A number of approaches may be used to collect inventory data for LCAs. These range from:[11]

- Unit process- and facility-specific: data from a particular process within a given facility that are not combined in any way
- Composite: data from the same process combined across locations
- Aggregated: data combining more than one process
- Industry-average: data derived from a representative sample of locations believed to statistically describe the typical process across technologies
- Generic: data whose representativeness may be unknown but which are qualitatively descriptive of a process

Since the goal of the BEES LCA is to generate U.S. average results, data are primarily collected using the industry-average approach. Data collection is done under contract with Environmental Strategies and Solutions, Inc. (ESS) and Ecobalance, Inc., using the Ecobalance LCA database covering more than 6,000 industrial processes gathered from actual site and literature searches from more than 15 countries. Where necessary, the data are adjusted to be representative of U.S. operations and conditions. Approximately 90

[11] U.S. Environmental Protection Agency, Office of Research and Development, *Life Cycle Assessment: Inventory Guidelines and Principles*, EPA/600/R-92/245, February 1993.

percent of the data come directly from industry sources, with about 10 percent coming from generic literature and published reports. The generic data include inventory flows for electricity production from the average United States grid, and for selected raw material mining operations (e.g., limestone, sand, and clay mining operations). In addition, ESS and Ecobalance gathered additional LCA data to fill data gaps for the BEES products. Assumptions regarding the unit processes for each building product are verified through experts in the appropriate industry to assure the data are correctly incorporated in BEES.

2.1.3 Impact Assessment

The impact assessment step of LCA quantifies the potential contribution of a product's inventory flows to a range of environmental impacts. There are several well-known LCA impact assessment approaches.

Direct Use of Inventories. In the most straightforward approach to LCA, the impact assessment step is skipped, and the life cycle inventory results are used as-is in the final interpretation step to help identify opportunities for pollution prevention or increases in material and energy efficiency for processes within the life cycle. However, this approach in effect gives the same weight to all inventory flows (e.g., to the reduction of carbon dioxide emissions and to the reduction of lead emissions). For most impacts, equal weighting of flows is unrealistic.

Critical Volumes (Switzerland). The "weighted loads" approach, better known as the Swiss critical volume approach, was the first method proposed for aggregating inventory flow data.[12] The critical volume for a substance is a function of its load and its legal limit. Its load is the total quantity of the flow per unit of the product. Critical volumes can be defined for air and water, and in principle also for soil and groundwater, providing there are legal limit values available.

This approach has the advantage that long lists of inventory flows, especially for air and water, can be aggregated by summing the critical volumes for the individual flows within the medium being considered--air, water, or soil. However, the critical volume approach is rarely used today due to the following disadvantages of using legal limit values:

- Legal limit values are available only for certain chemicals and pollutants. Long-term global effects such as global warming are excluded since there are no legal limits for the chemicals involved.
- Legal limit values often differ from country to country, and their basis is far from being purely scientific. Socioeconomic factors, technical limitations (for example, analytical detection limits), and the feasibility of supervision and control are also taken into account when arriving at legal limits.

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[12] K. Habersatter, *Ecobalance of Packaging Materials - State of 1990*, Swiss Federal Office of Environment, Forests, and Landscape, Bern, Switzerland, February 1991, and Bundesamt fur Umweltschutz, *Oekobilanzen von Packstoffen,* Schriftenreihe Umweltschutz 24, Bern, Switzerland, 1984.

Ecological Scarcity (Switzerland). A more general approach has been developed in a report from the Swiss Federal Office of Environment, Forests, and Landscape.[13] With this approach, "Eco-Points" are calculated for a product, using the "Eco-Factor" determined for each inventory flow. Eco-Factors are based on current annual flows relative to target maximum annual flows for the geographic area considered. The Eco-Points for all inventory flows are added together to give one single, final score.

The concept used in this approach is appealing but has the following difficulties:

- It is valid only in a specific geographical area.
- Estimating annual and target flows can be a difficult and time consuming exercise.
- The scientific calculation of environmental impacts is combined with political and subjective judgment, or valuation. The preferred approach is to separate the science from the valuation.

Environmental Priorities System (Sweden). The Environmental Priority Strategies in Product Design System, the EPS System, was developed by the Swedish Environmental Research Institute.[14] It takes an economic approach to assessing environmental impacts. The basis for the evaluation is the Environmental Load Unit, which corresponds to the willingness to pay 1 European Currency Unit. The final result of the EPS system is a single number summarizing all environmental impacts, based on:

- Society's judgment of the importance of each environmental impact.
- The intensity and frequency of the impact.
- Location and timing of the impact.
- The contribution of each flow to the impact in question
- The cost of decreasing each inventory flow by one weight unit.

The EPS system combines indices of ecological, sociological, and economic effects to give a total effect index for each flow. The total effect index is multiplied by the amount of the flow to give the "environmental load unit." Although this methodology is popular in Sweden, its use is criticized due to its lack of transparency and the quantity and quality of the model's underlying assumptions.

Classification/Characterization. The classification/characterization approach to impact assessment was developed within the Society for Environmental Toxicology and Chemistry (SETAC). It involves a two-step process:[15,16,17]

[13] Ahbe S. Braunschweig A., and R. Muller-Wenk, *Methodik fur Oekobilanzen auf der bases Okologischer Optimierung,* Schriftenreihn Umwelt 133, Swiss Federal Office of Environment, Forests, and Landscape, October 1990.

[14] Steen B., and S-O Ryding, *The EPS Enviro-Accounting Method,* IVL Report, Swedish Environmental Research Institute, Goteborg, Sweden, 1992.

[15] SETAC-Europe, *Life Cycle Assessment,* B. DeSmet, et al. (eds), 1992.

- Classification of inventory flows that contribute to specific environmental impacts. For example, greenhouse gases such as carbon dioxide, methane, and nitrous oxide are classified as contributing to global warming.
- Characterization of the potential contribution of each classified inventory flow to the corresponding environmental impact. This results in a set of indices, one for each impact, that is obtained by weighting each classified inventory flow by its relative contribution to the impact. For instance, the Global Warming Potential index is derived by expressing each contributing inventory flow in terms of its equivalent amount of carbon dioxide.

This classification/characterization method does not offer the same degree of relevance for all environmental impacts. For global and regional effects (e.g., global warming and acidification) the method may result in an accurate description of the potential impact. For impacts dependent upon local conditions (e.g., smog) it may result in an oversimplification of the actual impacts because the indices are not tailored to localities.

The BEES model uses this classification/characterization approach because it enjoys some general consensus among LCA practitioners and scientists.[18] For the reason stated above, and because BEES has a U.S. average scope, local impacts such as smog are not included. The following global and regional impacts are assessed using the classification/ characterization approach: Global Warming Potential, Acidification Potential, Nutrification Potential, and Natural Resource Depletion. Indoor Air Quality and Solid Waste impacts are also included in BEES, for a total of six impacts. Besides local impacts, other potential environmental impacts are not included. For example, ozone depletion, while an important global impact that has been successfully classified and characterized, is excluded. The primary inventory flows that contribute to ozone depletion (chlorofluorocarbons, halons, and chlorine-based solvents) are being phased out. Thus, inventory flow data are quickly changing, and soon there will be little left to report. Human health impacts are also not explicitly included in BEES because the science is not yet sufficiently developed. If the BEES user has important knowledge about these or other potential environmental impacts, it should be brought into the interpretation of the BEES results.

The six BEES impacts are discussed below.

Global Warming Potential. The Earth absorbs radiation from the Sun, mainly at the surface. This energy is then redistributed by the atmosphere and ocean and re-radiated to space at longer wavelengths. Some of the thermal radiation is absorbed by "greenhouse" gases in the atmosphere, principally water vapor, but also carbon dioxide, methane, the chlorofluorocarbons, and ozone. The absorbed energy is re-radiated in all directions, downwards as well as upwards, such that the radiation that is eventually lost to space is

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[16] SETAC, *A Conceptual Framework for Life Cycle Impact Assessment*, J. Fava, et al. (eds), 1993.

[17] SETAC, *Guidelines for Life Cycle Assessment: A "Code of Practice,"* F. Consoli, et al. (eds), 1993.

[18] SETAC, *Life-Cycle Impact Assessment: The State-of-the-Art*, J. Owens, et al. (eds), 1997.

from higher, colder levels in the atmosphere. The result is that the surface loses less heat to space than it would in the absence of the greenhouse gases and consequently stays warmer than it would be otherwise. This phenomenon, which acts rather like a 'blanket' around the Earth, is known as the greenhouse effect.

The greenhouse effect is a natural phenomenon. The issue is the increase in the greenhouse effect due to emissions generated by humankind. The resulting general increase in temperature can alter atmospheric and oceanic temperatures, which can potentially lead to alteration of circulation and weather patterns. A rise in sea level is also predicted due to thermal expansion of the oceans and melting of polar ice sheets. Global Warming Potentials, or GWPs, have been developed to measure the increase.

Several models have been developed to calculate GWPs. The Intergovernmental Panel on Climate Change (IPCC) has compiled a list of "provisional best estimates" for GWPs, based on the expert judgment of scientists worldwide. [19] Because of its broad support, this list has been used in the BEES model.

A single index, expressed in grams of carbon dioxide per functional unit of product, is derived to measure the quantity of carbon dioxide with the same potential for global warming:

$$\text{global warming index} = \Sigma_i \, w_i \times GWP_i, \text{ where}$$

w_i = weight (in grams) of inventory flow i, and
GWP_i = grams of carbon dioxide with the same heat trapping potential as one gram of inventory flow i, as listed in table 2.1.

Table 2.1 BEES Global Warming Potential Equivalency Factors

Flow (i)	***GWP_i (CO_2-equivalents)***
Carbon dioxide	1
Methane	24.5
Nitrous oxide	320

Acidification. Acidifying compounds may in a gaseous state either dissolve in water or fix on solid particles. They reach ecosystems through dissolution in rain or wet deposition. Acidification affects trees, soil, buildings, animals, and humans. The two

[19] International Panel on Climate Change (IPCC), *Report of Scientific Assessment Working Group of IPCC*, 1994.

compounds principally involved in acidification are sulfur and nitrogen compounds. Their principal human source is fossil fuel and biomass combustion. Other compounds released by human sources, such as hydrogen chloride and ammonia, also contribute to acidification.

An index for potential acid deposition onto the soil and in water can be developed by analogy with the global warming potential, with hydrogen as the reference substance. The result is a single index for potential acidification (in grams of hydrogen per functional unit of product), representing the quantity of hydrogen emissions with the same potential acidifying effect:

$$\text{acidification index} = \Sigma_i \ w_i \times AP_i, \text{ where}$$

w_i = weight (in grams) of inventory flow i, and

AP_i = grams of hydrogen with the same potential acidifying effect as one gram of inventory flow i, as listed in table 2.2.[20]

Table 2.2 BEES Acidification Potential Equivalency Factors

Flow (i)	***AP_i (Hydrogen-Equivalents)***
Sulfur oxides	0.031
Nitrogen oxides	0.022
Ammonia	0.059
Hydrogen Fluoride	0.05
Hydrogen Chloride	0.027

Nutrification Potential. Nutrification is the addition of mineral nutrients to the soil or water. In both media, the addition of large quantities of mineral nutrients, such as nitrogen and phosphorous, results in generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity. In water, it tends to increase algae growth, which can lead to lack of oxygen and therefore death of species like fish.

An index for potential nutrification can be developed by analogy with the global warming potential, with phosphate ions as the reference substance. The result is a single index for potential nutrification (in grams of phosphate ions per functional unit of product), representing the quantity of phosphate ions with the same potential nutrifying effect:

[20] CML, *Environmental Life Cycle Assessment of Products: Background*, Leiden, The Netherlands, October 1992.

$$\text{nutrification index} = \Sigma_i\, w_i \times NP_i, \text{ where}$$

w_i = weight (in grams) of inventory flow i, and
NP_i = grams of phosphate ions with the same potential nutrifying effect as one grams of inventory flow i, as listed in table 2.3.[21]

Table 2.3 BEES Nutrification Potential Equivalency Factors

Flow (i)	***NP_i* *(phosphate-equivalents)***
Phosphates	1
Nitrogen Oxides	0.13
Ammonia	0.42
Nitrogenous Matter	0.42
Nitrates	0.095
Phosphorous	3.06
Chemical Oxygen Demand	0.022

Natural Resource Depletion. Natural resource depletion can be defined as the decreasing availability of natural resources. The resources considered in this impact are fossil and mineral resources. It is important to recognize that this impact addresses only the depletion aspect of resource extraction, not the fact that the extraction itself may generate impacts. Extraction impacts, such as methane emissions from coal mining, are addressed in other impacts, such as global warming.

Some experts believe resource depletion is fully accounted for in market prices. That is, market price mechanisms are believed to take care of the scarcity issue, price being a measure of the level of depletion of a resource and the value society places on that depletion. However, price is influenced by many factors other than resource supply, such as resource demand and non-perfect markets (e.g., monopolies and subsidies). Furthermore, resource depletion is at the heart of the sustainability debate. Thus, in the BEES model, resource depletion is explicitly accounted for in the LCA impact assessment.

To assess resource depletion, the amount of reserves of a resource, or resource base, needs to be determined. For mineral resources, the reserve base is defined as follows:

[21] CML, 1992.

> The reserve base encompasses those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. It includes those resources that are currently economic, marginally economic, and subeconomic.[22]

Reserve base quantities used in the BEES model are listed in table 2.4.

Once reserves are established, an equivalency factor can be derived for each resource that will relate its inventory flow with the depletion of the resource. The equivalency factor addresses how long a given resource will continue to be available at current extraction levels, as well as the size of the reserve. Using equivalency factors, a single index is produced for natural resource depletion:

$$\text{Depletion Index} = \sum_i \frac{1}{\text{reserve}_i * \text{years}_i} * w_i = \sum_i \frac{\text{production}_i}{(\text{reserve}_i)^2} * w_i, \quad \text{where}$$

reserve_i = reserves (in kilograms) for natural resource i (the larger the reserve, the smaller the equivalency factor)
years_i = years of remaining use for natural resource i (the longer available, the smaller the equivalency factor)
production_i = annual production (in kilograms/year) for natural resource i
w_i = the weight (in kilograms) of the inventory flow for resource i

The BEES natural resource depletion equivalency factors are shown in the last column of table 2.4.

Solid Waste. Solid waste is an inventory outflow of the building products included in the BEES model. The BEES inventory analysis tracks the weight of non-recyclable solid waste resulting from the installation, replacement, and disposal of each building product over the fifty-year study period. Equivalency factors have not been developed to consider the ultimate fate of the non-recyclable solid waste (e.g., landfill leachate, gas or incinerator emissions, ash). Thus, the Direct Use of Inventories Approach, described at the beginning of this subsection, is used, with solid waste volume representing the solid waste impact of the product. Solid waste volume (in cubic meters, or cubic feet, of waste per functional unit of product) is derived as follows:

$$\text{solid waste volume} = (\Sigma_i \ w_i) / \text{density, where}$$

w_i = weight (in kilograms) of non-recyclable solid waste inventory flow i, and
density = density of the product (in kilograms per 0.0283 cubic meter, or kilograms per cubic foot), as listed in table 2.5.

[22]U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summary*, 1994.

Table 2.4 BEES Natural Resource Depletion Equivalency Factors

Inventory Flow	*Units*	*Source of Data*	*Annual Production (kg/yr) (1)*	*Reserve Base (kg) (2)*	*Years of Remaining Use (3)=(2)/(1)*	*Equivalency Factor (4)= 1/[(2)*(3)]*
Oil (in ground)	kg of oil	World Energy Council 1995	3.2 E+12	2.4 E+14	75	5.6 E-17
Natural Gas (in ground)	kg of natural gas	World Energy Council 1995	2.0 E+12	1.3 E+14	66	1.2 E-16
Coal (in ground)	kg of coal	World Energy Council 1995	4.5 E+12	3.0 E+15	666	5.0 E-19
Bauxite (Al_2O_3.2 H_2O, ore)	dry kg of bauxite	US Bureau of Mines 1996	1.1 E+11	2.8 E+13	257	1.4 E-16
Cadmium (Cd, ore)	kg of Cd content	US Bureau of Mines 1996	2.0 E+07	9.7 E+08	49	2.1 E-11
Copper (Cu, ore)	kg of Cu content	US Bureau of Mines 1996	9.8 E+09	6.1 E+11	62	2.6 E-14
Gold (Au, ore)	kg of Au content	US Bureau of Mines 1996	2.2 E+06	6.1 E+07	28	5.9 E-10
Iron (Fe, ore)	kg of Fe content	US Bureau of Mines 1996	4.3 E+11	1.0 E+14	231	4.3 E-17
Lead (Pb, ore)	kg of Pb content	US Bureau of Mines 1996	2.8 E+09	1.2 E+11	43	1.9 E-13
Manganese (Mn, ore)	kg of Mn content	US Bureau of Mines 1996	7.3 E+09	5.0 E+12	685	2.9 E-16
Mercury (Hg, ore)	kg of Hg content	US Bureau of Mines 1996	3.1 E+06	2.4 E+08	77	5.4 E-11
Nickel (Ni, ore)	kg of Ni content	US Bureau of Mines 1996	9.2 E+08	1.1 E+11	120	7.6 E-14
Phosphate Rock (in ground)	kg of rock	US Bureau of Mines 1996	1.4 E+11	3.4 E+13	248	1.2 E-16
Potash (K_2O, in ground)	kg of K_2O equivalent	US Bureau of Mines 1996	2.6 E+10	1.7 E+13	649	9.1 E-17
Silver (Ag, ore)	kg of Ag content	US Bureau of Mines 1996	1.4 E+07	4.2 E+08	30	7.9 E-11
Tin (Sn, ore)	kg of Sn content	US Bureau of Mines 1996	1.8 E+08	1.0 E+10	56	1.8 E-12
Uranium (U, ore)	kg of U content	World Energy Council 1995	3.3 E+07	1.3 E+10	412	1.8 E-13
Zinc (Zn, ore)	kg of Zn content	US Bureau of Mines 1996	7.1 E+09	3.3 E+11	47	6.5 E-14

Due to abundant resources, the depletion index has been set to zero for the following resources: Clay (in ground), Dolomite ($CaCO_3MgCO_3$, in ground), Feldspar (ore), Gypsum (ore), Kaolin (Al_2O_3.2SiO_2.2H_2O, ore), Limestone (in ground), Sand (in ground), Sodium Chloride (NaCl, in ground or in sea). Note that local shortages of these resources may exist. Local shortages are translated into higher transportation distances and therefore higher emissions, but they have no impact on the depletion factor.

Table 2.5 Densities of BEES Building Products

Product	*Density* *$kg/0.0283m^3 (lb/ft^3)$*
All Concrete Products	66 (145.51)
Roof and Wall Sheathing	
- Oriented Strand Board	17 (37.48)
- Plywood	12 (26.46)
Exterior Wall Finishes	
- Brick	60 (132.28)
- Stucco	55 (121.25)
Wall Insulation	
- R-13 Cellulose	1.07 (2.35)
- R-11 Fiberglass	0.23 (0.50)
- R-15 Fiberglass	0.54 (1.20)
- R-12 Mineral Wool	0.98 (2.15)
Roof Coverings	
- Asphalt Shingles	89 (196.21)
- Clay Tile	60 (132.28)
- Fiber Cement Shingles	44 (97.00)
R-30 Ceiling Insulation	
- Cellulose	0.73 (1.60)
- Fiberglass	0.23 (0.50)
- Mineral Wool	0.98 (2.15)
Floor Coverings	
- Ceramic Tile	61 (134.48)
- Linoleum	33 (72.75)
- Vinyl Composition Tile	59 (130.07)

Indoor Air Quality. Indoor air quality impacts are not included in traditional life-cycle impact assessments. Most LCAs conducted to date have been applied to relatively short-lived, non-building products (e.g., paper versus plastic bags), for which indoor air quality impacts are not an important issue. However, the indoor air quality performance of building products is of particular concern to the building community and should be explicitly considered in any building product LCA.

Ideally, equivalency factors would be available for indoor air pollutants as they are for global warming gases. However, there is little scientific consensus about the relative contributions of pollutants to indoor air performance. In the absence of equivalency factors, a product's total volatile organic compound (VOC) emissions is often used as a measure of its indoor air performance. Note that total VOCs equally weights the contributions of the individual compounds that make up the measure. Further, reliance on VOC emissions alone may be misleading if other indoor air contaminants, such as particulates and aerosols, are also present.

Indoor air quality should be considered for the following building elements currently covered in BEES: floor coverings, wall and roof sheathing, and wall and ceiling insulation. Other BEES building elements are primarily exterior elements for which indoor air quality is not an issue.

Floor Coverings. BEES currently includes three floor covering products: ceramic tile with recycled windshield glass, linoleum, and vinyl composition tile. Data for three components of their indoor air performance are considered—total VOC emissions from the products themselves, indoor air performance for their installation adhesives, and indoor air performance for associated maintenance products.

Recognizing the inherent limitations in using total VOCs to assess indoor air quality performance, and in the absence of more scientific data, estimates of total VOC emissions from the floor covering products are used as a proxy for their indoor air performance. As shown in table 2.6, total VOCs for linoleum and vinyl composition tile flooring measured in three laboratory studies are averaged to represent their indoor air performance.[23] Ceramic tile is inert and emits no VOCs.[24]

Table 2.6 Volatile Organic Compound Emissions for Linoleum and Vinyl Composition Tile

	Total Volatile Organic Compound Emissions by Testing Laboratory ($Mg/m^2/hr$ at 24 hours)			
Floor Covering	***Air Quality Sciences****	***Armstrong*****	***Ortech******	***Average***
Linoleum	1.667	1.192	0.511	1.123
Vinyl Composition Tile	0.155	0.203	0.179	0.179

*Averages for three linoleum and two VCT emissions tests conducted in a test chamber designed in accordance with ASTM D5116-90 at Air Quality Sciences Laboratory, Atlanta, Georgia, 1991-1992.

**Averages for four linoleum and ten VCT emissions tests conducted in a test chamber designed in accordance with ASTM D5116-90 at Armstrong Research and Development Laboratory, Lancaster, Pennsylvania, 1992-1997.

***Ortech Corporation, Toronto, Canada, 1996. Ortech results indicating 65% less VOC emissions for vinyl composition floor tile than linoleum are applied to average VCT emissions, 0.179 $Mg/m^2/hr$, measured at the other two testing laboratories.

The second component of the BEES indoor air assessment for floor coverings is indoor air performance for their installation adhesives. Both linoleum and vinyl composition tile

[23] Note that vinyl composition tile has substantially lower polyvinylchloride (PVC) and plasticizer contents than vinyl sheet flooring and thus emits lower levels of VOCs. Some vinyl sheet flooring may emit higher levels of VOCs than linoleum.

[24] American Institute of Architects, *Environmental Resource Guide,* Ceramic Tile Material Report, 1996, p. 1.

are assumed to be installed using a styrene-butadiene adhesive, and ceramic tile with recycled glass using a styrene-butadiene cement mortar. Assuming indoor air impacts are proportional to the amount of styrene-butadiene used per functional unit (as quantified in the BEES environmental performance data files), styrene-butadiene usage may be used as a proxy for indoor air performance as follows:

- ceramic tile with recycled windshield glass—0.00311 kg/m^2 (0.00028 kg/ft^2)
- linoleum—0.00878 kg/m^2 (0.00079 kg/ft^2)
- vinyl composition tile—0.00878 kg/m^2 (0.00079 kg/ft^2)

Finally, indoor air performance is assessed for periodic waxing of the floor coverings. Assuming indoor air impacts are proportional to the amount of acrylic lacquer used per year per functional unit (as quantified in the BEES environmental performance data files), acrylic lacquer usage may be used as a proxy for indoor air performance as follows:

- ceramic tile with recycled windshield glass—no waxing
- linoleum—0.5 grams (0.02 oz) of acrylic lacquer per functional unit, applied 4 times per year
- vinyl composition tile—0.5 grams (0.02 oz) of acrylic lacquer per functional unit, applied 2 times per year

To assess overall indoor air performance for BEES floor coverings, each product's performance data for product emissions, installation adhesives, and maintenance are normalized by dividing by the corresponding performance value for the worst performing product, then averaged across performance categories as shown in table 2.7. By taking the simple average, each performance category is weighted equally.

Table 2.7 BEES Indoor Air Performance Scores for Floor Covering Products

	Normalized Indoor Air Performance Score			
Floor Covering	***Product Emissions***	***Installation Adhesives***	***Maintenance***	***Average***
Ceramic Tile w/ Glass	0*	35	0*	12
Linoleum	100	100	100	100
Vinyl Composition Tile	16	100	50	55

*For this exercise, normalized scores of zero are assumed for tile emissions and maintenance

Note that due to shortcomings in indoor air science, the BEES indoor air performance scores for floor coverings are based on heuristics. If the BEES user has better knowledge, or simply wishes to test the effect on overall results of changes in relative indoor air performance, these scores may be changed by editing the "total" and "use" columns of the "Indoor Air" rows of the BEES environmental performance data files for floor coverings. Refer to section 4.4 for more information on these files.

Wall and Roof Sheathing. Indoor air quality is a concern for many wood products due to their formaldehyde emissions. Formaldehyde is thought to affect human health, especially for people with chemical sensitivity. Composite wood products using urea-formaldehyde adhesives have higher formaldehyde emissions than those using phenol-formaldehyde adhesives, and different composite wood products have different levels of emissions. Composite wood products include particleboard, insulation board, medium density fiberboard, oriented strand board (OSB), hardboard, and softwood and hardwood plywood.

BEES assumes formaldehyde emissions is the only significant indoor air concern for wood products. BEES currently analyzes two composite wood products—OSB and softwood plywood. Most OSB is now made using a methylene diphenylisocyanate (MDI) binder, which is the binder BEES uses in modeling OSB environmental performance. OSB using an MDI binder emits no formaldehyde other than the insignificant amount naturally occurring in the wood itself.[25] Softwood plywood also has extremely low formaldehyde emissions because it uses phenol-formaldehyde binders and because it is used primarily on the exterior shell of buildings.[26] Thus, neither of the two composite wood products as modeled in BEES are thought to significantly affect indoor air quality.

Wall and Ceiling Insulation. Indoor air quality is also discussed in the context of insulation products. The main issues are the health impacts of fibers, hazardous chemicals, and particles released from some insulation products. These releases are the only insulation-related indoor air issues addressed in BEES.

As a result of its listing by the International Agency for Research on Cancer as a "possible carcinogen," fiberglass products are now required to have cancer warning labels. The fiberglass industry has responded by developing fiberglass products that reduce the amount of loose fibers escaping into the air. For cellulose products, there are claims that fire retardant chemicals and respirable particles are hazardous to human health. Mineral wool is sometimes claimed to emit fibers and chemicals that could be health irritants. For all these products, however, there should be little or no health risks to building occupants if they are installed in accordance with manufacturer's recommendations. Assuming proper installation, then, none of these products as modeled in BEES are thought to significantly affect indoor air quality.[27]

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[25] Alex Wilson and Nadav Malin, "The IAQ Challenge: Protecting the Indoor Environment," *Environmental Building News,* Vol. 5, No. 3, p 15.

[26] American Institute of Architects, *Environmental Resource Guide,* Plywood Material Report, May 1996.

[27] Alex Wilson, "Insulation Materials: Environmental Comparisons," *Environmental Building News,* Vol. 4, No. 1, pp.15-16

2.1.4 Interpretation

At the LCA interpretation step, the impact assessment results are combined. Few products are likely to dominate competing products in all six BEES impact categories. Rather, one product may out-perform the competition relative to natural resource depletion and solid waste, fall short relative to global warming and acidification, and fall somewhere in the middle relative to indoor air quality and nutrification. To compare the overall environmental performance of competing products, the performance measures for all six impact categories need to be synthesized.

Synthesizing the six impact category performance measures involves combining apples and oranges. Global warming potential is expressed in carbon dioxide equivalents, acidification in hydrogen equivalents, nutrification in phosphate equivalents, natural resource depletion as a factor reflecting remaining years of use and reserve size, solid waste in non-recyclable volume to landfill, and indoor air quality as a dimensionless score.

How can the diverse measures of impact category performance be combined into a meaningful measure of overall environmental performance? The most appropriate technique is Multiattribute Decision Analysis (MADA). MADA problems are characterized by tradeoffs between apples and oranges, as is the case with the BEES impact assessment results. The BEES system follows the ASTM standard for conducting MADA evaluations of building-related investments.[28]

MADA first places all impact categories on the same scale by normalizing them. Within an impact category, each product's performance measure is normalized by dividing by the highest measure for that category. All performance measures are thus translated to the same, dimensionless, relative scale from 0 to 100, with the worst performing product in each category assigned the highest possible normalized score of 100. Refer to Appendix A for the BEES environmental performance computational algorithms.

MADA then weights each impact category by its relative importance to overall performance. In the BEES software, the set of importance weights is selected by the user. Several derived, alternative weight sets are provided as guidance, and may either be used directly or as a starting point for developing user-defined weights. The alternative weights sets are based on an EPA Science Advisory Board study, a Harvard University study, and a set of equal weights, representing a spectrum of ways in which people, including the experts, value various aspects of the environment.

EPA Science Advisory Board study. In 1990, EPA's Science Advisory Board (SAB) developed lists of the relative importance of various environmental impacts to help EPA best allocate its resources. The following criteria were used to develop the lists:

[28] American Society for Testing and Materials, *Standard Practice for Applying the Analytic Hierarchy Process to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems*, ASTM Designation E 1765-95, West Conshohocken, PA, 1995.

- The spatial scale of the impact
- The severity of the hazard
- The degree of exposure
- The penalty for being wrong

Five of the BEES impact categories were among the SAB lists of relative importance:[29]

- Relatively High-Risk Problems: global warming, indoor air quality
- Relatively Medium-Risk Problems: acidification, nutrification
- Relatively Low-Risk Problems: solid waste[30]

The SAB did not explicitly consider natural resource depletion as an impact. For this exercise, natural resource depletion is assumed to be a relatively medium-risk problem, based on other relative importance lists.[31]

Verbal importance rankings, such as "relatively high-risk," may be translated into numerical importance weights by following guidance provided by a MADA method known as the Analytic Hierarchy Process (AHP). [32] The AHP methodology suggests the following numerical comparison scale:

1	Two impacts contribute equally to the objective (in this case environmental performance)
3	Experience and judgment slightly favor one impact over another
5	Experience and judgment strongly favor one impact over another
7	One impact is favored very strongly over another, its dominance demonstrated in practice
9	The evidence favoring one impact over another is of the highest possible order of affirmation
2,4,6,8	When compromise between values of 1, 3, 5, 7, and 9, is needed

Through an AHP process known as pairwise comparison, numerical comparison values are assigned to each possible pair of environmental impacts. Relative importance weights can then be derived by computing the normalized eigenvector of the largest eigenvalue of the matrix of pairwise comparison values. Tables 2.8 and 2.9 list the pairwise comparison values assigned to the SAB verbal importance rankings, and the resulting importance weights computed for the six BEES impacts, respectively:

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[29] United States Environmental Protection Agency, Science Advisory Board, *Reducing Risk: Setting Priorities and Stretegies for Environmental Protection,* SAB-EC-90-021, Washington, D.C., September 1990, pp 13-14.

[30] The SAB report classifies solid waste under its low-risk groundwater pollution category (SAB, *Reducing Risk,* Appendix A, pp 10-15).

[31] See, for example, Hal Levin, "Best Sustainable Indoor Air Quality Practices in Commercial Buildings," *Third International Green Building Conference and Exposition--1996,* NIST Special Publication 908, Gaithersburg, MD, November 1996, p 148.

[32] Thomas L. Saaty, *MultiCriteria Decision Making: The Analytic Hierarchy Process--Planning, Priority Setting, Resource Allocation,* University of Pittsburgh, 1988.

Table 2.8 Pairwise Comparison Values for Deriving Impact Category Importance Weights

Verbal Importance Comparison	*Pairwise Comparison Value*
High vs. Medium	2
Medium vs. Low	2
High vs. Low	4

Table 2.9 Relative Importance Weights based on Science Advisory Board Study

Impact Category	*Relative Importance Weight (%)*
Global Warming	27
Acidification	13
Nutrification	13
Natural Resource Depletion	13
Indoor Air Quality	27
Solid Waste	7

Harvard University Study. In 1992, an extensive study was conducted at Harvard University to establish the relative importance of environmental impacts.[33] The study developed separate assessments for the United States, The Netherlands, India, and Kenya. In addition, separate assessments were made for "current consequences" and "future consequences" in each country. For current consequences, more importance is placed on impacts of prime concern today. Future consequences places more importance on impacts that are expected to become significantly worse in the next 25 years.

Five of the BEES impact categories were among the studied impacts. Table 2.10 shows the current and future consequence rankings assigned to these impacts in the United States.

The study did not explicitly consider solid waste as an impact. For this exercise, solid waste is assumed to rank low for both current and future consequences, based on other relative importance lists.[34]

Verbal importance rankings from the Harvard study are translated into numerical, relative importance weights using the same, AHP-based numerical comparison scale and pairwise

[33] Vicki Norberg-Bohm et al, *International Comparisons of Environmental Hazards: Development and Evaluation of a Method for Linking Environmental Data with the Strategic Debate Management Priorities for Risk Management*, Center for Science & International Affairs, John F. Kennedy School of Government, Harvard University, October 1992.

[34] See, for example, Hal Levin, "Best Sustainable Indoor Air Quality Practices in Commercial Buildings," p 148. As in the SAB report, solid waste is classified under groundwater pollution.

Table 2.10 U.S. Rankings for Current and Future Consequences by Impact Category

Impact Category	*Current Consequences*	*Future Consequences*
Global Warming	Low	High
Acidification	High	Low
Nutrification	Medium	High
Natural Resource Depletion[a]	Medium	Medium
Indoor Air Quality	Medium	Low

[a]Average of consequences for hazards contributing to natural resource depletion.

comparison process described above for the SAB study. Sets of relative importance weights are derived for current and future consequences, and then combined by weighing future consequences as twice as important as current consequences.[35] Table 2.11 lists the resulting importance weights for the six BEES impacts. The combined importance weight set is offered as an option in the BEES software. However the BEES user is free to use the current or future consequence weight sets by entering these weights under the user-defined software option.

Table 2.11 Relative Importance Weights based on Harvard University study

	Relative Importance Weight Set		
Impact Category	*Current (%)*	*Future (%)*	*Combined (%)*
Global Warming	8	38	28
Acidification	33	10	17
Nutrification	16	19	18
Natural Resource Depletion	16	14	15
Indoor Air Quality	16	10	12
Solid Waste	11	9	10

2.2 Economic Performance

Measuring the economic performance of building products is more straightforward than measuring environmental performance. Published economic performance data are readily available, and there are well-established ASTM standard methods for conducting economic performance evaluations. First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair*

[35] The Harvard study ranks impacts "high" in future consequences if the current level of impact is expected to double in severity over the next 25 years based on a "business as usual" scenario. Vicki Norberg-Bohm, *International Comparisons of Environmental Hazards*, pp 11-12.

Cost Reference 1997. The most appropriate method for measuring the economic performance of building products is the life-cycle cost (LCC) method. BEES follows the ASTM standard method for life-cycle costing of building-related investments.[36]

It is important to distinguish between the time periods used to measure environmental performance and economic performance. These time periods are different. Recall that in environmental LCA, the time period begins with raw material acquisition and ends with product end-of-life. Economic performance, on the other hand, is evaluated over a fixed period (known as the study period) that begins with the purchase and installation of the product, and ends at some point in the future that does not necessarily correspond with product end-of-life.

Economic performance is evaluated beginning at product purchase and installation because this is when out-of-pocket costs begin to be incurred, and investment decisions are made based upon out-of-pocket costs. The study period ends at a fixed date in the future. For a private investor, its length is set at the period of product or facility ownership. For society as a whole, the study period length is often set at the useful life of the longest-lived product alternative. However, when all alternatives have very long lives, (e.g., more than 50 years), a shorter study period may be selected for three reasons:

- Technological obsolescence becomes an issue
- Data become too uncertain
- The further in the future, the less important the costs

In the BEES model, economic performance is measured over a 50-year study period, as shown in Figure 2.3. This study period is selected to reflect a reasonable period of time over which to evaluate economic performance for society as a whole. The same 50-year period is used to evaluate all products, even if they have different useful lives. This is one of the strengths of the LCC method. It adjusts for the fact that different products have different useful lives when evaluating them over the same study period.

For consistency, the BEES model evaluates the use stage of environmental performance over the same 50-year study period. Product replacements over this 50-year period are accounted for in the environmental performance score, and end-of-life solid waste is prorated to year 50 for products with partial lives remaining after the 50-year period.

The LCC method sums over the study period all relevant costs associated with a product. Alternative products for the same function, say floor covering, can then be compared on the basis of their LCCs to determine which is the least cost means of providing that function over the study period. Categories of cost typically include costs for purchase, installation, maintenance, repair, and replacement. A negative cost item is the residual value. The residual value is the product value remaining at the end of the study period. In

[36]American Society for Testing and Materials, *Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems,* ASTM Designation E 917-94, West Conshohocken, PA, March 1994.

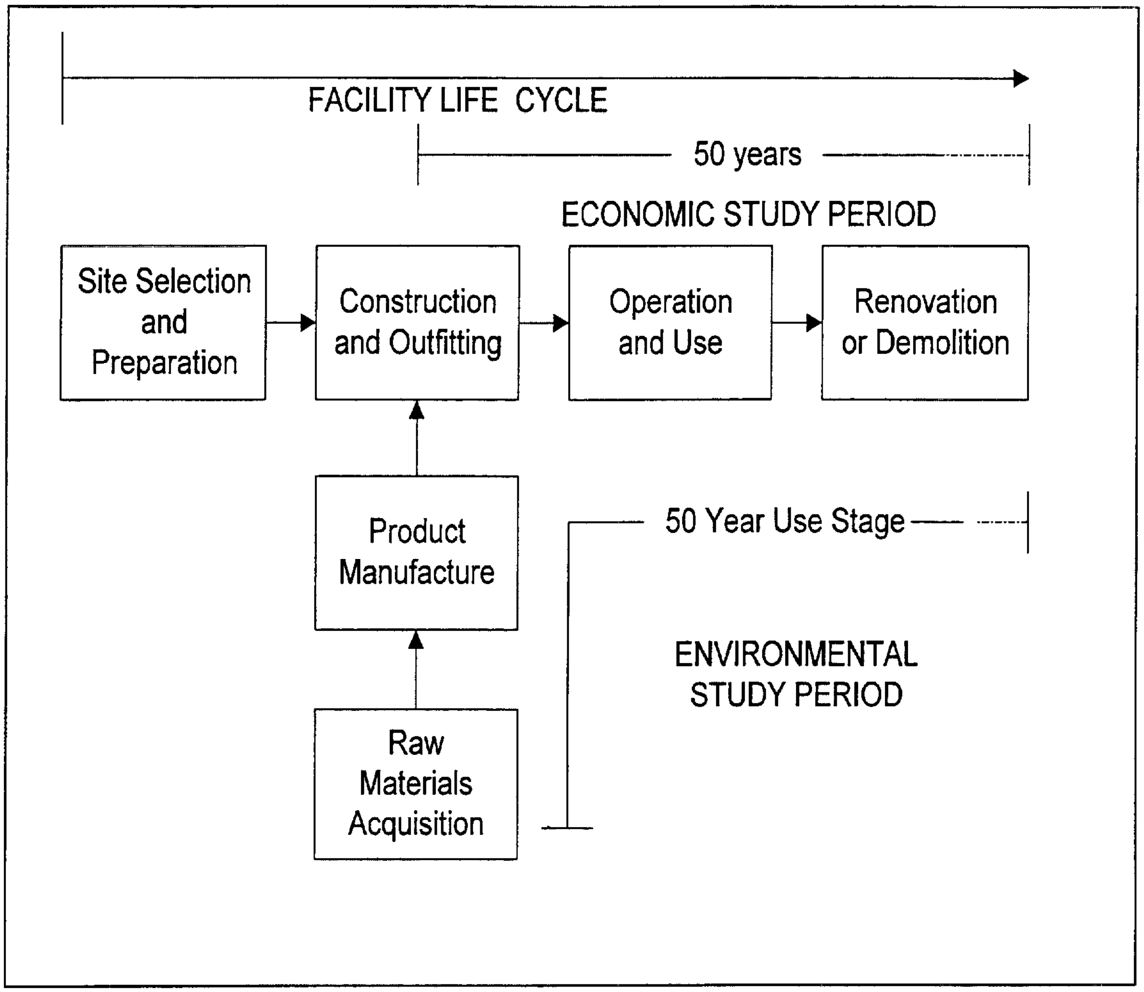

Figure 2.3 BEES Study Periods For Measuring Building Product Environmental And Economic Performance

the BEES model, the residual value is computed by prorating the purchase and installation cost over the product life remaining beyond the 50-year period.[37]

The LCC method accounts for the time value of money by using a discount rate to convert all future costs to their equivalent present value. Refer to Appendix A for the BEES economic performance computational algorithm showing the discounting technique.

Future costs must be expressed in terms consistent with the discount rate used. There are two approaches. First, a *real* discount rate may be used with constant-dollar (e.g., 1997) costs. Real discount rates reflect the portion of the time value of money attributable to the real earning power of money over time and not to general price inflation. Even if all

[37] For example, a product with a 40-year life that costs $10 per 0.09 square meters ($10 per square foot) to install would have a residual value of $7.50 in year 50, considering replacement in year 40.

future costs are expressed in constant 1997 dollars, they must be discounted to reflect this portion of the time-value of money. Second, a *market* discount rate may be used with current-dollar amounts (e.g., actual future prices). Market interest rates reflect the time value of money stemming from both inflation and the real earning power of money over time. When applied properly, both approaches yield the same LCC results. The BEES model computes LCCs using constant 1997 dollars and a real discount rate. As a default, the BEES tool uses a real rate of 3.6 percent, the 1997 rate mandated by the U.S. Office of Management and Budget (OMB) for most Federal projects.[38]

2.3 Overall Performance

The BEES overall performance score combines the environmental and economic results into a single score. To combine them, the two results must first be placed on a common basis. The environmental performance score reflects *relative* environmental performance, or how much better or worse products perform with respect to one another. The economic performance score, the LCC, reflects *absolute* performance, regardless of the set of alternatives under analysis. Before combining the two, the life-cycle cost is converted to the same, relative basis as the environmental score by dividing by the highest-life-cycle cost alternative. Then the two performance scores are combined into a relative, overall score by weighting environmental and economic performance by their relative importance values. The BEES user specifies the relative importance weights used to combine environmental and economic performance scores and may test the sensitivity of the overall scores to different sets of relative importance weights.

Figure 2.4 illustrates the synthesis of environmental and economic performance results into the BEES overall performance score. In this example, the Harvard environmental importance weight set, the 1997 OMB discount rate, and equal weights for environmental and economic performance are used. Refer to Appendix A for the BEES overall performance computational algorithm.

2.4 Limitations

Properly interpreting the BEES scores requires placing them in perspective. There are inherent limits to applying U.S. industry-average LCA and LCC results and in comparing building products outside the design context.

The BEES LCA and LCC approaches produce U.S. average performance results for generic product alternatives. The BEES results do not apply to products manufactured in other countries where manufacturing and agricultural practices, fuel mixes, environmental

[38] Office of Management and Budget (OMB) Circular A-94, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*, Washington, DC, October 27, 1992 and OMB Circular A-94, Appendix C, March 1997.

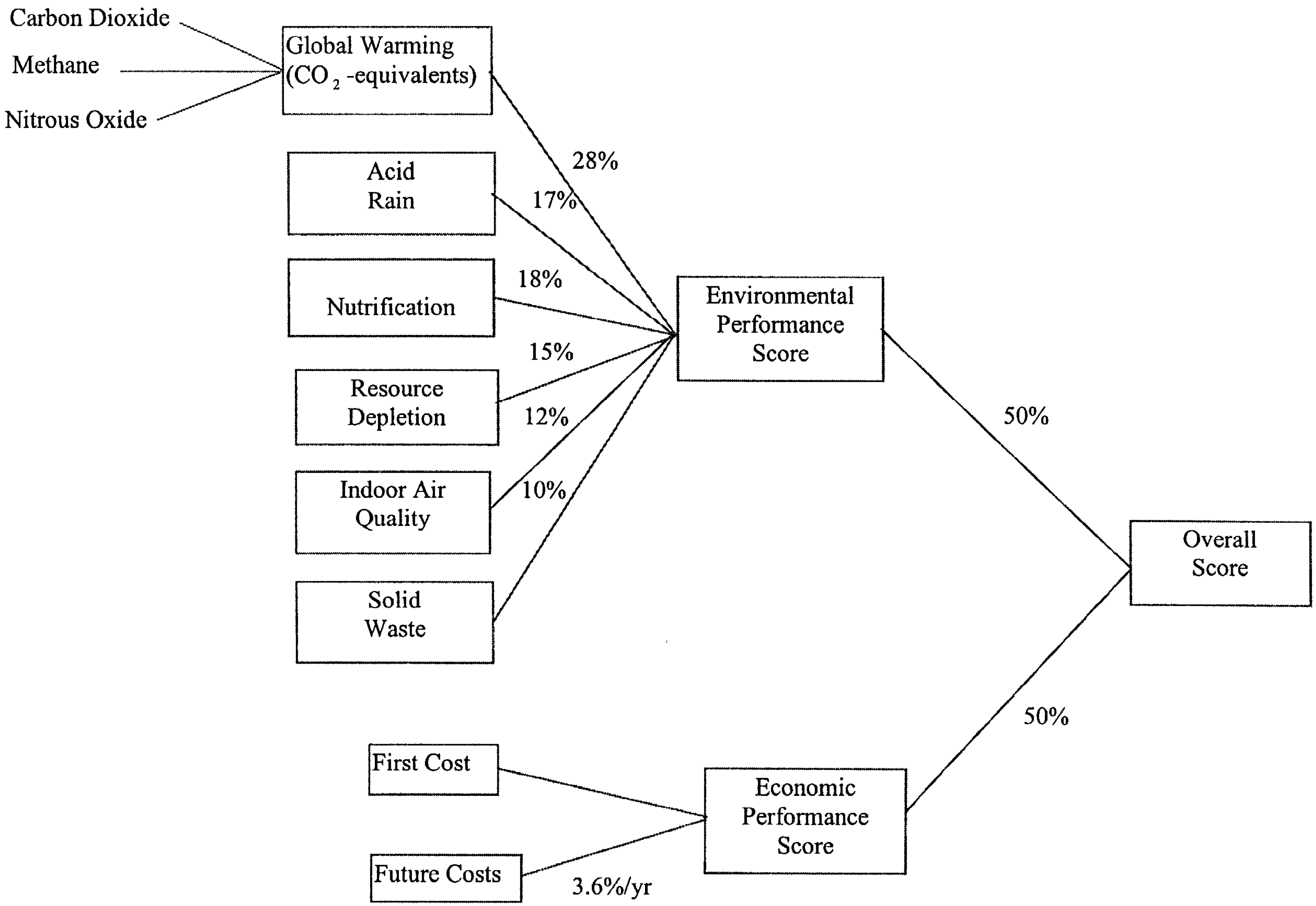

Figure 2.4. Deriving the BEES Overall Performance Score

regulations, transportation distances, and labor and material markets may differ.[39] Furthermore, all products in an industry-average, generic product group, such as vinyl composition tile floor covering, are not created equal. Product composition, manufacturing technologies, fuel mixes, transportation practices, useful lives, and cost can all vary for individual products in a generic product group. Thus, the BEES results for the generic product group do not necessarily represent the performance of an individual product.

The BEES LCA uses selected inventory flows converted to selected regional and global environmental impacts to assess environmental performance. Those inventory flows which currently do not have scientifically proven or quantifiable impacts on the environment are excluded, such as mineral extraction and wood harvesting which are qualitatively thought to lead to loss of habitat and an accompanying loss of biodiversity. Human health impacts, such as the carcinogenic potential of glass fibers used in building insulation, are also excluded because they cannot yet be quantified and in some cases scientifically proven. Finally, since BEES develops U.S. average results, local impacts such as smog are excluded even though the science is proven and quantification is possible. If the BEES user has important knowledge about these or other potential environmental impacts, it should be brought into the interpretation of the BEES results.

During the interpretation step of the BEES LCA, the six environmental impacts are combined into a single environmental performance score using relative importance weights. These weights necessarily incorporate values and subjectivity. BEES users may test the effects on the environmental performance score of changes in the set of importance weights.

The BEES environmental scores do not represent *absolute* environmental damage. Rather, they represent proportional differences in damage, or *relative* damage, among competing alternatives. Consequently, the environmental performance score for a given product alternative can change if one or more competing alternatives are added to or removed from the set of alternatives under consideration. Keep in mind, however, that rank reversal, or a reordering of scores, is impossible. For example, when comparing Products A, B, and C, if Product A has the best score and Product C the worst, Product A will continue to score better than Product C when Product B is removed from the alternative set. Finally, since they are relative performance scores, no conclusions may be drawn by comparing scores across building elements. That is, if exterior wall finish Product A has an environmental performance score of 60, and roof covering Product C has an environmental performance score of 40, Product C does not necessarily perform better than Product A (keeping in mind that lower performance scores are better). The same limitation to comparing relative scores across building elements applies to the overall performance scores.

[39] Since most linoleum manufacturing takes place in Europe, linoleum is modeled based on European manufacturing practices, fuel mixes, and environmental regulations. However, the BEES linoleum results are only applicable to linoleum imported into the United States because transport from Europe to the United States is built into the BEES linoleum data.

There are limits inherent in comparing product alternatives without reference to the whole building design context. This approach may overlook important environmental and cost interactions among building elements. For example, the useful life of one building element (e.g., floor coverings), which influences both its environmental and economic performance scores, may depend on the selection of related building elements (e.g., subflooring). There is no substitute for good building design.

Environmental and economic performance are but two attributes of building product performance. The BEES model assumes that competing product alternatives all meet minimum technical performance requirements[40]. However, there may be significant differences in technical performance, such as acoustical performance, fire performance, or aesthetics, that may outweigh environmental and economic considerations.

[40] Environmental and economic performance results for wall insulation, and for concrete beams and columns do consider technical performance differences. For wall insulation, BEES accounts for differential heating and cooling energy use, based on insulation R-value, building location, and heating fuel. For concrete beams and columns, BEES accounts for different compressive strengths.

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3. BEES Product Data

The BEES model uses the ASTM standard classification system, UNIFORMAT II,[41] to organize building products into comparable groups. The ASTM standard classifies building components into a three-level hierarchy: major group elements (e.g., substructure, shell, interiors), group elements (e.g., foundations, roofing, interior finishes), and individual elements (e.g., slab on grade, roof coverings, floor finishes). Elements are defined such that each performs a given function, regardless of design specifications or materials used. The UNIFORMAT II classification system is well suited to the BEES environmental and economic performance methodologies, which define comparable products as those that fulfill the same basic function. The BEES model uses the UNIFORMAT II classification of individual elements, the third level of the hierarchy, as the point of departure for selecting functional applications for BEES product comparisons.

3.1 Portland Cement Concrete Product Alternatives (BEES Codes A1030, A2020, B1011, B1012, G2010)

Portland cement concrete, typically referred to as "concrete," is a mixture of portland cement (a fine powder), water, fine aggregate such as sand or finely crushed rock, and coarse aggregate such as gravel or crushed rock. The mixture creates a semi-fluid material that forms a rock-like material when it hardens. Note that the terms "cement" and "concrete" are often used interchangeably, yet cement is actually only one of several concrete constituents.

Concrete is specified for different building elements by its compressive strength measured 28 days after casting. Concretes with greater compressive strengths generally contain more cement. While the compressive strength of concrete mixtures can range from 0.69 to 138 Megapascals (100 to 20,000 pounds per square inch), concrete for residential slabs, basements, driveways, and sidewalks often has a compressive strength of 21 MPa (3000 psi) or less, and concrete for structural applications such as beams and columns often have compressive strengths of 28 or 34 MPa (4000 or 5000 psi). Thus, concrete mixes modeled in the BEES software are limited to compressive strengths of 21, 28, and 34 MPa (3000, 4000, and 5000 psi).

To reduce costs, heat generation, and the environmental burden of concrete, fly ash may be substituted for a portion of the portland cement in the concrete mix. Fly ash is a waste material that is a result of burning coal to produce electricity. When used in concrete, fly ash is a cementitious material and can act in a similar manner as cement by facilitating compressive strength development.

[41] American Society for Testing and Materials, *Standard Classification for Building Elements and Related Sitework--UNIFORMAT II*, ASTM Designation E 1557-93, West Conshohocken, PA, September 1993.

BEES performance data apply to six building elements: 21 MPa (3000 psi) Slabs on Grade, Basement Walls, Driveways, and Sidewalks; and 28 or 34 MPa (4000 or 5000 psi) Beams and Columns. For each building element, concrete alternatives with 0%, 15%, and 20% fly ash content (by weight of cement) may be compared. While life-cycle costs differ among building elements, the environmental performance for a given fly ash content and compressive strength rating is the same. The detailed environmental performance data for concrete products may be viewed by opening the following files under the File/Open menu item in the BEES software:

- A10301.DBF—0% Fly Ash Content Concrete
- A10302.DBF—15% Fly Ash Content Concrete
- A10303.DBF—20% Fly Ash Content Concrete

Within each of these three environmental performance data files, there are three complete sets of environmental performance data corresponding to compressive strength ratings of 21, 28, and 34 MPa (3000, 4000, and 5000 psi).

BEES environmental performance data for concrete products are from the Portland Cement Association LCA database. This subsection incorporates extensive documentation provided by the Portland Cement Association for incorporating their LCA data into BEES.[42]

Since comparisons within each building element are limited to concrete products, the environmental performance data for all concrete mixes could be modeled from "cradle-to-ready-mix plant gate" rather than from "cradle-to-grave" as for all other BEES products. That is, environmental flows for transportation from the ready-mix plant to the building site, installation (including concrete forms, reinforcing steel, welded wire fabric, and wire mesh), and end of life are ignored. This modeling change does not affect environmental performance results since BEES assesses *relative* environmental performance within a given building element, and there will be no environmental performance *differences* based on fly ash content for the ignored life-cycle stages.

Figures 3.1 and 3.2 show the elements of concrete production with and without fly ash.

Raw Materials. Table 3.1 shows quantities of concrete constituents for the three compressive strengths modeled. Other materials that are sometimes added, such as silica fume and chemical admixtures, are not considered. Typically, fly ash is an equal replacement for cement. Quantities of constituent materials used in an actual project may vary.

Portland Cement. Cement plants are located throughout North America at locations with adequate supplies of raw materials. Major raw materials for cement manufacture include

[42] Portland Cement Association, *Concrete Products Life Cycle Inventory (LCI) Data Set for Incorporation into the NIST BEES Model*, PCA R&D Serial No. 2168, PCA Project 94-04a, prepared by Michael Nisbet, JAN Consultants, 1998.

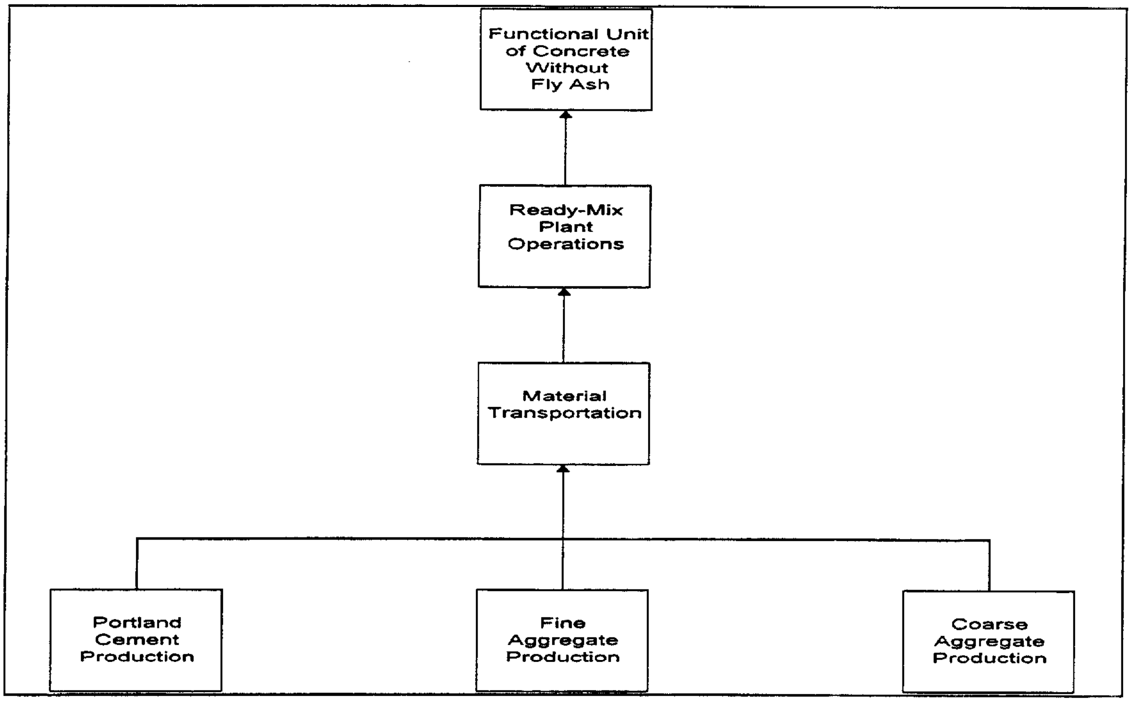

Figure 3.1 Portland Cement Concrete Without Fly Ash Flow Chart

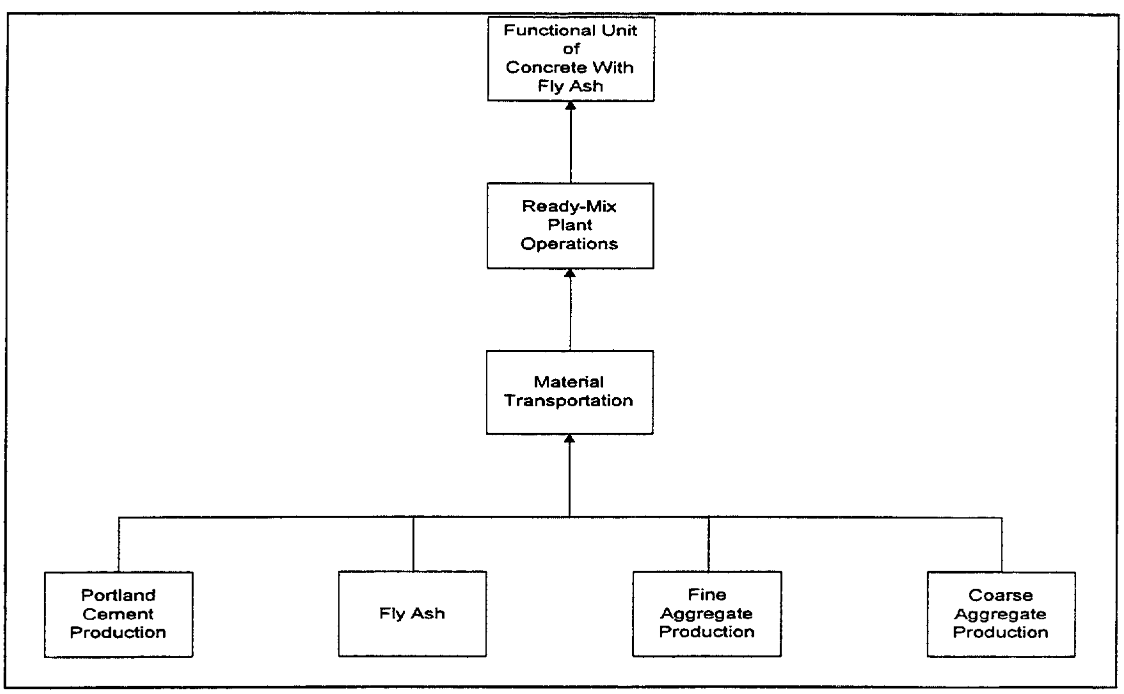

Figure 3.2 Portland Cement Concrete With Fly Ash Flow Chart

Table 3.1 Concrete Constituent Quantities by Compressive Strength of Concrete

Concrete Constituents	*Constituent Weight in kilograms per cubic meter (pounds per cubic yard)*		
	21 MPa (3000 psi)	*28 MPa (4000 psi)*	*34 MPa (5000 psi)*
Cement and Fly Ash	223 (376)	279 (470)	335 (564)
Coarse Aggregate	1127 (1900)	1187 (2000)	1187 (2000)
Fine Aggregate	831 (1400)	771 (1300)	712 (1200)
Water	141 (237)	141 (237)	141 (237)

limestone, cement rock/marl, shale, and clay. These raw materials contain various proportions of calcium oxide, silicon dioxide, aluminum oxide, and iron oxide, with oxide content varying widely across North America. Since portland cement must contain the appropriate proportion of these oxides, the mixture of the major raw materials and minor ingredients (as required) varies among cement plants. BEES data for cement manufacture is based on the average raw material mix and oxide content for all U.S. cement plants for an ASTM C150 Type I/II cement, the most commonly used cement in North America. The average raw materials for U.S. cement include limestone, cement rock/marl, shale, clay, bottom ash, fly ash, foundry sand, sand, and iron/iron ore.

In the manufacturing process, major raw materials are blended with minor ingredients, as required, and processed at high temperatures in a cement kiln to form an intermediate material known as clinker. Gypsum is interground with clinker to form portland cement. Gypsum content is assumed to be added at 5.15 percent (by weight) of portland cement.

Aggregate. Aggregate is a general term which describes a filler material in concrete. Aggregate generally provides 60 to 75 percent of the concrete volume. Typically, aggregate consists of a mixture of coarse and fine rocks. Aggregate is either mined or manufactured.

Sand and gravel are examples of mined aggregate. These materials are dug or dredged from a pit, river bottom, or lake bottom and require little or no processing. Crushed rock is an example of manufactured aggregate. Crushed rock is produced by crushing and screening quarry rock, boulders, or large sized gravel. Approximately half of the coarse aggregate used in the United States is crushed rock.

Fly Ash. Fly ash is a waste material which is a result of burning coal to produce electricity. In LCA terms, fly ash is an environmental outflow of coal combustion, and an environmental inflow of concrete production. As in most LCAs, this waste product is assumed to be an environmentally "free" input material.[43] However, transport of the fly ash to the ready mix plant is included.

Energy Requirements: *Portland Cement.* Portland cement is manufactured using one of four processes: wet process, dry process, preheater, or precalciner. The wet process is the oldest and uses the most energy due to the energy required to evaporate the water. New cement manufacturing plants are being constructed, and older plants converted, to use the more energy efficient preheater/precalciner processes. As of 1995, the mix of production processes was 30 percent wet, 27 percent dry, 19 percent preheater, and 24 percent precalciner. Table 3.2 presents U.S. industry-average energy use by process and fuel type, and, for all processes combined, average energy use weighted by the 1996 process mix. Note that the production of waste fuels is assumed to be free of any environmental burdens to portland cement production (LCA dictates that waste fuel production burdens be allocated to the product whose manufacture generated the waste fuels).

Table 3.2 Energy Requirements for Portland Cement Manufacturing

Fuel Use	***Cement Manufacturing Process****				
	Wet *(%)*	***Dry*** *(%)*	***Preheater*** *(%)*	***Precalciner*** *(%)*	***Weighted Average*** *(%)*
Coal	49	45	67	60	54
Petroleum Coke	18	31	6	8	17
Natural Gas	9	8	10	16	11
Liquid Fuels**	1	1	2	1	1
Wastes	16	6	4	3	8
Electricity	7	9	12	12	10
All Fuels:	100	100	100	100	100
Total Energy in kJ/kg of cement (Btu/lb)	6838 (2940)	6117 (2630)	4885 (2100)	4699 (2020)	5745 (2470)

* Cement constitutes only 10 to 15 percent by weight of concrete's total mass.

** Liquid fuels include gasoline, middle distillates, residual oil, and liquefied petroleum gas

Aggregate. In BEES, coarse and fine aggregate are assumed to be crushed rock, which tends to slightly overestimate the energy use of aggregate production. Production energy for both coarse and fine aggregate is assumed to be 155 kilojoules per kilogram of aggregate (66.8 Btu/lb).

Fly Ash. Fly ash is a waste material with no production energy burdens.

[43] The environmental burdens associated with waste products are typically allocated to the products generating the waste.

Round-trip distances for transport of concrete raw materials to the ready mix plant are assumed to be 97 kilometers (60 miles) for portland cement and fly ash, and 80 kilometers (50 miles) for aggregate. The method of transport is truck, consuming 1.18 kilojoules per kilogram of material per kilometer (0.818 Btu per pound per mile).

Concrete. In BEES, concrete is assumed to be produced in a central ready-mix operation. Energy use in the batch plant includes electricity and fuel used for heating and mobile equipment. Average energy use is assumed to be 247 Megajoules per cubic meter of concrete (0.179 MBtu/CYD, or about 45 Btu/lb of concrete).

Emissions. Emissions for concrete raw materials are from the Portland Cement Association cement LCA database. Emissions include particulate matter, carbon dioxide (CO_2) , carbon monoxide (CO), sulfur oxide (SO_x), nitrogen oxide (NO_x), total hydrocarbons, and hydrogen chloride (HCl). Emissions vary for the nine different mixtures of compressive strength and fly ash content as shown in the concrete environmental performance data files.

Cost. The detailed life-cycle cost data for concrete products may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). Costs are listed under the BEES codes listed in table 3.3. First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

3.2 Roof and Wall Sheathing Alternatives (B1020, B2015)

3.2.1 Oriented Strand Board Sheathing (B10201, B20151)

Oriented strand board (OSB) is made from strands of low density wood (e.g., lodgepole pine, ponderosa pine, and white fir). A wax, primarily a petroleum-based wax, is used to bind the strands. Methylene diphenylisocyanate (MDI) is also used as a binder material in making most OSB. For the BEES system, 1.3 centimeter (1/2 inch) thick OSB boards are studied. The flow diagram shown in Figure 3.3 shows the major elements of oriented strand board production.

BEES performance data are provided for both roof and wall sheathing. Life-cycle costs differ for the two applications, while the environmental performance data are assumed to be the same. The detailed environmental performance data for OSB roof and wall sheathing may be viewed by opening the file B10201.DBF under the File/Open menu item in the BEES software.

Table 3.3 Life-Cycle Cost Data Specifications and Codes for Concrete Products

Concrete Product	*Specifications*	*BEES Code*
0% Fly Ash Content Slab on Grade	10.2cm-15.2cm (4"-6") thick	A1030,10
15% Fly Ash Content Slab on Grade	10.2cm-15.2cm (4"-6") thick	A1030,20
20% Fly Ash Content Slab on Grade	10.2cm-15.2cm (4"-6") thick	A1030,30
0% Fly Ash Content Basement Wall	20.3-38.1cm (8"-15") thick	A2020,10
15% Fly Ash Content Basement Wall	20.3-38.1cm (8"-15") thick	A2020,20
20% Fly Ash Content Basement Wall	20.3-38.1cm (8"-15") thick	A2020,30
0% Fly Ash Content Beams	3.0-7.6 m (10'-25') span	B1011,10
15% Fly Ash Content Beams	3.0-7.6 m (10'-25') span	B1011,20
20% Fly Ash Content Beams	3.0-7.6 m (10'-25') span	B1011,30
0% Fly Ash Content Columns	40.6-61.0cm (16"-24") diameter	B1012,10
15% Fly Ash Content Columns	40.6-61.0cm (16"-24") diameter	B1012,20
20% Fly Ash Content Columns	40.6-61.0cm (16"-24") diameter	B1012,30
0% Fly Ash Content Driveways & Sidewalks	10.2cm-15.2cm (4"-6") thick	G2010,10
15% Fly Ash Content Driveways & Sidewalks	10.2cm-15.2cm (4"-6") thick	G2010,20
20% Fly Ash Content Driveways & Sidewalks	10.2cm-15.2cm (4"-6") thick	G2010,30

Raw Materials. Production of the raw materials for oriented strand board sheathing is based on the Ecobalance LCA database. The average diameter of the logs is assumed to be 18 centimeters (7 inches), which occurs at a density of about 11 kilograms per square meter (50 tons/acre). The MDI binder is added at about 0.26 kilograms per square meter (0.05 lbs per square foot) of 1.3 centimeter (1/2 inch) thickness. The wax used in the binding of the strands is assumed to be petroleum-based wax. OSB constituents are shown in Table 3.4.

Table 3.4 Oriented Strand Board Sheathing Constituents

Oriented Strand Board Constituents	*Physical Weight (%)*
Wood (low density)	97
Methylene diphenylisocyanate (MDI)	2
Wax (petroleum-based)	1

Production requirements for OSB constituents are based on the Ecobalance LCA database.

Energy Required. The energy requirement for OSB production is assumed to be 0.6 MJ of electricity per kilogram (258 Btu per pound) of OSB produced.

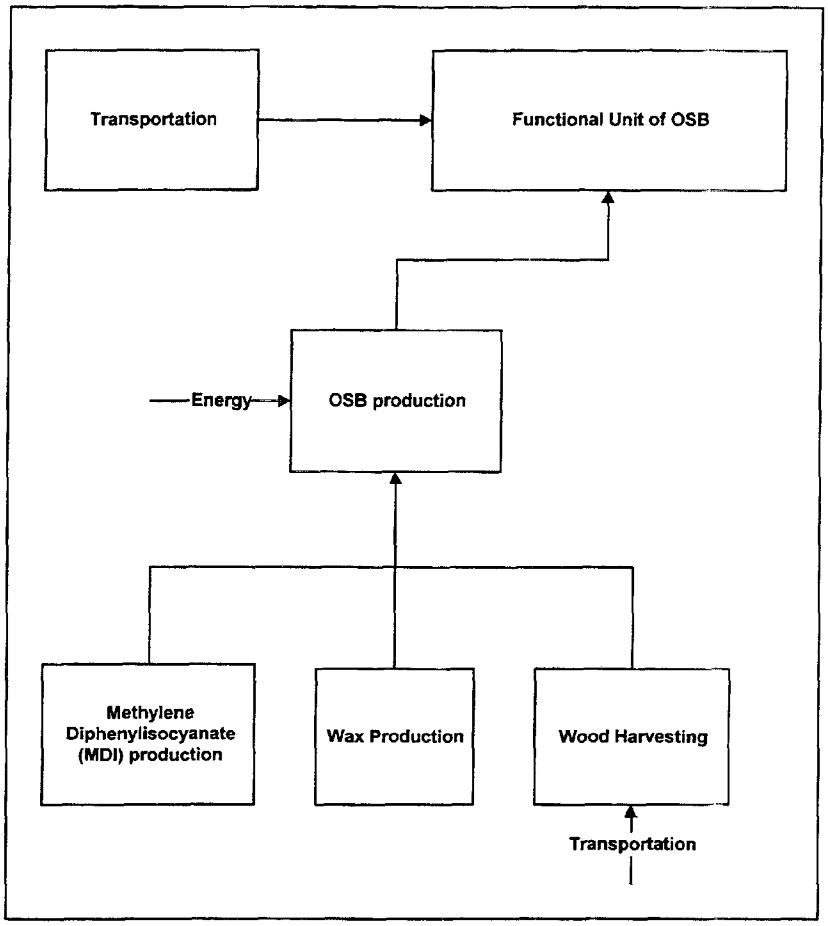

Figure 3.3 Oriented Strand Board Flow Chart

Emissions. Emissions data are from Forintek environmental impact study for wood products.[44]

Transportation. Transportation of the raw materials to the oriented strand board manufacturing facility is not taken into account (often manufacturing facilities are located close to forests). However, transportation to the building site is modeled as a variable of the BEES system.

Cost. Installation costs for OSB sheathing vary by application. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under the following codes:

- B1020,10—Oriented Strand Board Roof Sheathing
- B2015,10—Oriented Strand Board Wall Sheathing

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[44] Forintek Canada Corporation, *Building Materials in the Context of Sustainable Development: Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates for Structural Wood Products*, March 1993, p 27.

Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

3.2.2 Plywood Sheathing (B10202, B20152)

Softwood plywood sheathing is made from lower density wood (e.g., lodgepole pine, ponderosa pine, and white fir). Phenol formaldehyde is used in the manufacturing process. For the BEES system, 1.3 centimeter (1/2 inch) thick plywood boards are studied. The flow diagram shown in Figure 3.4 shows the major elements of softwood plywood sheathing production.

BEES performance data are provided for both roof and wall sheathing. Life-cycle costs differ for the two applications, while the environmental performance data are assumed to be the same. The detailed environmental performance data for plywood roof and wall sheathing may be viewed by opening the file B10202.DBF under the File/Open menu item in the BEES software

Raw Materials. Production of the raw materials for plywood sheathing is based on the Ecobalance LCA database. The average diameter of the logs, assumed harvested from well-managed forests, is assumed to be 18 centimeters (7 inches), which occurs at a density of about 11 kilograms per square meter (50 tons/acre). Phenol formaldehyde is assumed to constitute 1.4% of the total mass of the product. Plywood sheathing constituents are shown in Table 3.5.

Table 3.5 Plywood Constituents

Plywood Sheathing Constituents	*Physical Weight (%)*
Wood (low density)	98.6
Phenol formaldehyde	1.4

Production requirements for plywood sheathing are based on the Ecobalance LCA database.

Energy Required. The energy requirement for plywood sheathing production is assumed to be 0.45 MJ of electricity per kilogram (193 Btu per pound) of plywood produced.

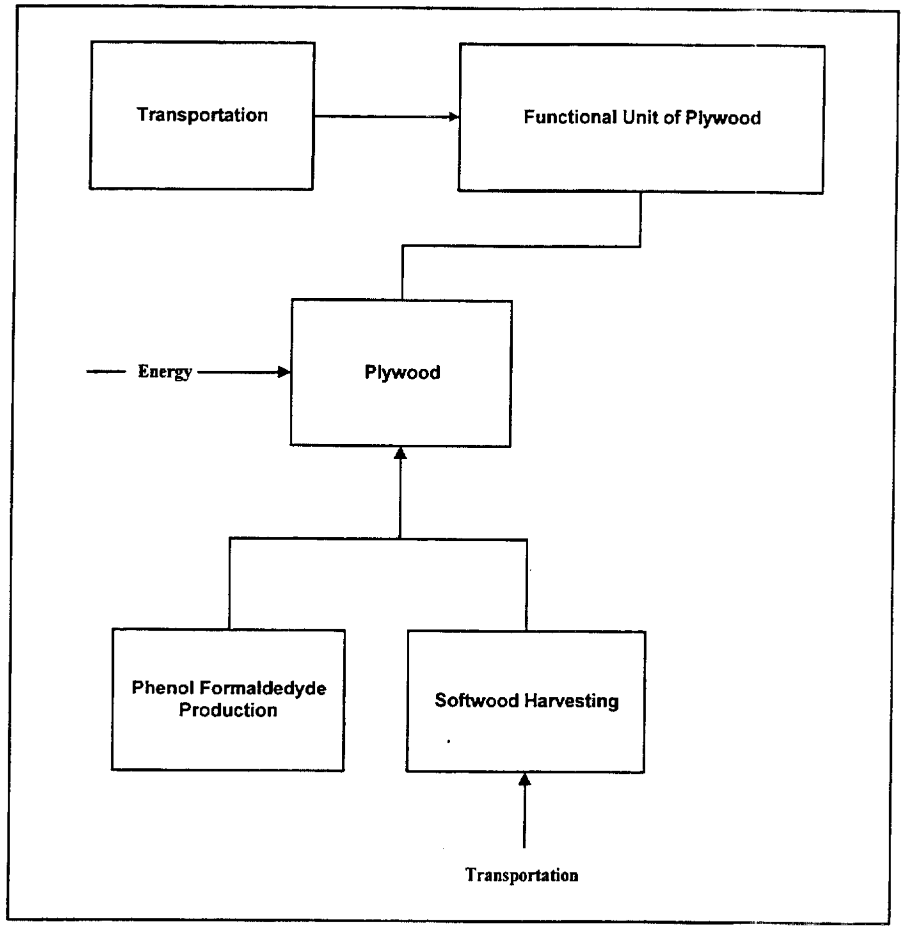

Figure 3.4 Softwood Plywood Flow Chart

Emissions. Emissions data are from the Forintek environmental impact study for wood products.[45]

Transportation. Transportation of the raw materials to the plywood sheathing manufacturing facility is not taken into account (often manufacturing facilities are located close to forests). However, transportation to the building site is modeled as a variable of the BEES system.

Cost. Installation costs for plywood vary by application. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under the following codes:

- B1020,20—Plywood Roof Sheathing
- B2015,20—Plywood Wall Sheathing

[45] Forintek Canada Corporation, *Building Materials in the Context of Sustainable Development: Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates for Structural Wood Products*, March 1993, pp 20-24.

Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

3.3 Exterior Wall Finish Alternatives (B2011)

3.3.1 Brick and Mortar (B20111)

Brick is a masonry unit of clay or shale, formed into a rectangular shape while plastic, then burned or fired in a kiln. Mortar is used to bond the bricks into a single unit. Facing brick is used on exterior walls for an attractive appearance.

For the BEES system, solid, fired clay facing brick (10cm x 6.8cm x 20 cm, or 4" x 2-2/3" x 8") and Type N mortar are studied. The flow diagram shown in Figure 3.5 shows the major elements of clay facing brick and mortar production. The detailed environmental performance data for this product may be viewed by opening the file B20111.DBF under the File/Open menu item in the BEES software.

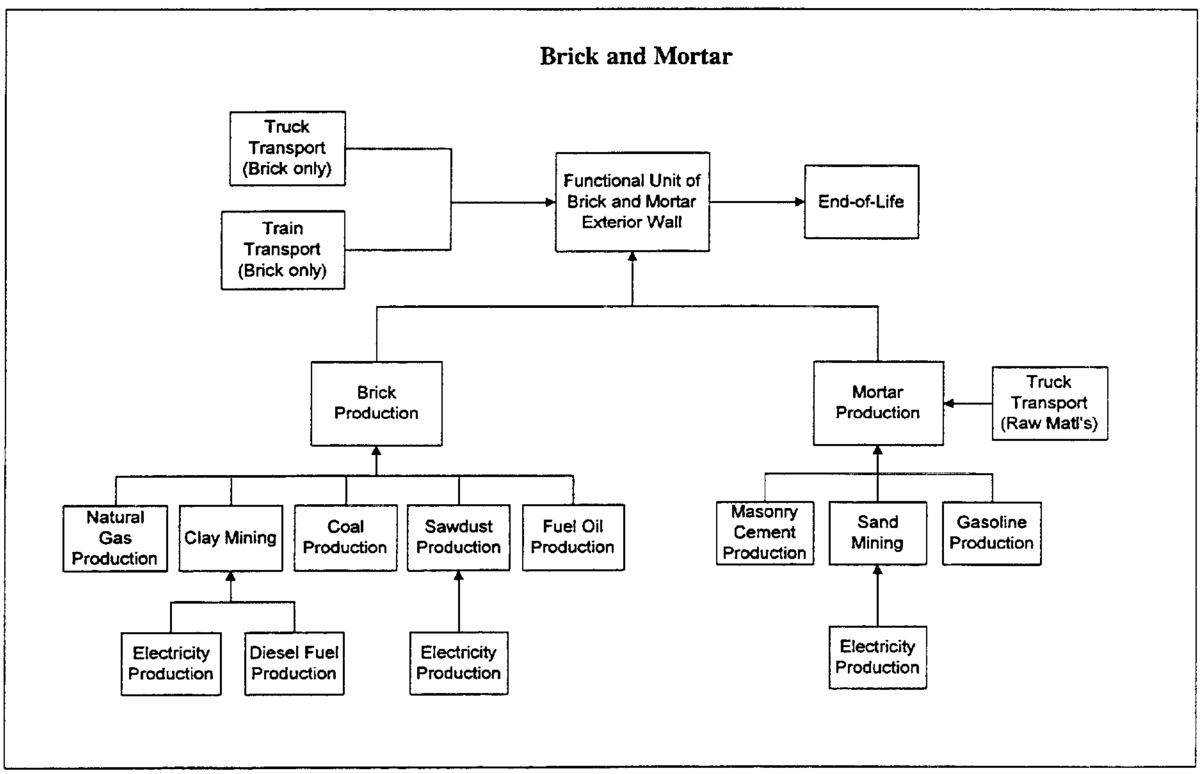

Figure 3.5 Brick and Mortar Flow Chart

Raw Materials. Production of the raw materials for brick and mortar are based on the Ecobalance LCA database. Type N mortar consists of 1 part (by volume) masonry cement, 3 parts sand,[46] and 6.3 liters (1.67 gallons) of water. Masonry cement is modeled based on the assumptions outlined below for stucco exterior walls.

Energy Required. The energy requirements for brick production (drying and firing) are listed in table 3.6. The production of the different types of fuel was based on the Ecobalance LCA database.

Table 3.6 Energy Requirements for Brick Manufacturing

Fuel Use	*Manufacturing Energy*
Total Fossil Fuel	2.88 MJ/kg (1238 Btu/lb)
% Coal	9.6 %
% Natural Gas (*)	71.9 %
% Fuel Oil	7.8 %
% Wood	10.8 %

(*) Includes Propane

The mix of brick manufacturing technologies is 73 percent tunnel kiln technology and 27 percent periodic kiln technology.

The mortar is assumed to be mixed in a 8 Horsepower, gasoline powered mixer with a flow rate of 0.25 cubic meters (9 cubic feet) of mortar per hour, running for five minutes.

Emissions. Emissions were based on AP-42[47] data for emissions from brick manufacturing for each manufacturing technology and type of fuel burned.

Transportation. Transportation of the raw materials to the brick manufacturing facility was not taken into account (often manufacturing facilities are located close to mines). However, transportation to the building site is modeled as a variable. Bricks are assumed to be transported by truck and train (86% and 14%, respectively) to the building site. The BEES user can select from among three travel distances.

Use. The density of brick is assumed to be 2.95 kilograms (6.5 pounds) per brick. The density of the Type N mortar is assumed to be 2007 kilograms per cubic meter (125 pounds per cubic foot). A brick wall is assumed to be 80% brick and 20% mortar by surface area.

End-Of-Life. The brick wall is assumed to have a useful life of 200 years. Seventy-five percent of the bricks are assumed to be recycled after the 200 year use.

[46] Based on ASTM Specification C 270-96.

[47] *Clearinghouse for Inventories and Emission Factors*, Version 4.0, EPA-454/c-95-001, CD-ROM, July 1995.

Cost. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under BEES code *B2011*, product code *10.* Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

3.3.2 Stucco (B20112)

Stucco is cement plaster used to cover exterior wall surfaces. For the BEES system, three coats of stucco (two base coats and one finish coat) are studied. A layer of bonding agent, polyvinyl acetate, is assumed to be applied between the wall and the first layer of base coat stucco.

Figures 3.6 and 3.7 show the elements of stucco production from both portland cement (for a base coat Type C plaster, finish coat Type F plaster) and masonry cement (for a base coat Type MS plaster, finish coat Type F plaster). Since both cements are commonly used for stucco exterior walls, LCA data for both portland cement and masonry cement stucco were collected and then averaged for use in the BEES system. Figure 3.8 shows the steps in the manufacture of masonry cement, and figure 3.9 the steps in the manufacture of portland cement.

The detailed environmental performance data for stucco exterior walls may be viewed by opening the file B20112.DBF under the File/Open menu item in the BEES software.

Raw Materials. The raw material consumption for masonry cement is based on Type N masonry cement as shown in table 3.7.

Table 3.7 Masonry Cement Constituents

Masonry Cement Constituent	*Physical Weight (%)*
Portland Cement Clinker	50
Limestone	47.5
Gypsum	2.4

Production of these raw materials is based on the Ecobalance LCA database.

Stucco consists of the raw materials listed in table 3.8.[48]

[48] Based on ASTM Specification C 926-94.

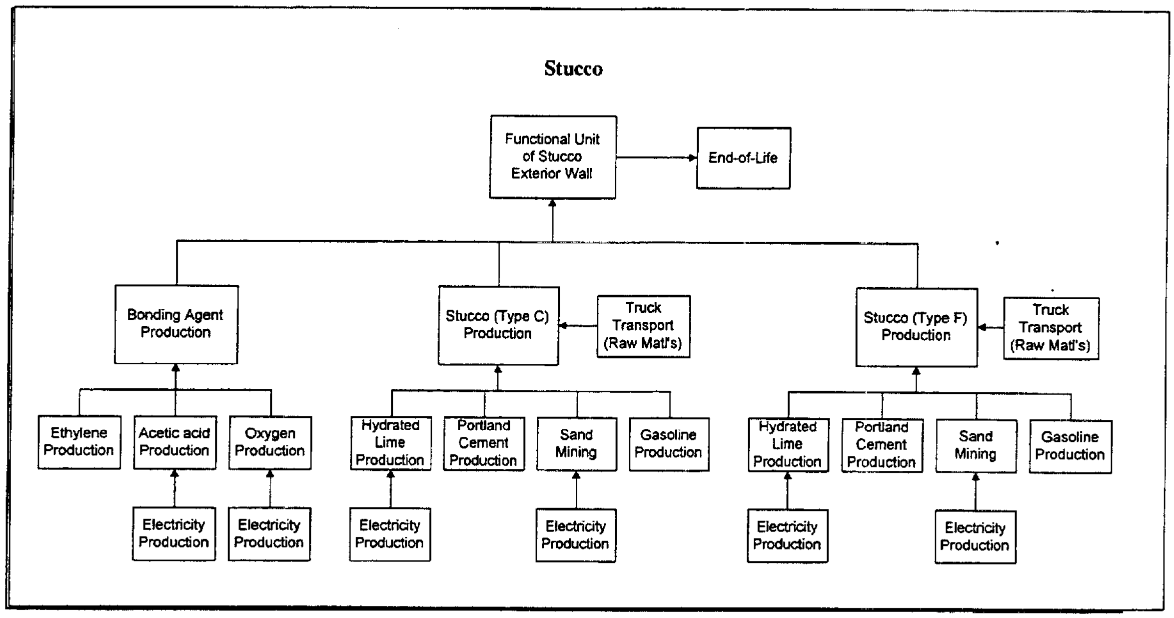

Figure 3.6 Stucco (Type C) Flow Chart

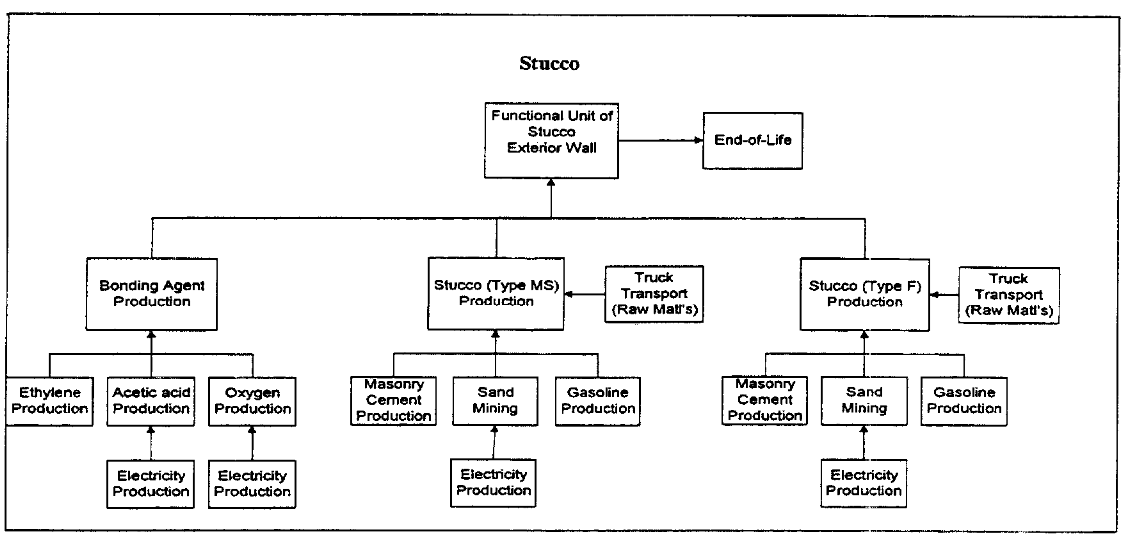

Figure 3.7 Stucco (Type MS) Flow Chart

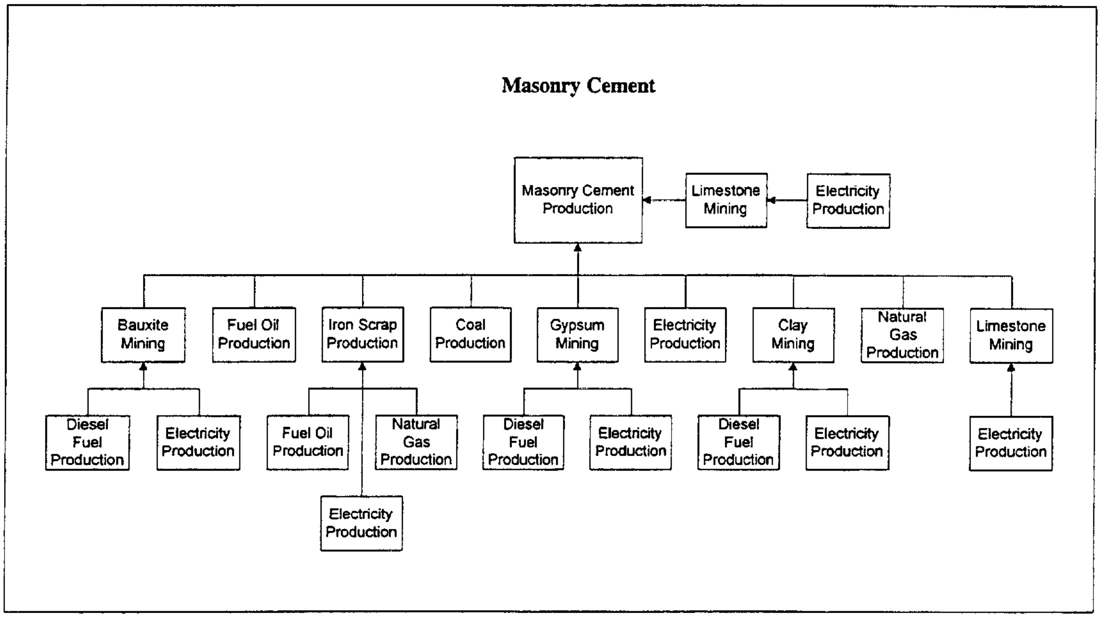

Figure 3.8 Masonry Cement Flow Chart

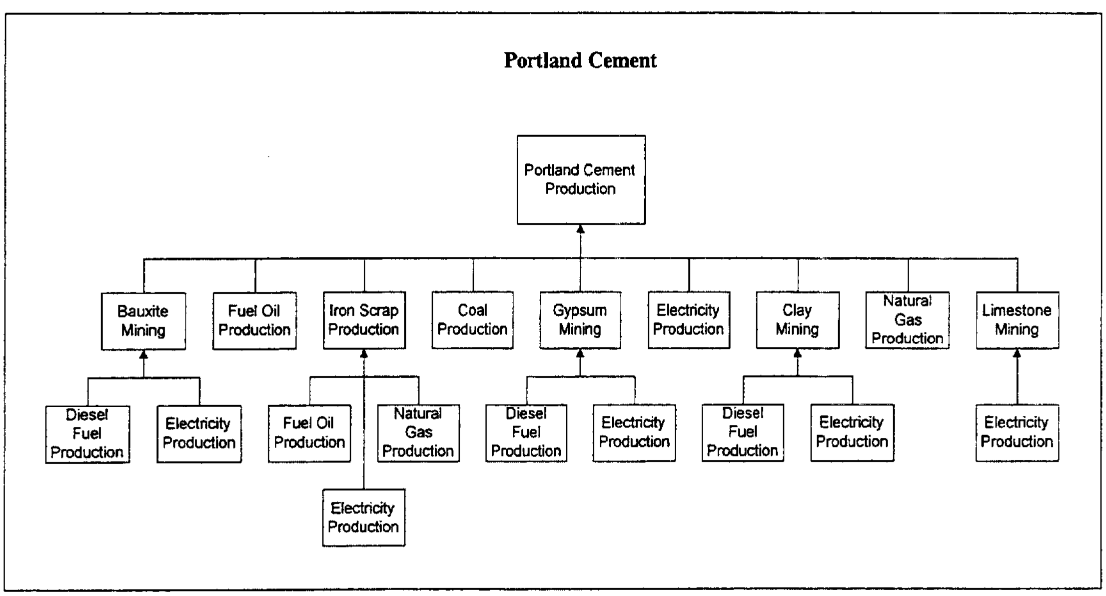

Figure 3.9 Portland Cement Flow Chart

Table 3.8 Stucco Constituents

Type of Stucco	*Cementitious Materials (parts by volume)* Portland Cement	Masonry Cement	Lime	*Sand* per volume of cementitious mat'l
Base Coat C	1		0.5	3.75
Finish Coat F	1		1.125	2.25
Base Coat MS		1		3.75
Finish Coat FMS		1		2.25

The coat of bonding agent is assumed to be 0.15 millimeters (0.006 inches) thick. The bonding agent is polyvinyl acetate.

Production of sand, lime, and polyvinyl acetate is modeled from the Ecobalance database.

Energy Requirements. The energy requirements for masonry cement production are shown in table 3.9.

Table 3.9 Energy Requirements for Masonry Cement Manufacturing

Fuel Use	*Manufacturing Energy*
Total Fossil Fuel	2.72 MJ/kg (1169 Btu/lb)
% Coal	84 %
% Natural Gas	7 %
% Fuel Oil	1 %
% Wastes	8 %
Total Electricity	0.30 MJ/kg (129 Btu/lb)

These percentages are based on average fuel use in portland cement manufacturing.

Stucco is assumed to be mixed in a 8 Horsepower, gasoline powered mixer with a flow rate of 0.25 cubic meters (9 cubic feet) of stucco per hour, running for five minutes.

Emissions. Emissions for masonry cement production are based on AP-42 data for controlled emissions from cement manufacturing. Clinker is assumed to be produced in a wet process kiln.

Transportation. Transportation distance to the building site is modeled as a variable.

Use. The thickness of the three layers of stucco is assumed to be 1.6 centimeters (5/8 inch) each.

The densities of the different types of stucco are shown in table 3.10.

Table 3.10 Density of Stucco by Type

Type of Stucco	*Density kg/0.0283m³(kg/ft³)*
Base Coat C	51.79
Finish Coat F	55.78
Base Coat MS	53.97
Finish Coat FMS	61.55

Cost. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under BEES code *B2011*, product code *20*. Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

3.4 Wall and Ceiling Insulation Alternatives (B2012, B3014)

3.4.1 Blown Cellulose Insulation (B20121, B30141)

Blown cellulose insulation is produced primarily from post-consumer wood pulp (newspapers), accounting for about 80% of the insulation by weight. Cellulose insulation is treated with fire retardant. Ammonium sulfate, borates, and boric acid are used most commonly and account for the other 20% of the cellulose insulation by weight. The flow diagram shown in Figure 3.10 shows the elements of blown cellulose insulation production.

BEES performance data are provided for thermal resistance values of R-13 for a wall application and R-30 for a ceiling application. The detailed environmental performance data files for this product may be viewed by opening the following files under the File/Open menu item in the BEES software:

- B20121.DBF—R-13 Blown Cellulose Wall Insulation
- B30141.DBF—R-30 Blown Cellulose Ceiling Insulation

Raw Materials. Blown cellulose insulation is composed of the materials listed in table 3.11. Production requirements for these constituents are based on the Ecobalance LCA database.

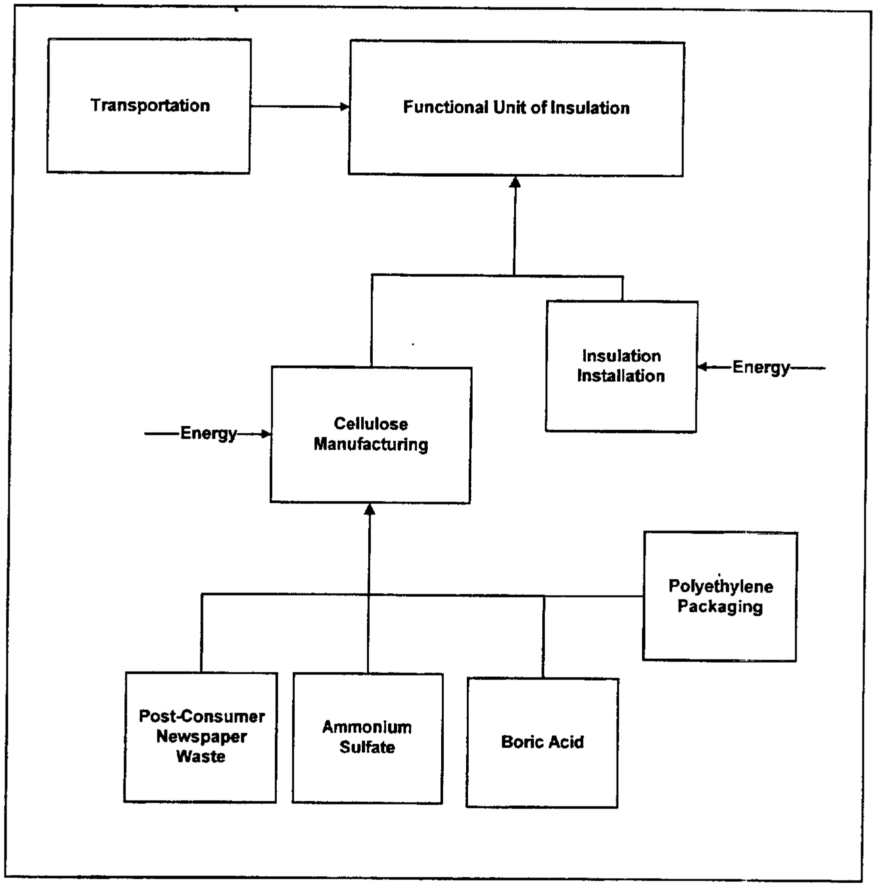

Figure 3.10 Blown Cellulose Insulation Flow Chart

Table 3.11 Blown Cellulose Constituents

Blown Cellulose Insulation Constituents	*Physical Weight (%)*
Pulp waste (newspapers)	80
Ammonium sulfate	15.5
Boric acid	4.5

Blown cellulose insulation manufacture involves the energy requirements as listed in table 3.12.

Table 3.12 Energy Requirements for Blown Cellulose Insulation Manufacturing

Fuel Use	*Manufacturing Energy*
Electricity	0.35 MJ/kg (150 Btu/lb)

Use. It is important to consider thermal performance differences when assessing environmental and economic performance for insulation product alternatives. Thermal performance affects building heating and cooling loads, which in turn affect energy-related LCA inventory flows and building energy costs over the 50-year use stage. Since alternatives for ceiling insulation all have R-30 thermal resistance values, thermal performance differences are at issue only for the R-11, R-12, R-13, and R-15 wall insulation alternatives.

For wall insulation, thermal performance differences are separately assessed for 14 U.S. cities spread across a wide range of climate and fuel cost zones, and for electricity, distillate oil, and natural gas heating fuel types (electricity is assumed for all cooling). When selecting wall insulation alternatives for analysis, the BEES user selects the U.S. city closest to the building location, and the building heating fuel type, so that thermal performance differences may be customized to these important contributors to building energy use. A NIST study of the economic efficiency of energy conservation measures (including insulation), tailored to these cities and fuel types, is used to estimate 50-year heating and cooling requirements per functional unit of insulation.[49] BEES environmental performance results account for the energy-related inventory flows resulting from these energy requirements. To account for the 50-year energy requirements in BEES economic performance results, 1997 fuel prices by State,[50] and U.S. Department of Energy fuel price projections over the next 30 years[51] are used to compute the present value cost of operational energy per functional unit for each alternative R-value.

Cellulose insulation is typically blown into place. It is assumed to be blown at a rate of 1134 kilograms per hour (2500 lbs/hr). During installation, there is negligible waste because excess cellulose is typically added back into the hopper for re-blowing or is simply placed by hand into wall or ceiling cavities.

Cost. Installation costs for blown cellulose insulation vary by application. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under the following codes:

- B2012,10—R-13 Blown Cellulose Wall Insulation
- B3014,10—R-30 Blown Cellulose Ceiling Insulation

Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). Operational energy costs for wall insulation (discussed above under "Use") are found in the file USEENRGY.DBF. All other future

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[49] Stephen R. Petersen, *Economics and Energy Conservation in the Design of New Single-Family Housing,* NBSIR 81-2380, National Bureau of Standards, Washington, D.C., 1981.

[50] Therese K. Stovall, *Supporting Documentation for the 1997 Revision to the DOE Insulation Fact Sheet,* ORNL-6907, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1997.

[51] Sieglinde K. Fuller, *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis—April 1997,* NISTIR 85-3273-12, National Institute of Standards and Technology, 1997. The year 30 DoE cost esclation factor is assumed to hold for years 31-50.

cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews. First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data.*

3.4.2 Fiberglass Batt Insulation (B20122, B20123, B30142)

Fiberglass batt insulation is made by forming spun-glass fibers into batts. Using a rotary process, molten glass is poured into a rapidly spinning disc that has thousands of fine holes in its rim. Centrifugal force extrudes the molten glass through the holes, creating the glass fibers. The fibers are made thinner by jets, air, or steam and are immediately coated with a binder and/or de-dusting agent. The material is then cured in ovens and formed into batts.

The flow diagram shown in Figure 3.11 shows the elements of fiberglass batt insulation production.

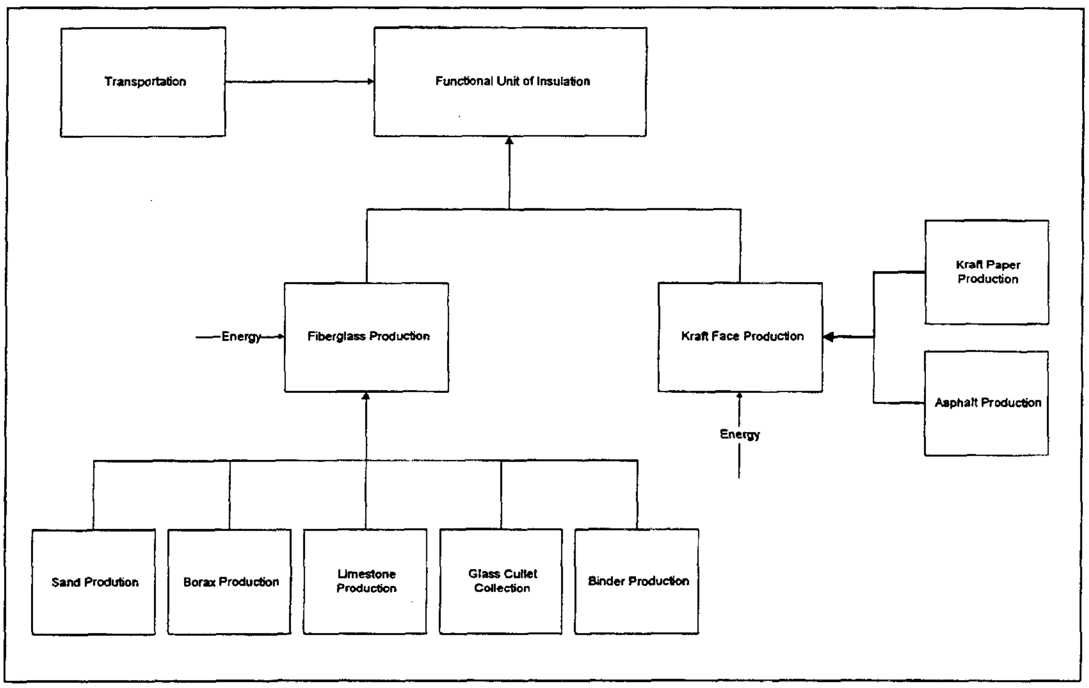

Figure 3.11 Fiberglass Batt Insulation Flow Chart

BEES performance data are provided for thermal resistance values of R-11 and R-15 for a wall application, and R-30 for a ceiling application. The detailed environmental performance data for fiberglass batt insulation may be viewed by opening the following files under the File/Open menu item in the BEES software:

- B20122.DBF—R-11 Fiberglass Wall Insulation
- B20123.DBF—R-15 Fiberglass Wall Insulation

- B30142.DBF—R-30 Fiberglass Ceiling Insulation

Raw Materials. Fiberglass batts are composed of the materials listed in table 3.13.

Table 3.13 Fiberglass Batt Constituents

Fiberglass Batt Constituents	*Physical Weight (%)*
High silica-content sand and limestone	64
Binder (phenol formaldehyde)	6
Boron oxide	5
Glass cullet (industry average)	25

Production requirements for the fiberglass batt insulation constituents are based on the Ecobalance LCA database.

Fiberglass batt production involves the energy requirements as listed in table 3.14.

Table 3.14 Energy Requirements for Fiberglass Batt Insulation Manufacturing

Fuel Use	*Manufacturing Energy*
Electricity	3.1 MJ/kg (1333 Btu/lb)
Natural Gas	17.17 MJ/kg (7382 Btu/lb)

Emissions. Emissions associated with fiberglass batt insulation manufacture are based on AP-42 data for the glass fiber manufacturing industry.

Use. It is important to consider thermal performance differences when assessing environmental and economic performance for insulation product alternatives. Thermal performance affects building heating and cooling loads, which in turn affect energy-related LCA inventory flows and building energy costs over the 50-year use stage. Since alternatives for ceiling insulation all have R-30 R-values, thermal performance differences are at issue only for the R-11, R-12, R-13, and R-15 wall insulation alternatives.

For wall insulation, thermal performance differences are separately assessed for 14 U.S. cities spread across a wide range of climate and fuel cost zones, and for electricity, distillate oil, and natural gas heating fuel types (electricity is assumed for all cooling). When selecting wall insulation alternatives for analysis, the BEES user selects the U.S. city closest to the building location and the building heating fuel type, so that thermal performance differences may be customized to these important contributors to building energy use. A NIST study of the economic efficiency of energy conservation measures (including insulation), tailored to these cities and fuel types, is used to estimate 50-year heating and cooling requirements per functional unit of insulation.[52] BEES environmental performance results account for the energy-related inventory flows resulting from these energy requirements. To account for the 50-year energy requirements in BEES economic performance results, 1997 fuel prices by State,[53] and U.S. Department of Energy fuel price projections over the next 30 years[54] are used to compute the present value cost of operational energy per functional unit for each R-value.

When installing fiberglass batt insulation, approximately 5% of the product is lost to waste. Although fiberglass insulation reuse or recycling is feasible, very little occurs now. Most fiberglass insulation waste is currently disposed of in landfills.

Cost. Purchase and installation costs for fiberglass batt insulation vary by R-value and application. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under the following codes:

- B2012,20—R-11 Fiberglass Batt Wall Insulation
- B2012,30—R-15 Fiberglass Batt Wall Insulation
- B3014,20—R-30 Fiberglass Batt Ceiling Insulation

Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). Operational energy costs for wall insulation (discussed above under "Use") are found in the file USEENRGY.DBF. All other future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews. First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data.*

3.4.3 Blown Mineral Wool Insulation (B20124, B30143)

Blown mineral wool insulation is made by spinning fibers from natural rock (rock wool) or iron ore blast furnace slag (slag wool). Rock wool and slag wool are manufactured by melting the constituent raw materials in a cupola. A molten stream is created and poured onto a rapidly spinning wheel or wheels. The viscous molten material adheres to the wheels and the centrifugal force throws droplets of melt away from the wheels, forming fibers. The fibers are then collected and cleaned to remove non-fibrous material. During

[52] Stephen R. Petersen, *Economics and Energy Conservation in the Design of New Single-Family Housing,* NBSIR 81-2380, National Bureau of Standards, Washington, D.C., 1981.

[53] Therese K. Stovall, *Supporting Documentation for the 1997 Revision to the DOE Insulation Fact Sheet,* ORNL-6907, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1997.

[54] Sieglinde K. Fuller, *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis—April 1997,* NISTIR 85-3273-12, National Institute of Standards and Technology, 1997. The year 30 DoE cost esclation factor is assumed to hold for years 31-50.

the process a phenol formaldehyde binder and/or a de-dusting agent are applied to reduce free, airborne wool during application. The flow diagram in Figure 3.12 shows the elements of blown mineral wool insulation production.

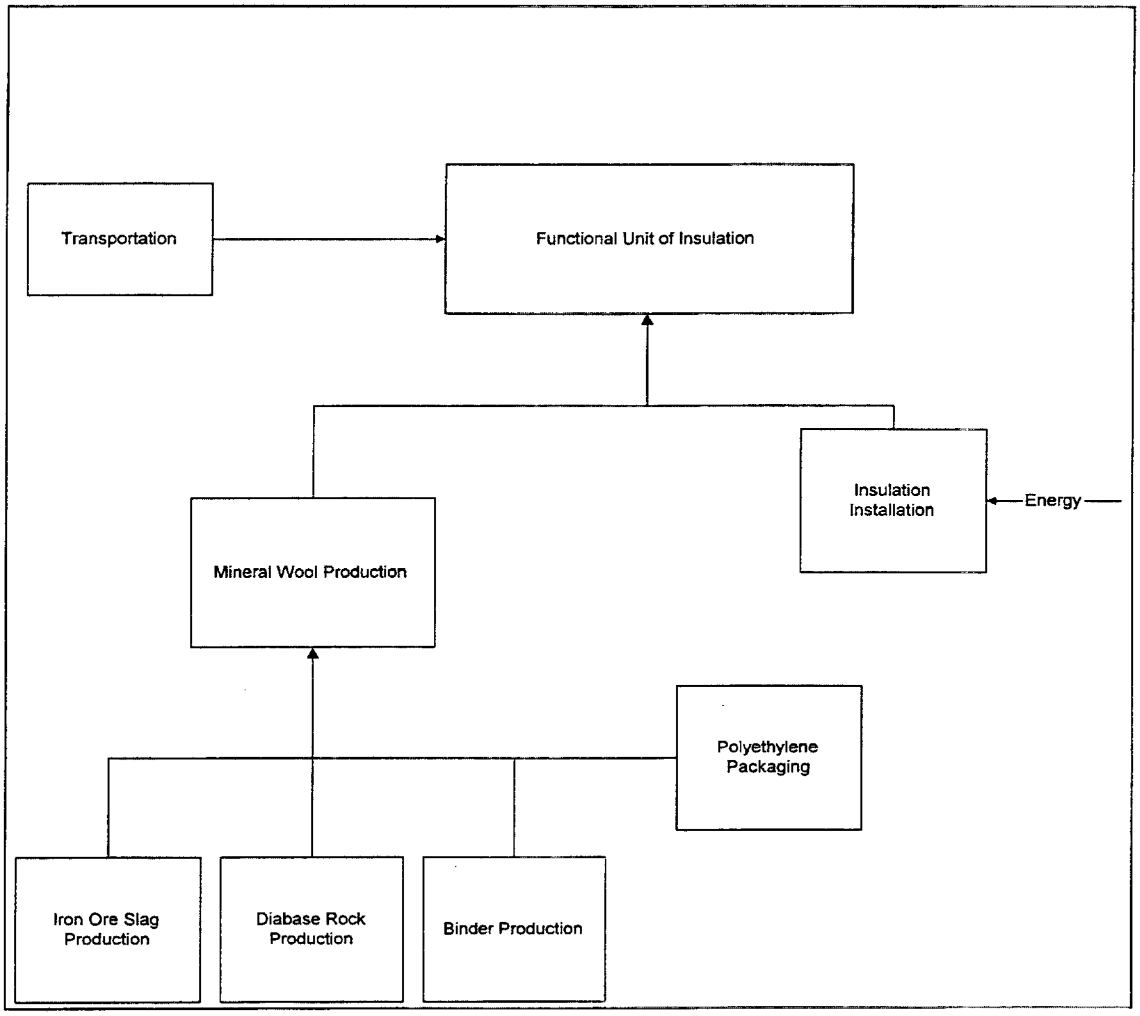

Figure 3.12 Blown Mineral Wool Insulation Flow Chart

BEES performance data are provided for a thermal resistance value of R-12 for a wall application, and R-30 for a ceiling application. The detailed environmental performance data for blown mineral wool insulation may be viewed by opening the following files under the File/Open menu item in the BEES software:

- B20124.DBF—R-12 Mineral Wool Wall Insulation
- B30143.DBF—R-30 Mineral Wool Ceiling Insulation

Raw Materials. Mineral wool insulation is composed of the materials listed in table 3.15. Production requirements for the mineral wool constituents are based on the Ecobalance LCA database.

Table 3.15 Blown Mineral Wool Constituents

Mineral Wool Constituents	*Physical Weight (%)*
Iron-ore slag (North American)	80
Diabase/basalt	20

Mineral wool production involves the energy requirements listed in table 3.16.

Table 3.16 Energy Requirements for Mineral Wool Insulation Manufacturing

Fuel Use	*Manufacturing Energy*
Natural Gas	15.85 MJ/kg (6814 Btu/lb)
Coke	6.38 MJ/kg (2473 Btu/lb)

Emissions. Emissions associated with mineral wool insulation production are based on AP-42 data for the mineral wool manufacturing industry.

Use. It is important to consider thermal performance differences when assessing environmental and economic performance for insulation product alternatives. Thermal performance affects building heating and cooling loads, which in turn affect energy-related LCA inventory flows and building energy costs over the 50-year use stage. Since alternatives for ceiling insulation all have R-30 R-values, thermal performance differences are at issue only for the R-11, R-12, R-13, and R-15 wall insulation alternatives.

For wall insulation, thermal performance differences are separately assessed for 14 U.S. cities spread across a wide range of climate and fuel cost zones, and for electricity, distillate oil, and natural gas heating fuel types (electricity is assumed for all cooling). When selecting wall insulation alternatives for analysis, the BEES user selects the U.S. city closest to the building location and the building heating fuel type, so that thermal performance differences may be customized to these important contributors to building energy use. A NIST study of the economic efficiency of energy conservation measures (including insulation), tailored to these cities and fuel types, is used to estimate 50-year heating and cooling requirements per functional unit of insulation.[55] BEES environmental performance results account for the energy-related inventory flows resulting from these energy requirements. To account for the 50-year energy requirements in BEES economic performance results, 1997 fuel prices by State,[56] and U.S. Department of Energy fuel

[55] Stephen R. Petersen, *Economics and Energy Conservation in the Design of New Single-Family Housing,* NBSIR 81-2380, National Bureau of Standards, Washington, D.C., 1981.

[56] Therese K. Stovall, *Supporting Documentation for the 1997 Revision to the DOE Insulation Fact Sheet,* ORNL-6907, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1997.

price projections over the next 30 years[57] are used to compute the present value cost of operational energy per functional unit for each R-value.

Mineral wool insulation is typically blown into place. It is assumed to be blown at a rate of 1134 kilograms per hour (2500 lbs/hr). During installation, there is negligible waste because excess mineral wool is typically added back into the hopper for re-blowing or is simply placed by hand into wall or ceiling cavities.

Cost. Purchase and installation costs for blown mineral wool insulation vary by application. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under the following codes:

- B2012,40—R-12 Mineral Wool Wall Insulation
- B3014,30—R-30 Mineral Wool Ceiling Insulation

Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). Operational energy costs for wall insulation (discussed above under "Use") are found in the file USEENRGY.DBF. All other future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews. First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data.*

3.5 Roof Covering Alternatives (B3011)

3.5.1 Asphalt Shingles (B30111)

Asphalt shingles are commonly made from fiberglass mats filled with asphalt, then coated on the exposed side with mineral granules for both a decorative finish and a wearing layer. Asphalt shingles are nailed over roofing felt onto sheathing.

For BEES, a roof covering of 20-year asphalt shingles, roofing felt, and galvanized nails is analyzed. The flow diagram shown in Figure 3.13 shows the elements of asphalt shingle production. The detailed environmental performance data for this product may be viewed by opening the file B30111.DBF under the File/Open menu item in the BEES software.

[57] Sieglinde K. Fuller, *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis—April 1997*, NISTIR 85-3273-12, National Institute of Standards and Technology, 1997. The year 30 DoE cost esclation factor is assumed to hold for years 31-50.

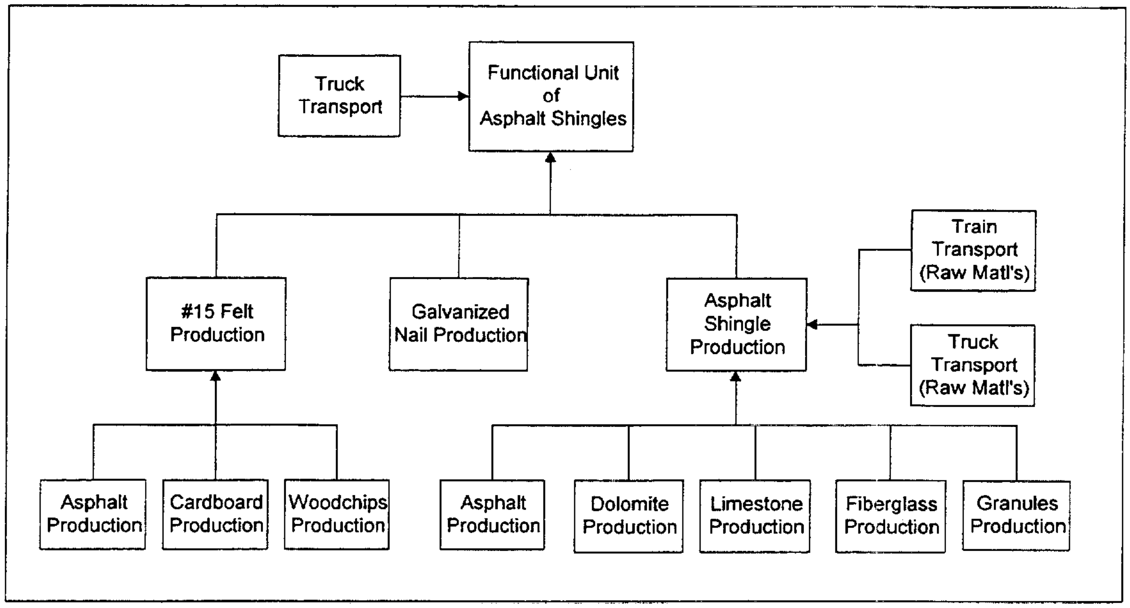

Figure 3.13 Asphalt Shingles Flow Chart

Raw Materials. Asphalt shingles are composed of the materials listed in table 3.17.

Table 3.17 Asphalt Shingle Constituents

Asphalt Shingle Constituents	*Physical Weight*
Asphalt	1.9 kg/m^2 (40 lbs/sq.)
Filler	4.2 kg/ m^2 (86 lbs/sq.)
Fiberglass	0.2 kg/ m^2 (4 lbs/sq.)
Granules	3.7 kg/ m^2 (75 lbs/sq.)

Filler is assumed to be 50 percent dolomite and 50 percent limestone. Granules production is modeled as rock mining and grinding. Production requirements for the asphalt shingle constituents are based on the Ecobalance LCA database.

Seven kilogram (fifteen pound) felt consists of asphalt and organic felt as listed in table 3.18. The organic felt is assumed to consist of 50 percent recycled cardboard and 50 percent wood chips. The production of these materials, and the asphalt, is based on the Ecobalance LCA database.

Energy Requirements. The energy requirement for asphalt shingle production is assumed to be 33 MJ of natural gas per square meter (2843 Btu per square foot) of shingles.

Table 3.18 Seven Kilogram (15 pound) Roofing Felt Constituents

7 kg (15 lb) Felt Constituents	*Physical Weight*
Asphalt	0.5 kg/ m^2 (9.6 lbs/sq.)
Organic Felt	0.3 kg/ m^2 (5.4 lbs/sq.)
Total:	0.8 kg/ m^2 (15 lbs/sq.)

Emissions. Emissions associated with manufacturing asphalt shingles and roofing felt is taken into account based on AP-42 data for asphalt shingle processing and saturated felt processing.

Transportation. Transport of the asphalt shingle raw materials is taken into account. The distance transported is assumed to be 402 km (250 mi) for all of the components. Asphalt is assumed to be transported by truck, train, and pipeline in equal proportions. Dolomite, limestone, and granules are assumed to be transported by truck and train in equal proportions. Fiberglass is assumed to be transported by truck.

Transport of the raw materials for roofing felt is also taken into account. The distance transported is assumed to be 402 km (250 mi) for all of the components. Asphalt is assumed to be transported by truck, train, and pipeline in equal proportions, while the cardboard and wood chips are assumed to be transported by truck.

Transport of the shingles, roofing felt, and nails to the building site is a variable of the BEES system.

Use. Asphalt shingle and roofing felt installation is assumed to require 47 nails per square meter (440 nails per square). Installation waste from scrap is estimated at 5 percent of the installed weight. At 20 years, new shingles are installed over the existing shingles. At 40 years, both layers of roof covering are removed before installing replacement shingles.

Cost. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under BEES code *B3011*, product code *10*. Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

3.5.2 Clay Tile (B30112)

Clay tiles are made by shaping and firing clay. The most commonly used clay tile is the red Spanish tile. For the BEES system, a roof covering of 70-year red Spanish clay tiles, roofing felt, and nails is studied. Due to weight of the tile and its relatively long useful life, 14 kilogram (30 pound) felt and copper nails are used. The flow diagram shown in Figure 3.14 shows the elements of clay tile production. The detailed environmental performance data for this product may be viewed by opening the file B30112.DBF under the File/Open menu item in the BEES software.

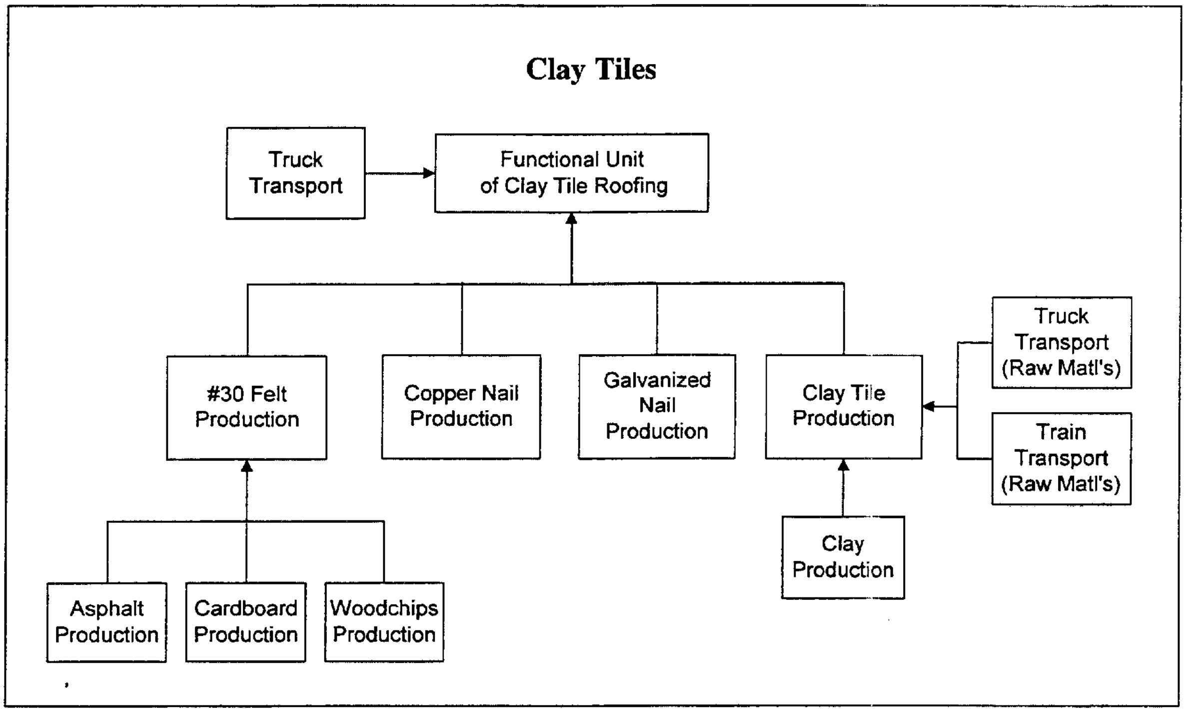

Figure 3.14 Clay Tile Flow Chart

Raw Materials. The weight of the clay tile studied is 381 kilograms (840 pounds) per square, requiring 171 pieces of tile. Production of the clay is based on the Ecobalance LCA database.

Table 3.19 Fourteen Kilogram (30 pound) Roofing Felt Constituents

14 kg (30 lb) Felt Constituents	*Physical Weight*
Asphalt	0.9 kg/m^2 (19.2 lbs/sq.)
Organic Felt	0.5 kg/ m^2 (10.8 lbs/sq.)
Total:	1.4 kg/ m^2 (30 lbs/sq.)

Fourteen kilogram (thirty pound) felt consists of asphalt and organic felt as listed in table 3.19. The organic felt is assumed to consist of 50 percent recycled cardboard and 50 percent wood chips. The production of these materials, and the asphalt, is based on the Ecobalance LCA database.

Energy Requirements. The energy required to fire clay tile is 6.3 MJ per kilogram (2708 Btu per pound) of clay tile. The fuel type is natural gas.

Emissions. Emissions associated with natural gas combustion are based on AP-42 emission factors.

Transportation. Transport of the clay raw material is taken into account. The distance transported is assumed to be 402 km (250 mi) for the clay by train and truck. Transport of the raw materials for roofing felt is also taken into account. The distance transported is assumed to be 402 km (250 mi) for all of the components. Asphalt is assumed to be transported by truck, train, and pipeline in equal proportions, while the cardboard and wood chips are assumed to be transported by truck. Transport of the tiles to the building site is a variable of the BEES model.

Use. Clay tile roofing is assumed to require two layers of 14 kilogram (30 pound) roofing felt, 13 galvanized nails per square meter (120 per square) for underlayment, and 37 copper nails per square meter (342 per square) for the tile (2 copper nails per tile). Installation waste from scrap is estimated at 5 percent of the installed weight. One-fourth of the tiles are replaced after 20 years, and another one-fourth at 40 years. All tiles are replaced at 70 years.

Cost. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under BEES code *B3011*, product code *20*. Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

3.5.3 Fiber Cement Shingles (B30113)

In the past, fiber cement shingles were manufactured using asbestos fibers. Now asbestos fibers have been replaced with cellulose fibers. For the BEES study, a 45-year fiber cement shingle consisting of cement, sand, and cellulose fibers is studied. Roofing felt and galvanized nails are used for installation. The flow diagram shown in Figure 3.15 shows the elements of fiber cement shingle production. The detailed environmental performance data for this product may be viewed by opening the file B30113.DBF under the File/Open menu item in the BEES software.

Raw Materials. Fiber cement shingles are composed of the materials listed in table 3.20. The filler is sand, and the organic fiber is wood chips. The weight of fiber cement shingles is assumed to be 16 kilograms per square meter (325 pounds per square), based on 36cm x 76cm x 0.4cm (14in x 30in x 5/32in) size shingles.

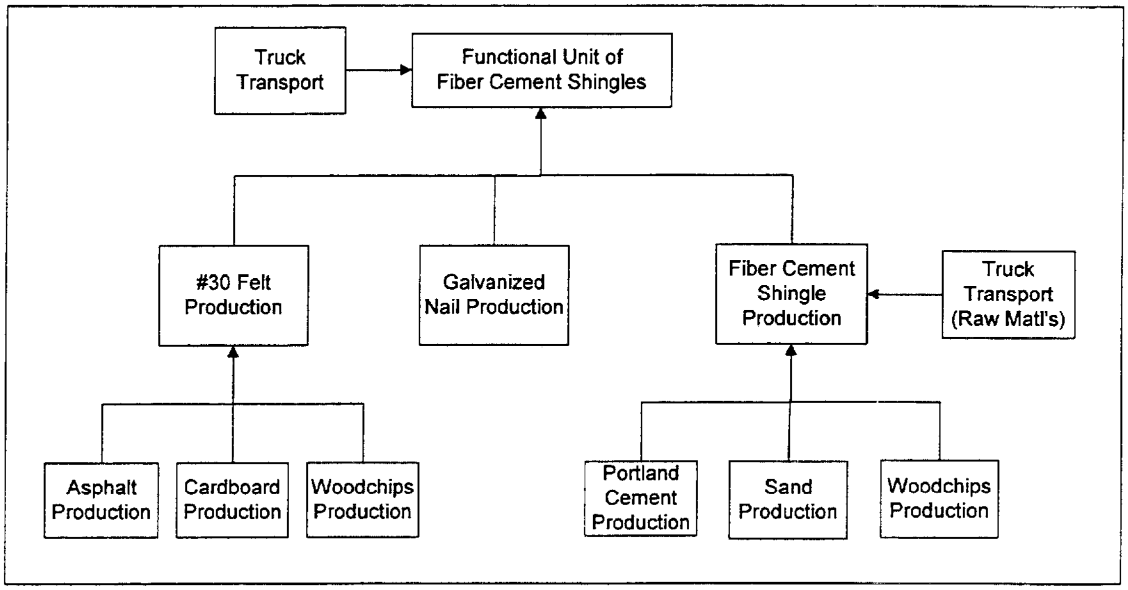

Figure 3.15 Fiber Cement Shingles Flow Chart

Table 3.20 Fiber Cement Shingle Constituents

Fiber Cement Shingle Constituents	*Physical Weight (%)*
Portland Cement	90
Filler	5
Organic Fiber	5

Portland cement production requirements are identical to those noted above for stucco exterior wall finish. Fourteen kilogram (30 pound) roofing felt is modeled as noted above for clay tile roofing.

Production requirements for the raw materials is based on the Ecobalance LCA database.

Energy Requirements. The energy requirements for fiber cement shingle production are assumed to be 33 MJ of natural gas and 11 MJ of electricity per square meter (2843 Btu of natural gas and 948 Btu of electricity per square foot) of shingle.

Transportation. Transport of the raw materials is taken into account. The distance over which all materials are transported is assumed to be 402 km (250 mi). Shingle materials are assumed to be transported by truck. For roofing felt, asphalt is assumed to be transported by truck, train, and pipeline in equal proportions, while the cardboard and wood chips are assumed to be transported by truck.

Transport of the shingles to the building site is a variable of the BEES model.

Use. Fiber cement shingle roofing requires one layer of 14 kilogram (30 pound) felt underlayment, 13 nails per square meter (120 nails per square) for the underlayment, and 32 nails per square meter (300 nails per square) for the shingles. Installation waste from scrap is estimated at 5 percent of the installed weight. Fiber cement roofing is assumed to have a useful life of 45 years.

Cost. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under BEES code *B3011*, product code *30*. Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

3.6 Floor Covering Alternatives (C3020)

3.6.1 Ceramic Tile with Recycled Windshield Glass (C30201)

Ceramic tile flooring consists of clay, or a mixture of clay and other ceramic materials, which is baked in a kiln to a permanent hardness. To improve environmental performance, recycled windshield glass can be added to the ceramic mix. For the BEES system, 50-year ceramic tile with 75 percent recycled windshield glass content, installed using a latex-cement mortar, is studied. The flow diagram shown in Figure 3.16 shows the elements of ceramic tile with recycled glass production. The detailed environmental performance data for this product may be viewed by opening the file C30201.DBF under the File/Open menu item in the BEES software.

Raw Materials. For a 15cm x 15cm x 1cm (6in x 6in x 1/2in) ceramic tile with 75 percent recycled glass content, clay and glass are found in the quantities listed in table 3.21.

Table 3.21 Ceramic Tile with Recycled Glass Constituents

Ceramic Tile w/ Recycled Glass Constituents	***Physical Weight***
Recycled Glass	475.5 g (17 oz)
Clay	156.9 g (6 oz)
Total:	632.4 g (23 oz)

Production requirements for clay are based on the Ecobalance LCA database. The recycled windshield glass is environmentally "free." The transportation of the glass to the

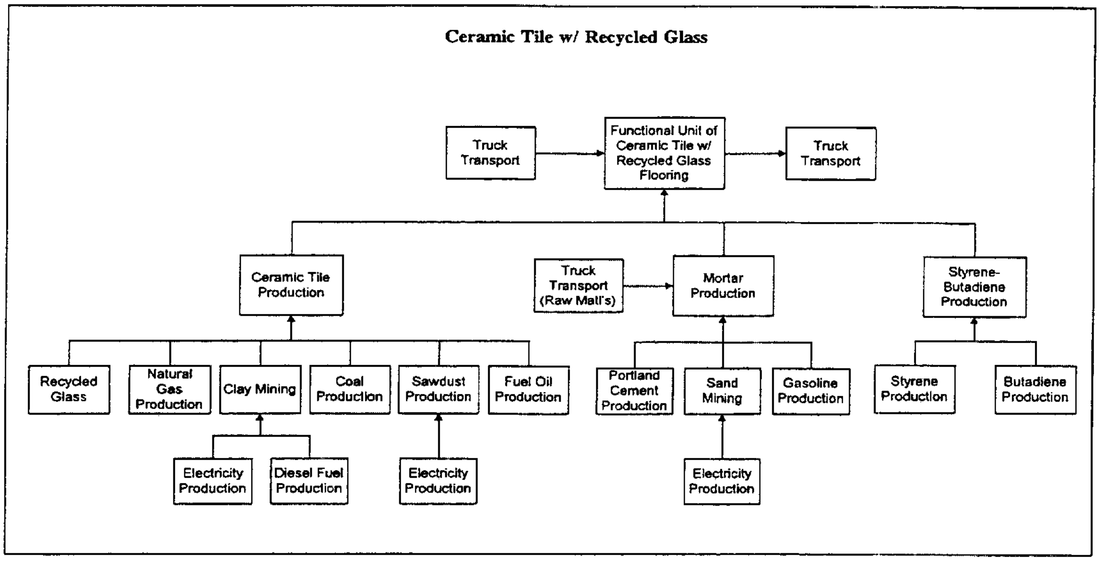

Figure 3.16 Ceramic Tile with Recycled Glass Flow Chart

tile facility and the processing of the glass are taken into account. However, the burdens associated with glass production should be allocated to the product with the first use of the glass (vehicle windshields).

The production of mortar (1 part portland cement, 5 parts sand) and styrene-butadiene is based on the Ecobalance LCA database.

Energy Requirements. The energy requirements for the drying and firing processes of ceramic tile production are listed in table 3.22.

Table 3.22 Energy Requirements for Ceramic Tile with Recycled Glass Manufacturing

Fuel Use	***Manufacturing Energy***
Total Fossil Fuel	4.19 MJ/kg (1801 Btu/lb)
% Coal	9.6 %
% Natural Gas (*)	71.9 %
% Fuel Oil	7.8 %
% Wood	10.8 %

(*) Includes Propane

Emissions. Emissions associated with fuel combustion for tile manufacturing are based on the AP-42 emission factors.

Use. The installation of the ceramic tile is assumed to require a layer of latex-mortar approximately 1.3 centimeters (1/2 inch) thick. The relatively small amount of latex-mortar between tiles is not included.

The ceramic tile with recycled glass is assumed to have a useful life of 50 years.

Refer to section 2.1.3 for indoor air performance assumptions for this product.

Cost. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under BEES code *C3020*, product code *10*. Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

3.6.2 Linoleum Flooring (C30202)

Linoleum is a resilient, organic-based floor covering consisting of a backing covered with a thick wearing surface. For the BEES system, a 2.5 millimeter (98 mil) sheet linoleum, manufactured in Europe, and with a jute backing and an acrylic lacquer finish coat is studied. A styrene-butadiene adhesive is included for installation. The flow diagram shown in Figure 3.17 shows the elements of linoleum flooring production. The detailed environmental performance data for this product may be viewed by opening the file C30202.DBF under the File/Open menu item in the BEES software.

Raw Materials. Table 3.23 lists the constituents of 2.5 millimeter (98 mil) linoleum and their proportions.

Table 3.23 Linoleum Constituents

Linoleum Constituents	*Physical Weight (%)**	*Physical Weight*
linseed oil	23.3	670 g/m^2 (2.2 oz/ft^2)
pine rosin	7.8	224 g/m^2 (0.7oz/ft^2)
limestone	17.7	509 g/m^2 (1.7 oz/ft^2)
wood flour	30.5	877 g/m^2 (2.9 oz/ft^2)
cork flour	5.0	144 g/m^2 (0.5 oz/ft^2)
pigment	4.4	127 g/m^2 (0.4 oz/ft^2)
backing (jute)	10.9	313 g/m^2 (1.0 oz/ft^2)
acrylic lacquer	0.35	10 g/m^2 (0.03 oz/ft^2)
Total:	100.0	2874 g/m^2 (9.4 oz/ft^2)

*Jonsson Asa, Anne-Marie Tillman, and Torbjorn Svensson, *Life-Cycle Assessment of Flooring Materials*, Chalmers University of Technology, Sweden, 1995.

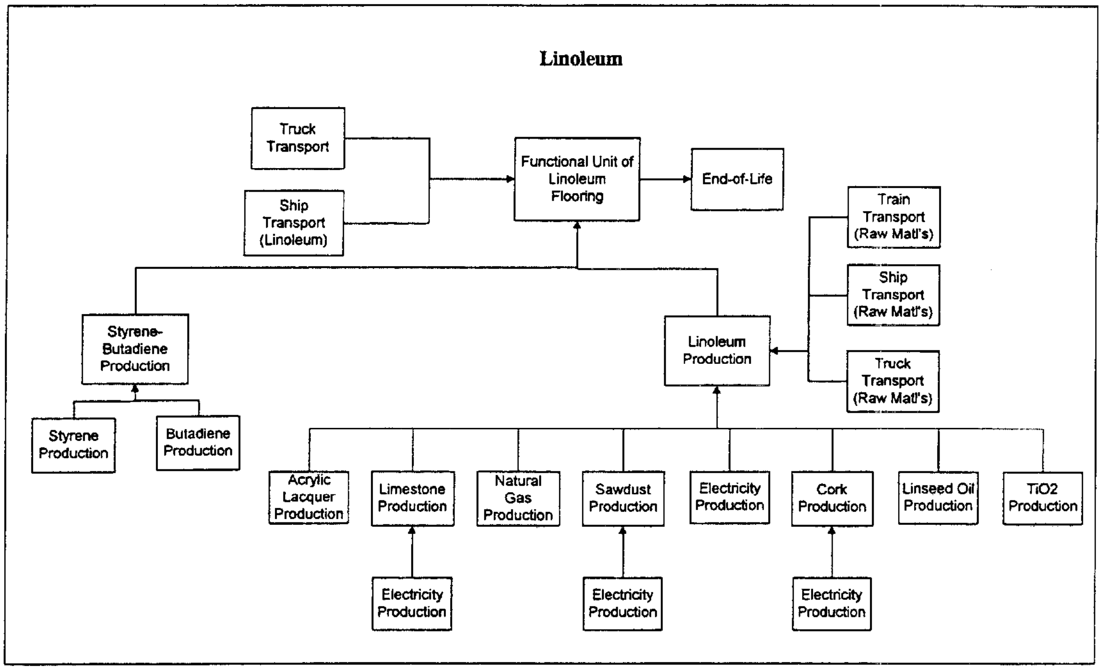

Figure 3.17 Linoleum Flow Chart

The cultivation of linseed is based on a United States agricultural model which estimates soil erosion and fertilizer run-off,[58] with the following inputs:[59]

- Fertilizer: 35 kg nitrogen fertilizer per hectare (31 lbs/acre), 17 kg phosphorous fertilizer per hectare (15 lbs/acre), and 14 kg potassium fertilizer per hectare (12 lbs/acre)
- Pesticides: 0.5 kg active compounds per hectare (0.4 lbs/acre), with 20 percent lost to air
- Diesel farm tractor: 0.65 MJ per kilogram (279 Btu per pound) linseed
- Linseed yield: 0.6 metric tons/hectare (536 lbs/acre)

The production of the fertilizers and pesticides is based on the Ecobalance LCA database.

The cultivation of pine trees for pine rosin is based on the Ecobalance LCA data for cultivated forestry, with inventory flows allocated between pine rosin and its coproduct, turpentine.

The production of limestone is based on the Ecobalance data for open pit limestone quarrying and processing.

[58] Ecobalance, *Life Cycle Assessment of Petroleum-Based Diesel Fuel and Biodiesel*, US DOE/NREL & US Department of Agriculture (not yet published).

[59] Potting Jose and Kornelis Blok, *Life-cycle Assessment of Four Types of Floor Covering*, Utrecht University, The Netherlands, 1994.

Wood flour is sawdust produced as a coproduct of wood processing. Its production is based on the Ecobalance LCA database.

Cork flour is a coproduct of wine cork production. Cork tree cultivation is not included but the processing of the cork is included as shown below.

Heavy metal pigments are used in linoleum production. Production of these pigments are modeled based on the production of titanium dioxide pigment.

Jute used in linoleum manufacturing is mostly grown in India and Bangladesh. Its production is based on the Ecobalance LCA database.

The production of acrylic lacquer is based on the Ecobalance LCA database.

Energy Requirements. Energy requirements for linseed oil production include fuel oil and steam, and are allocated on a mass basis between linseed oil (34%) and linseed cake (64%). Allocation is necessary because linseed cake is a coproduct of linseed oil production whose energy requirements should not be included in the BEES data.

Cork Flour production involves the energy requirements as listed in table 3.24.

Table 3.24 Energy Requirements for Cork Flour Production

Cork Product	***Electricity Use***
Cork Bark	0.06 MJ/kg (26 Btu/lb)
Ground Cork	1.62 MJ/kg (696 Btu/lb)

Linoleum production involves the energy requirements as listed in table 3.25.

Table 3.25 Energy Requirements for Linoleum Manufacturing

Fuel Use	***Manufacturing Energy***
Electricity	2.3 MJ/kg (989 Btu/lb)
Natural Gas	5.2 MJ/kg (2235 Btu/lb)

Emissions. Tractor emissions for linseed cultivation are based on the Ecobalance LCA database. The emissions associated with linseed oil production are allocated on a mass basis between oil (34%) and cake (64%).

Since most linoleum manufacturing takes place in Europe, it is assumed to be a European product in the BEES model. European linoleum manufacturing results in the following air emissions in addition to those from the energy use:

- Volatile Organic Compounds: 1.6 g/kg (0.025 oz/lb)
- Solvents: 0.94 g/kg (0.015 oz/lb)
- Particulate: 0.23 g/kg (0.004 oz/lb)

Transportation. Transport of linoleum raw materials from point of origin to a European manufacturing location is shown in table 3.26.[60]

Table 3.26 Linoleum Raw Materials Transportation

Raw Material	***Distance***	***Mode of Transport***
linseed oil	4350 km (2703 mi)	Ocean Freighter
	1500 km (932 mi)	Train
pine rosin	2000 km (1243 mi)	Ocean Freighter
limestone	800 km (497 mi)	Train
wood flour	600 km (373 mi)	Train
cork flour	2000 km (1243 mi)	Ocean Freighter
pigment	500 km (311 mi)	Diesel Truck
backing (jute)	10,000 km (6214 mi)	Ocean Freighter
acrylic lacquer	500 km (311 mi)	Diesel Truck

Transport of the finished product from Europe to the United States is included. Transport of the finished product from the point of U.S. entry to the building site is a variable of the BEES model.

Use. The installation of linoleum requires a styrene-butadiene adhesive.

Maintenance for this floor covering is assumed to be 0.5 grams (0.02 oz) of acrylic lacquer applied 4 times per year.

Linoleum flooring has a useful life of 18 years.

Refer to section 2.1.3 for indoor air performance assumptions for this product.

Cost. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under BEES code *C3020*, product code *20*. Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

[60] *Life-Cycle Assessment of Flooring Materials*, Jonsson Asa, Anne-Marie Tillman, & Torbjorn Svensson, Chalmers University of Technology, Sweden, 1995.

3.6.3 Vinyl Composition Tile (C30203)

Vinyl composition tile is a resilient floor covering. Relative to the other types of vinyl flooring (vinyl sheet flooring and vinyl tile), vinyl composition tile contains a high proportion of inorganic filler. For the BEES study, vinyl composition tile is modeled with a composition of limestone, plasticizer, and a copolymer of vinyl chloride-vinyl acetate. A layer of styrene-butadiene adhesive is used during installation. Figure 3.18 shows the elements of vinyl composition tile production. The detailed environmental performance data for this product may be viewed by opening the file C30203.DBF under the File/Open menu item in the BEES software.

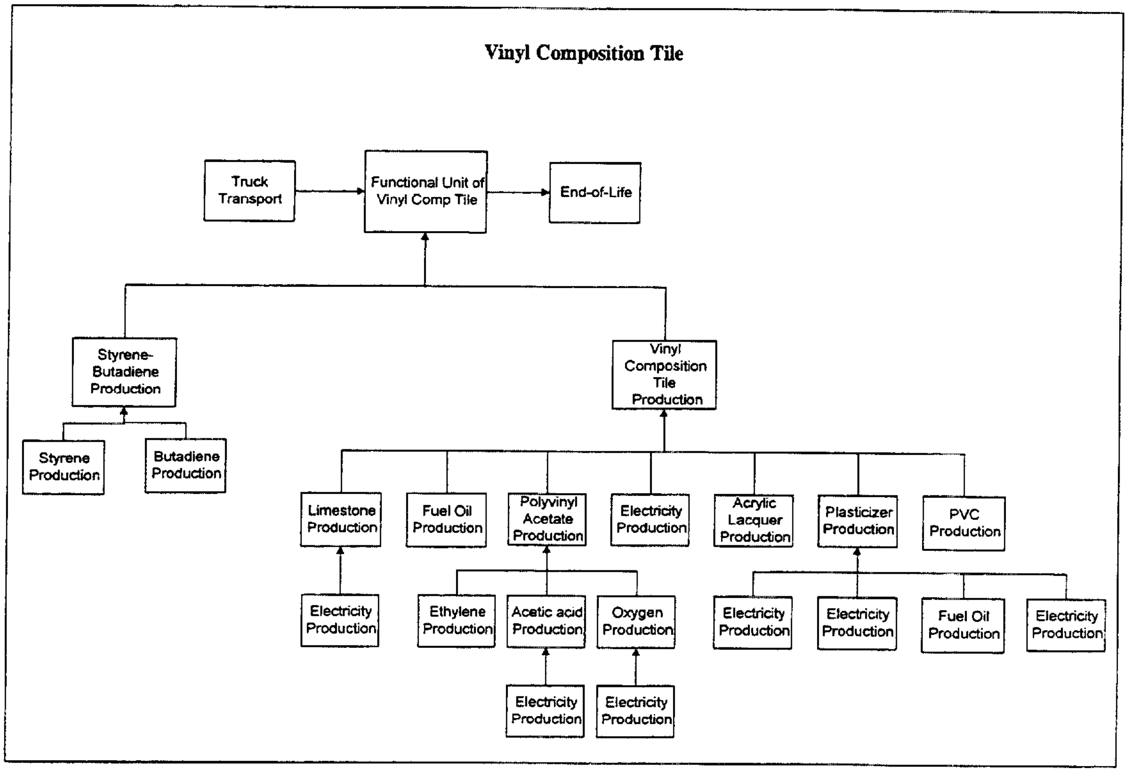

Figure 3.18 Vinyl Composition Tile Flow Chart

Raw Materials. Table 3.27 lists the constituents of 30cm x 30cm x 0.3cm (12in x 12in x 1/8in) vinyl composition tile and their proportions.

A finish coat of acrylic latex is applied to the vinyl composition tile at manufacture. The thickness of the finish coat is assumed to be 0.025 millimeters (0.98 mils).

The production of these raw materials, and the styrene-butadiene adhesive, is based on the Ecobalance LCA database.

Table 3.27 Vinyl Composition Tile Constituents

Vinyl Composition Tile Constituents	*Physical Weight (%)*
Limestone	84
Vinyl resins:	
(10% vinyl acetate / 90% vinyl chloride)	12
Plasticizer: bis(2-ethylhexyl) phthalate	4

Energy Requirements. The energy requirements for the manufacturing process (mixing, folding/calendaring, finish coating, die cutting) are listed in table 3.28.

Table 3.28 Energy Requirements for Vinyl Composition Tile Manufacturing

Fuel Use	*Manufacturing Energy*
Electricity	1.36 MJ / kg (585 Btu/lb)
Natural Gas	0.85 MJ / kg (365 Btu/lb)

Emissions. Emissions associated with the manufacturing process arise from the combustion of fuel oil and are based on AP-42 emission factors.

Use. Installing vinyl composition tile requires a layer of styrene-butadiene adhesive 0.0025 millimeters (0.10 mils) thick.

It is assumed that maintenance for this floor covering involves 0.5 grams (0.02 ounces) of acrylic lacquer twice a year.

The life of the flooring is assumed to be 18 years.

Refer to section 2.1.3 for indoor air performance assumptions for this product.

Cost. The detailed life-cycle cost data for this product may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Its costs are listed under BEES code *C3020*, product code *30*. Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement, and where appropriate and data are available, of operation, maintenance, and repair). First cost data are collected from the R.S. Means publication, *1997 Building Construction Cost Data*, and future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1997*, supplemented by industry interviews.

4. BEES Tutorial

To balance the environmental and economic performance of building products, follow three main steps:

1. Set your study parameters to customize key assumptions

2. Define the alternative building products for comparison. BEES results may be computed once alternatives are defined.

3. View the BEES results to compare the overall environmental/economic performance balance for your alternatives.

4.1 Setting Parameters

Select Analysis/Set Parameters from the BEES Main Menu to set your study parameters. A window listing these parameters appears, as shown in figure 4.1. Move around this window by pressing the Tab key.

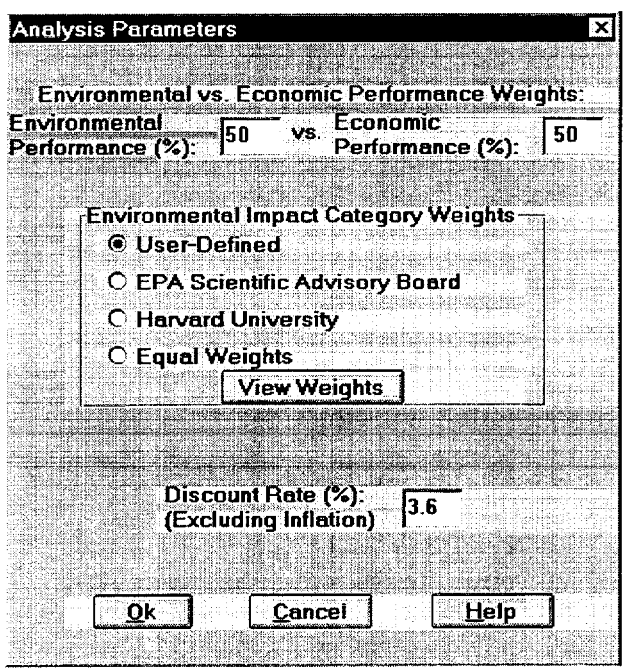

Figure 4.1 Setting Analysis Parameters

The first set of parameters are your relative preference weights for environmental versus economic performance. These values must sum to 100. Enter a value between 0 and 100 for environmental performance reflecting your percentage weighting. For example, if environmental performance is all-important, enter a value of 100. The corresponding economic preference weight is automatically computed.

Next you are asked to select your relative preference weights for the six environmental impact categories included in the BEES environmental performance score: Global Warming Potential, Acidification Potential, Nutrification Potential, Natural Resource Depletion, Indoor Air Quality, and Solid Waste. You are presented with four sets of alternative weights. You may choose to define your own set of weights, or select the built-in weight sets derived from an EPA Scientific Advisory Board study, a Harvard University study, or a set of equal weights. Press View Weights to display the impact category weights for all four weight sets, as shown in figure 4.2. These may not be changed. If you select the user-defined weight set, you will be asked to enter weights for all six impacts, as shown in figure 4.3. These six weights must sum to 100.

Environmental Impact Category Weights

Weight Set	Globalwarm:	Acidifcatn:	Nutrifcatn:	Natresdepn:	Indoor Air:	Solidwaste:
User-Defined	17	17	17	17	16	16
EPA Science Advisory Board-bas	27	13	13	13	27	7
Harvard University Study-based	28	17	18	15	12	10
Equal Weights	17	17	17	17	16	16

Figure 4.2 Viewing Impact Category Weights

Finally, enter the real (excluding inflation) discount rate for converting future building product costs to their equivalent present value. All future costs are converted to their equivalent present values when computing life-cycle costs. Life-cycle costs form the basis of the economic performance scores. The higher the discount rate, the less important to you are future building product costs such as repair and replacement costs. The maximum value allowed is 20%. A discount rate of 20% would value each dollar spent 50 years hence as only $0.0001 in present value terms. The 1997 rate mandated by the U.S. Office

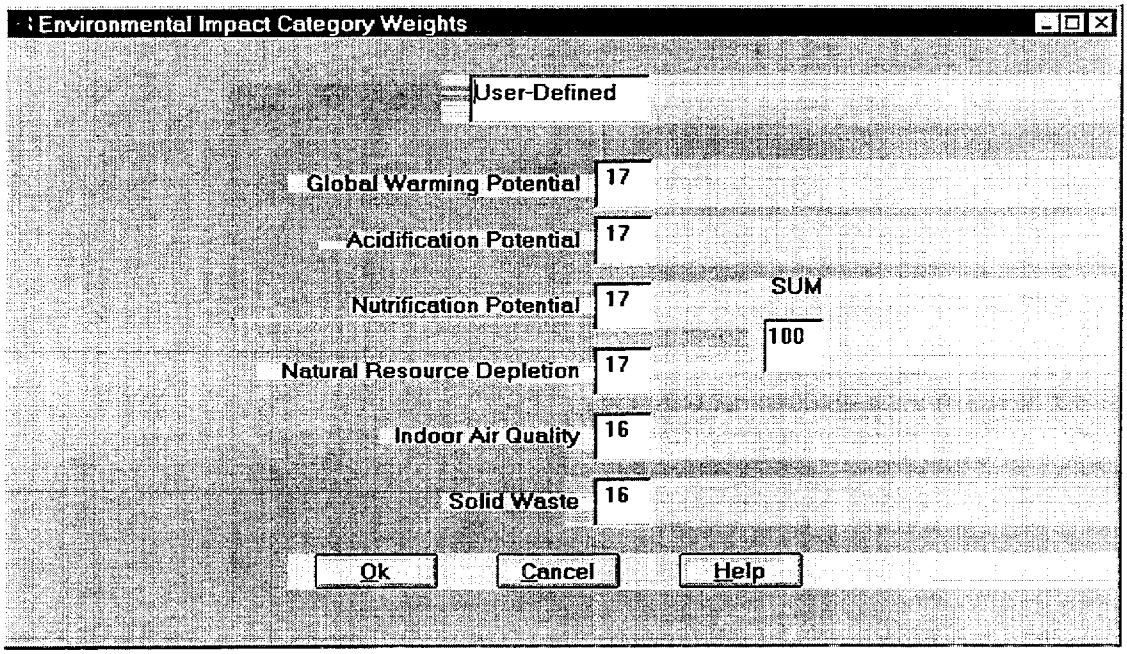

Figure 4.3 Entering User-Defined Weights

of Management and Budget for most Federal projects, 3.6%, is provided as the default value.[61]

4.2 Defining Alternatives

Select Analysis/Define Alternatives from the Main Menu to select the alternative building products you want to compare. A window appears as in figure 4.4.

Selecting alternatives is a two-step process.

> 1. Select the building element for which you want to compare alternatives. Building elements are organized using the hierarchical structure of the ASTM standard BEES classification system.[62] Click on the down arrows to display the complete lists of available choices at each level of the hierarchy. BEES 1.0 contains environmental and economic performance data for 12 individual building elements: slabs on grade, basement walls, beams, columns, roof sheathing, exterior wall finishes, wall insulation,

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[61] Office of Management and Budget (OMB) Circular A-94, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*, Washington, DC, October 27, 1992 and OMB Circular A-94, Appendix C, March 1997.

[62] American Society for Testing and Materials, *Standard Classification for Building Elements and Related Sitework--UNIFORMAT II*, ASTM Designation E 1557-93, West Conshohocken, PA, September 1993.

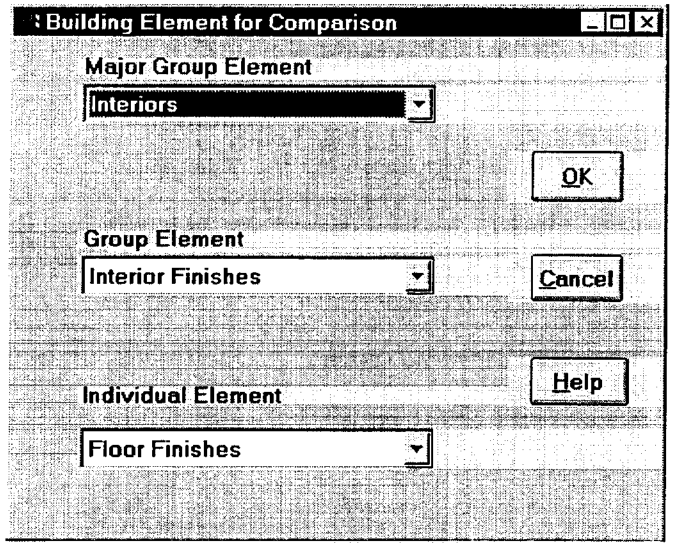

Figure 4.4 Selecting Building Element for Bees Analysis

wall sheathing, roof coverings, ceiling insulation, floor coverings, and driveways and sidewalks. Press Ok to select the choice in view.

2. Once you have selected the building element, you are presented with a window of product alternatives available for BEES scoring, such as in figure 4.5.[63] Select an alternative with a mouse click. You may then be presented with a window, such as in figure 4.6, asking for the assumed distance for transporting this product from the manufacturing plant to your building site. Your choice affects the resource depletion, global warming, and acidification impact category scores. You must select at least two alternatives.

If you have already set your study parameters, next press Compute BEES Results to compute and display the BEES environmental and economic performance scores.

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[63] If you have chosen the wall insulation element, you will first be asked, for the building in which insulation will be installed, its location and fuel used for heating so that heating and cooling energy use over the 50-year study period can be properly estimated. If you have chosen concrete beams or columns, you will be asked for assumed compressive strength after selecting each product alternative.

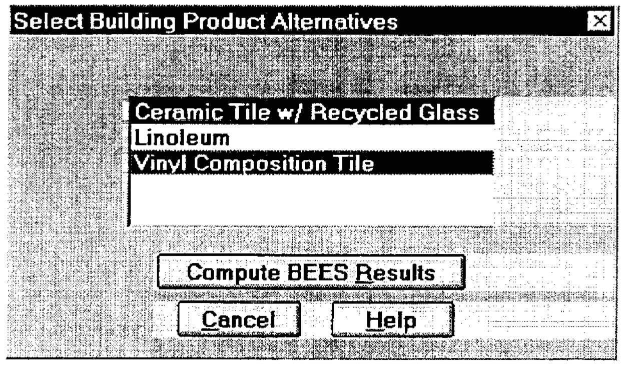

Figure 4.5 Selecting Building Product Alternatives

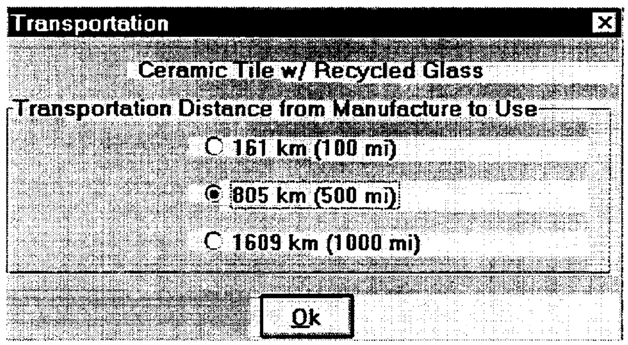

Figure 4.6 Setting Transportation Parameters

4.3 Viewing Results

Once you have set your study parameters, defined your product alternatives, and computed BEES results, BEES displays three summary graphs such as in figures 4.7, 4.8, and 4.9. For all BEES graphs, the larger the value, the *worse* the performance. Also, the values displayed across the back row are always the sum of the values in the preceding rows.

1. The Overall Performance Results graph displays the weighted environmental and economic performance scores and their sum, the overall performance score.

2. The Environmental Performance Results graph displays the weighted environmental impact category scores and their sum, the environmental performance score. On this graph, if an alternative performs worst with respect to all six environmental impact categories, it receives a score of 100, the worst possible score.

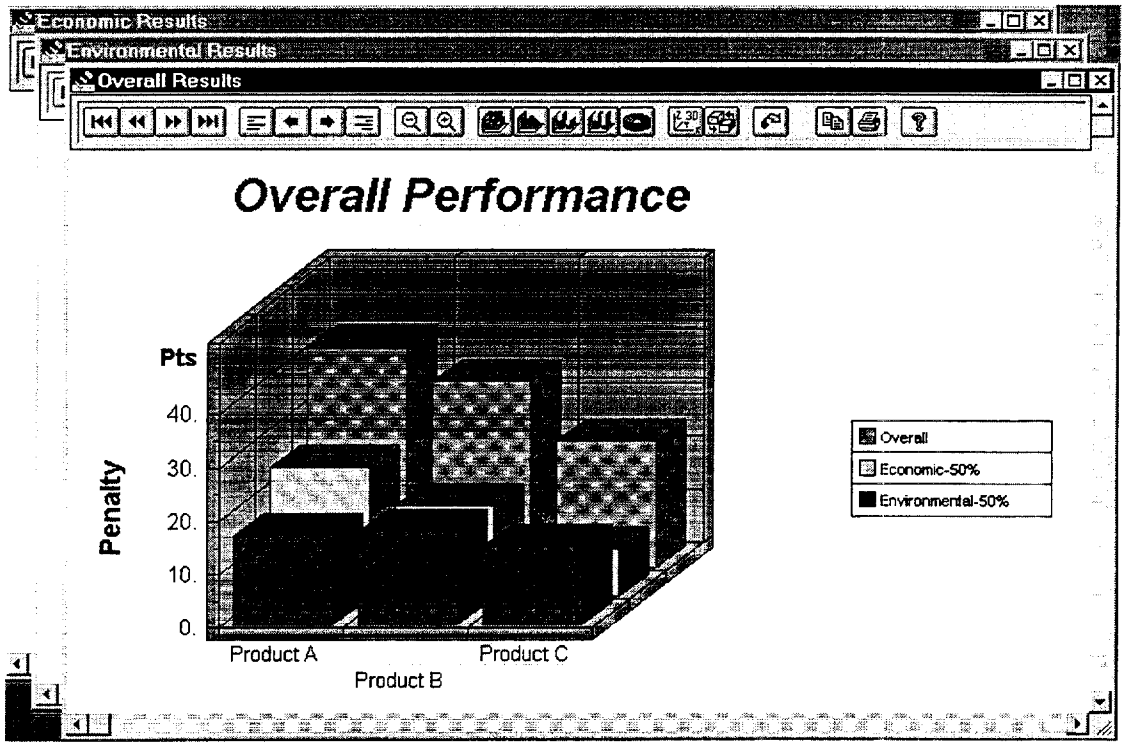

Figure 4.7 Viewing BEES Overall Performance Results

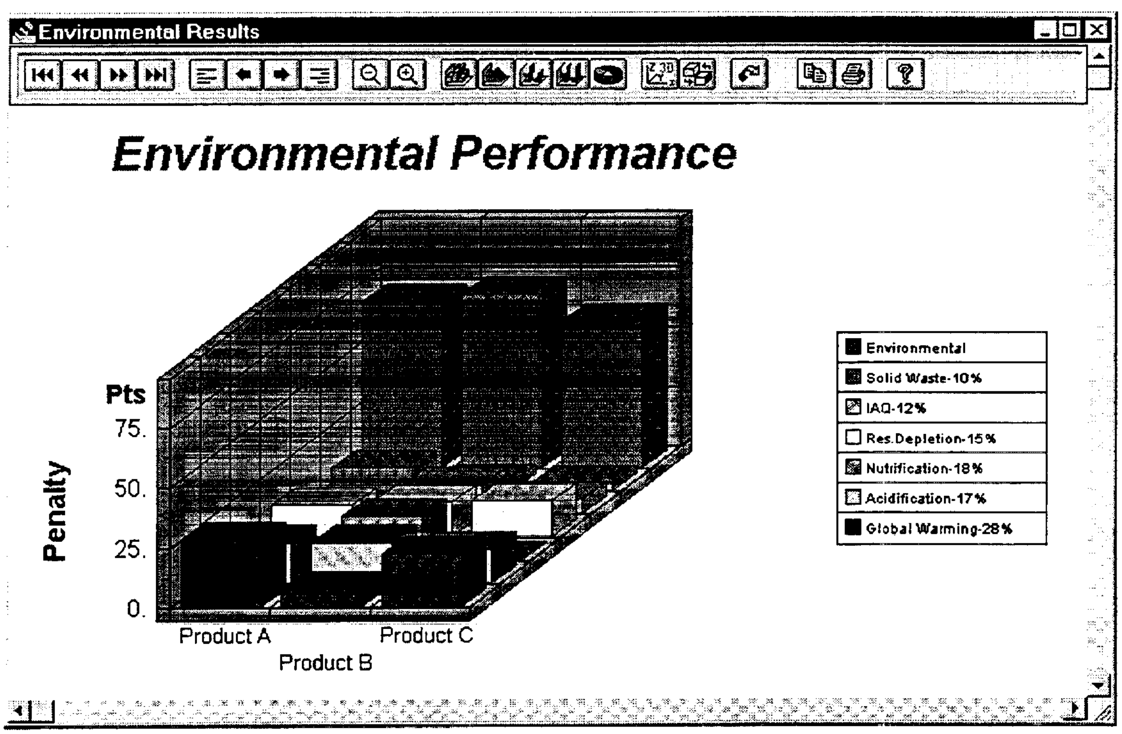

Figure 4.8 Viewing BEES Environmental Performance Results

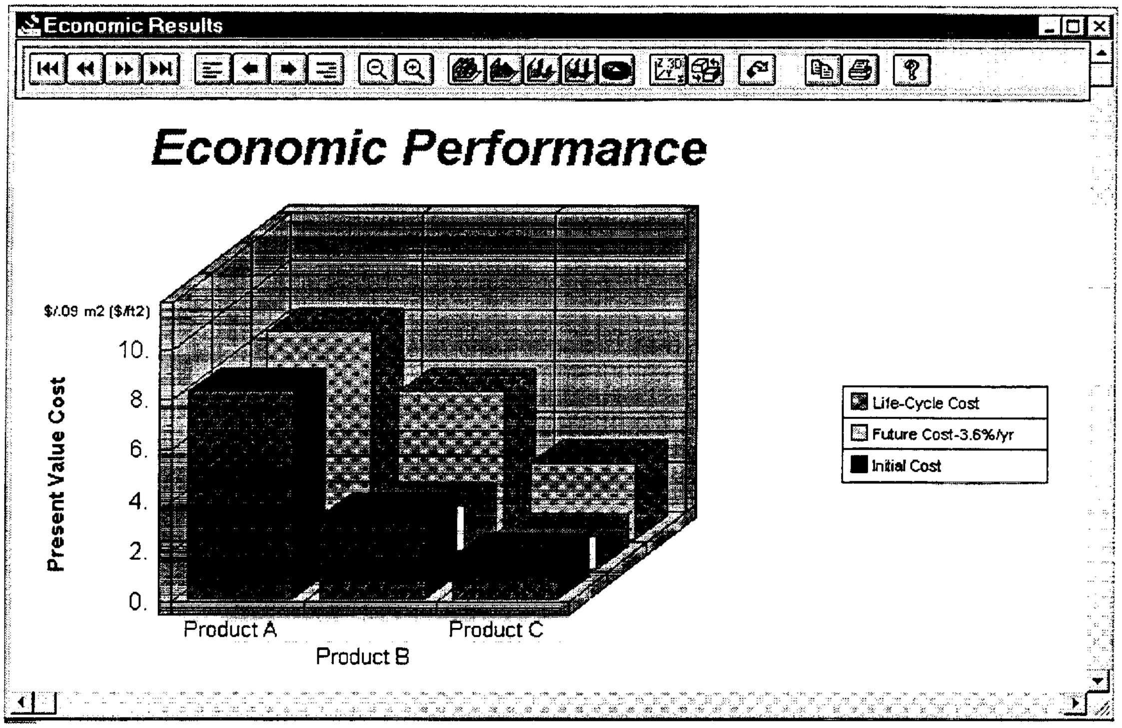

Figure 4.9 Viewing BEES Economic Performance Results

3. The Economic Performance Results graph displays the initial cost, discounted future costs and their sum, the life-cycle cost.

BEES results are derived by using the BEES methodology to combine the BEES environmental and economic performance data using your study parameters. The methodology is described in section 2. The BEES environmental and economic performance data, documented in section 3, may be browsed by selecting File/Open from the Main Menu.

The displayed graphs are "live." Clicking on a graph column will bring up a window displaying the column value, and from which you may customize colors, labels, and other display attributes. Also note that columns and rows may be conveniently moved into and out of view by pressing toolbar button numbers 5 though 10. The next 5 toolbar buttons provide further functionality by offering alternative graph types. The Percent Stacked and Pie Graph alternatives are particularly informative ways to display the BEES scores. Press the Print toolbar button to print the graph. You can even copy an entire graph to the clipboard and then paste it into another Windows application. You may then use the application's graphics editor to resize the graph.

You may choose to display more detailed environmental performance graphs by selecting Results/Environmental Performance from the Main Menu. You may display graphs for each environmental impact category, by life-cycle stage, and for embodied energy performance, such as in figures 4.10, 4.11, and 4.12.

To compare BEES results based on different parameter settings, simply select Analysis/Set Parameters from the Main Menu, change your parameters, and press Ok. Once the new graphs are displayed, select Window/Tile from the Main Menu to view graphs side-by-side. Note that parameter settings are displayed on each graph's legend.

4.4 Browsing Environmental and Economic Performance Data

The BEES environmental and economic performance data may be browsed by selecting File/Open from the Main Menu. Environmental data files are specific to products, while there is a single economic data file, LCCOSTS.DBF, with cost data for all products. As explained in section 3, some environmental data files map to a product in more than one application, while the economic data are listed separately for each application. Table 4.1 lists the products by environmental data file name (all with the .DBF extension) and by code number within the economic performance data file LCCOSTS.DBF

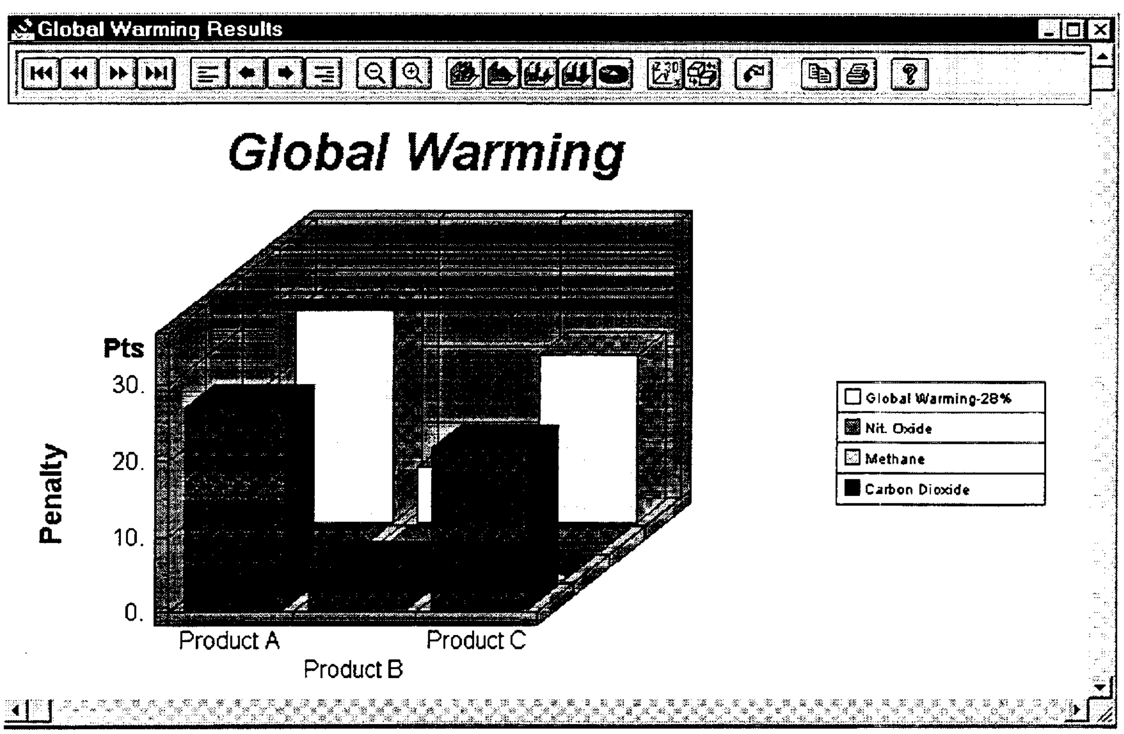

Figure 4.10 Viewing BEES Environmental Impact Category Performance Results

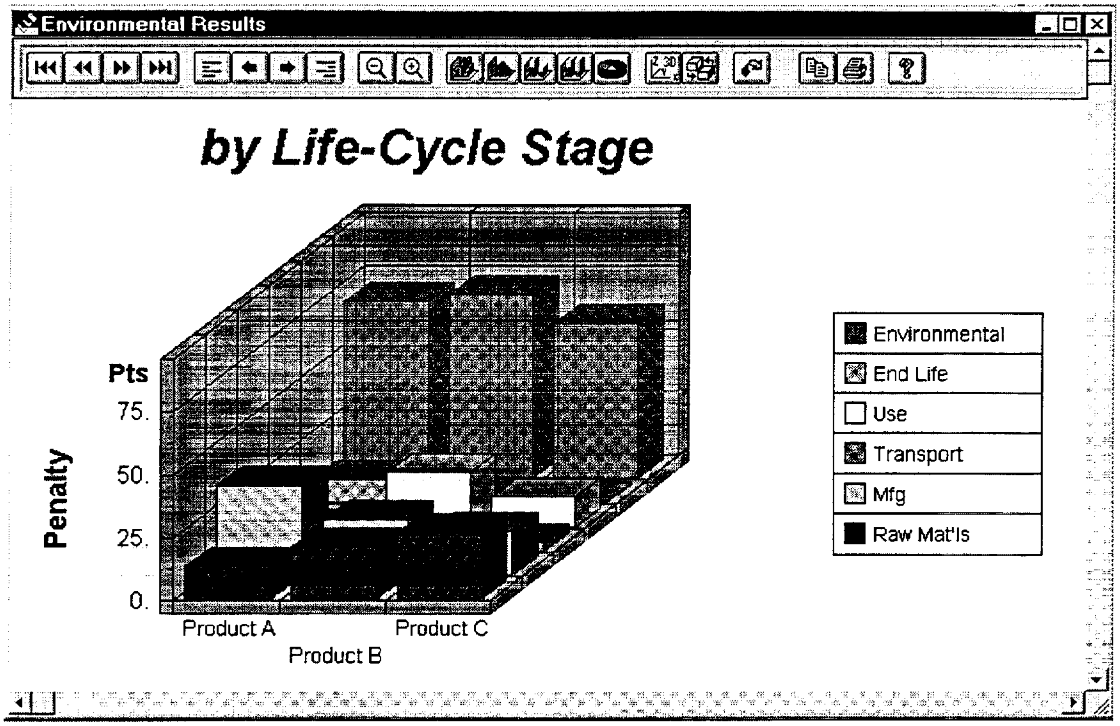

Figure 4.11 Viewing BEES Environmental Performance by Life-Cycle Stage Results

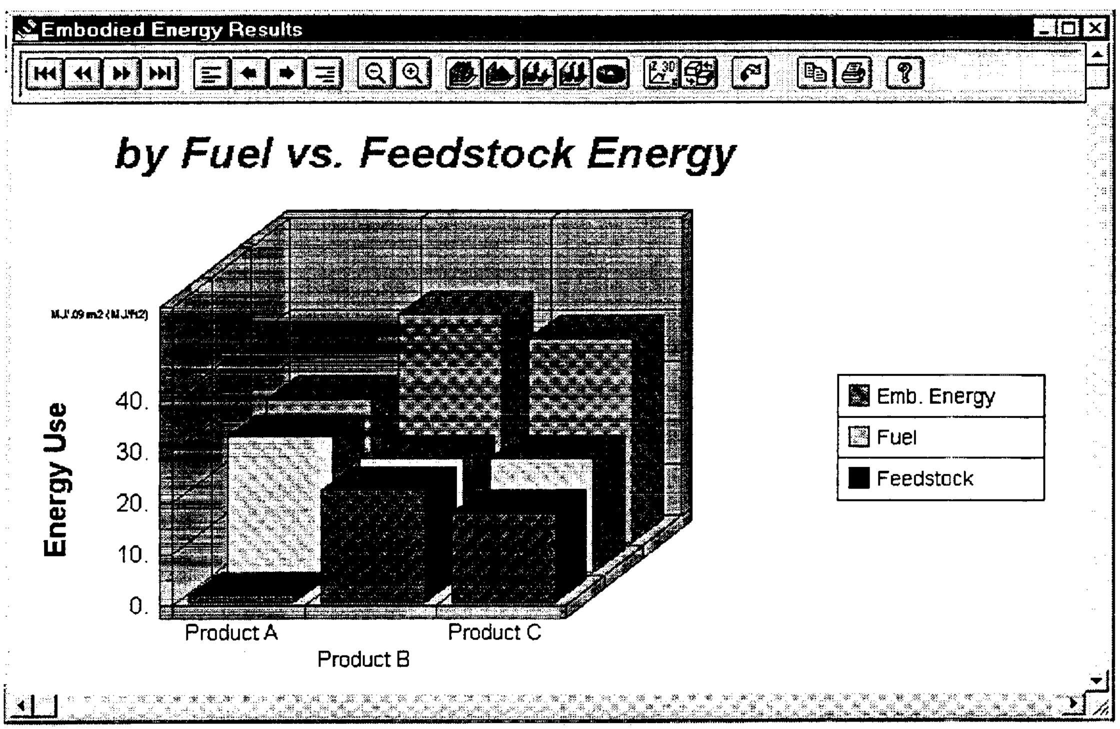

Figure 4.12 Viewing BEES Embodied Energy Performance Results

Table 4.1 BEES Building Products Keyed to Environmental and Economic Performance Data Codes

Group Element	*Building Product*	*Environmental Data File Name*	*Economic Data Code*
Foundations	0% Fly Ash Content Slab on Grade	A10301	A1030,10
Foundations	15% Fly Ash Content Slab on Grade	A10302	A1030,20
Foundations	20% Fly Ash Content Slab on Grade	A10303	A1030,30
Basement Construction	0% Fly Ash Content Basement Wall	A10301	A2020,10
Basement Construction	15% Fly Ash Content Basement Wall	A10302	A2020,20
Basement Construction	20% Fly Ash Content Basement Wall	A10303	A2020,30
Superstructure	0% Fly Ash Content Beams	A10301	B1011,10
Superstructure	15% Fly Ash Content Beams	A10302	B1011,20
Superstructure	20% Fly Ash Content Beams	A10303	B1011,30
Superstructure	0% Fly Ash Content Columns	A10301	B1012,10
Superstructure	15% Fly Ash Content Columns	A10302	B1012,20
Superstructure	20% Fly Ash Content Columns	A10303	B1012,30
Superstructure	Oriented Strand Board Roof Sheathing	B10201	B1020,10
Superstructure	Plywood Roof Sheathing	B10202	B1020,20
Exterior Closure	Brick & Mortar Exterior Wall	B20111	B2011,10
Exterior Closure	Stucco Exterior Wall	B20112	B2011,20
Exterior Closure	R-13 Cellulose Wall Insulation	B20121	B2012,10
Exterior Closure	R-11 Fiberglass Wall Insulation	B20122	B2012,20
Exterior Closure	R-15 Fiberglass Wall Insulation	B20123	B2012,30
Exterior Closure	R-12 Mineral Wool Wall Insulation	B20124	B2012,40
Exterior Closure	Oriented Strand Board Wall Sheathing	B10201	B2015,10
Exterior Closure	Plywood Wall Sheathing	B10202	B2015,20
Roofing	Asphalt Shingle Roof Covering	B30111	B3011,10
Roofing	Clay Tile Roof Covering	B30112	B3011,20
Roofing	Fiber Cement Shingle Roof Covering	B30113	B3011,30
Roofing	R-30 Cellulose Ceiling Insulation	B30121	B3012,10
Roofing	R-30 Fiberglass Ceiling Insulation	B30122	B3012,20
Roofing	R-30 Mineral Wool Ceiling Insulation	B30123	B3012,30
Interior Finishes	Ceramic Tile with Recycled Glass Floor Covering	C30201	C3020,10
Interior Finishes	Linoleum Floor Covering	C30202	C3020,20
Interior Finishes	Vinyl Composition Tile Floor Covering	C30203	C3020,30
Site Improvements	0% Fly Ash Content Driveways and Sidewalks	A10301	G2010,10
Site Improvements	15% Fly Ash Content Driveways and Sidewalks	A10302	G2010,20
Site Improvements	20% Fly Ash Content Driveways and Sidewalks	A10303	G2010,30

The environmental performance data files are similarly structured, with 3 simulations in each. The first column in all these files, "Sim," represents the transportation simulation number for non-concrete products, or compressive strength simulation number for concrete products. All files contain 3 sets of inventory data corresponding to the 3 simulations. The simulation codes are defined below in tables 4.2 and 4.3. For each simulation, the environmental performance data file lists 97 environmental flows. Flows marked "(r)" are raw materials inputs, "(a)" are air emissions, "(w)" are water effluents, and "E" are energy usage. All quantities for concrete products except driveways and sidewalks are given per 0.76 cubic meters (1 cubic yard) of concrete, and for all other products, including driveways and sidewalks, per 0.09 square meters (1 square foot) of product. The column labeled "Total" is the primary data column, giving total flow quantities. Next are columns giving flow quantities for each product component, followed by columns giving flow quantities for each life-cycle stage. The product component columns sum to the total column, as do the life-cycle stage columns. The Iaindex column is for internal BEES use.

The economic performance data file LCCOSTS.DBF lists for each cost the year of occurrence (counting from year 0) and amount (in 1997 dollars) per 0.76 cubic meters (1 cubic yard) for concrete products except driveways and sidewalks, and cost (in 1997 dollars) per 0.09 square meters (1 square foot) for all other products (including driveways and sidewalks).

Warning: If you change any of the data in the environmental or economic performance data files, you will need to reinstall BEES to restore the original BEES data.

Table 4.2 BEES Simulation Codes: All But Concrete Products

	Transportation Distance from Manufacturing Plant to Building Site	
Simulation Code	***Insulation Products***	***All Other Non-Concrete Products***
1	80 km (50 mi)	161 km (100 mi)
2	322 km (200 mi)	805 km (500 mi)
3	483 km (300 mi)	1609 km (1000 mi)

Table 4.3 BEES Simulation Codes: Concrete Products

Simulation Code	***Compressive Strength***
1	21 MPa (3000 psi)
2	28 MPa (4000 psi)
3	34 MPa (5000 psi)

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5. Future Directions

Development of the BEES tool does not end with the release of version 1.0. Plans to expand and refine BEES include releasing updates every 12 to 18 months with model and software enhancements as well as expanded building product coverage. A BEES training program is also being considered. Listed below are a number of directions for future research that have been proposed in response to obvious needs and through feedback from the 125 BEES Beta version reviewers:

Proposed Model Enhancements

- Conduct and apply research leading to the addition of more environmental impacts, such as human health and resource extraction impacts
- Update the BEES LCA methodology in line with future developments in the evolving LCA field
- Add a third performance measure to the overall performance score—product technical performance
- Characterize uncertainty in the underlying environmental and cost data, and reflect this uncertainty in BEES performance scores

Proposed Data Enhancements

- Add building products covering many more building elements, and add more products to currently covered elements
- Refine all data to permit U.S. region-specific BEES analyses. This enhancement would yield BEES results tailored to regional fuel mixes and labor and material markets, and would permit inclusion of local environmental impacts such as smog and locally scarce resources (e.g., water)
- Permit greater flexibility in product specifications such as useful lives and product composition
- Every three years, revisit products included in previous BEES releases for updates to their environmental and cost data
- In support of the EPA Environmentally Preferable Purchasing Program, add key non-building products to the BEES tool to assist the Federal procurement community in carrying out the mandate of Executive Order 12873 (results of this effort may be disseminated as a separate software tool)

Proposed Software Enhancements

- Add feature permitting users to enter their own environmental and cost data for BEES analysis
- Display additional BEES graphs reporting more detailed results, such as the raw environmental impact assessment scores before weighting and normalizing (e.g.,CO_2-equivalents for the global warming impact)
- Revise product data file names and customize their column headings to be more descriptive of their content

- Add feature permitting integrated sensitivity analysis so that the effect on BEES results of changes in parameter settings may be displayed on a single graph

Appendix A. BEES Computational Algorithms

A.1 Environmental Performance

BEES environmental performance scores are derived as follows.

$$EnvScore_j = \sum_{k=1}^{p} IAScore_{jk}, \quad \text{where}$$

$EnvScore_j$ = environmental performance score for building product alternative j;
p = number of environmental impact categories;
$IAScore_{jk}$ = weighted, normalized impact assessment score for alternative j with respect to environmental impact k:

$$IAScore_{jk} = \frac{IA_{jk} * IVwt_k}{Max\{IA_{1k}, IA_{2k} \ldots IA_{mk}\}} * 100 \ , \quad \text{where}$$

$IVwt_k$ = impact category importance weight for impact k;
m = number of product alternatives;
IA_{jk} = raw impact assessment score for alternative j with respect to impact k:

$$IA_{jk} = \sum_{i=1}^{n} I_{ij} * IAfactor_i \, , \quad \text{where}$$

i = inventory flow;
n = number of inventory flows in impact category k;
I_{ij} = inventory flow quantity for alternative j with respect to flow i, from environmental performance data file (See section 4.4.);
$IAfactor_i$ = impact assessment factor for inventory flow i

The BEES inventory flow scores, $IScore_{ij}$, which are displayed on graphs for single impacts, are derived as follows:

$$IScore_{ij} = IAScore_{jk} * IPercent_{ij} \, , \quad \text{where}$$

$Iscore_{ij}$ = inventory flow score for alternative j with respect to flow i;

$$IPercent_{ij} = \frac{I_{ij} * IAfactor_i}{\sum_{i=1}^{n} I_{ij} * IAfactor_i}$$

The BEES life-cycle stage scores, $LCScore_{sj}$, which are displayed on the life-cycle stage graph, are derived as follows:

$$LCScore_{sj} = \sum_{i=1}^{n} IScore_{ij} * LCPercent_{sij} \, , \quad \text{where}$$

$LCScore_{sj}$ = life cycle stage score for alternative j with respect to stage s;

$$LCPercent_{sij} = \frac{I_{sij}}{\sum_{s=1}^{r} I_{sij}}, \text{ where}$$

I_{sij} = inventory flow quantity for alternative j with respect to flow i for life cycle stage s;
r = number of life cycle stages

A.2 Economic Performance

BEES measures economic performance by computing the product life-cycle cost as follows:

$$LCC_j = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t}, \text{ where}$$

LCC_j = total life-cycle cost in present value dollars for alternative j;
C_t = sum of all relevant costs, less any positive cash flows, occurring in year t;
N = number of years in the study period;
d = discount rate used to adjust cash flows to present value

A.3 Overall Performance

The overall performance scores are derived as follows:

$$Score_j = \frac{\left[EnvWt(EnvScore_j) + EconWt\left(\frac{LCC_j}{Max(LCC_1, LCC_2, \ldots, LCC_n)}\right)\right]}{[SumEnvEconWt_1 + SumEnvEconWt_2 + \cdots + SumEnvEconWt_n]}, \text{ where}$$

$Score_j$ = overall performance score for alternative j;
EnvWt, EconWt = environmental and economic performance weights, respectively (EnvWt + EconWt = 1);
n = number of alternatives;
$EnvScore_j$ = (see section A.1);
LCC_j = (see section A.2);
$SumEnvEconWt_j = EnvWt(EnvScore_j) + EconWt[LCC_j/Max(LCC_1,LCC_2,\ldots,LCC_n)]$