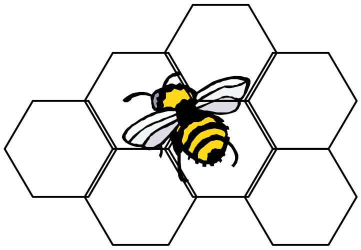
NISTIR 6520

BEES 2.0

Building for **E**nvironmental and **E**conomic **S**ustainability
Technical Manual and User Guide



Barbara C. Lippiatt

With Support From:
U.S. Environmental Protection Agency
Office of Pollution Prevention and Toxics
and
U.S. Department of Housing and Urban Development
Partnership for Advancing Technology in Housing

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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Building for **E**nvironmental and **E**conomic **S**ustainability
Technical Manual and User Guide

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June 2000

With Support From:

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Abstract

The BEES (**B**uilding for **E**nvironmental and **E**conomic **S**ustainability) version 2.0 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 65 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 ISO 14040 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 (E 917), 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 (E 1765). For the entire BEES analysis, building products are defined and classified based on the ASTM standard classification for building elements known as UNIFORMAT II (E 1557).

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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Acknowledgments

The BEES tool could not have been completed without the help of others. Thanks are due the NIST Building and Fire Research Laboratory (BFRL) for its support of this work from its inception. The U.S. Environmental Protection Agency (EPA), Pollution Prevention Division also deserves thanks for its continued support. Deserving special thanks is the BEES environmental data contracting team of Environmental Strategies and Solutions and Ecobalance, Inc., for its superb data development, documentation, and technical support. The author is grateful to the EPA *Framework for Responsible Environmental Decisionmaking* team, led by Mary Ann Curran of the EPA Sustainable Technology Division, for recommending methodology improvements that have been incorporated into BEES 2.0. Thanks are also due Sarah Bretz and her colleagues from Lawrence Berkeley National Laboratory for providing the Energy Star "Cool Roof" data used to analyze BEES roof covering alternatives. Also deserving special thanks are the 60 BEES 2.0 Beta Testers for their time spent reviewing the BEES 2.0 Beta version and their comments leading to many improvements. The author is particularly grateful for the key cooperation and support offered by a wide variety of industry associations and manufacturers with products represented in BEES. Their cooperation exceeded all expectations, and led to improvements in the underlying BEES performance data. The comments of NIST BFRL colleagues Hunter Fanney, Harold Marshall, Stephen Weber, and Mark Ehlen inspired many improvements. Special thanks are due Amy Boyles for helping test, document, and review BEES 2.0. Thanks are also due Cathy Linthicum for her wonderful secretarial support.

Copyright Information

Getting Started

System Requirements

BEES runs on Windows 95, Windows 98, Windows 2000, and Windows NT personal computers with a 486 or higher microprocessor, 32 Mb or more of RAM, and at least 31 Mb of available disk space. At least one printer must be installed

Installing BEES

From Download Site. Once you've completed the BEES registration form, click Submit, and then click bees20.exe to download the self-extracting file. If prompted during the download, choose to save the file to disk. Once downloaded, from Windows Explorer double click on the file to begin the self-extraction process. Choose to unzip the file to a new folder. Once unzipped, from Windows Explorer double click on the file SETUP.EXE in your new folder to begin the self-explanatory BEES 2.0 installation process. During installation, you will need to choose a directory to install BEES 2.0; you must choose a directory different from the one that contains the setup file (SETUP.EXE). Once installation is complete, you are ready to run BEES 2.0 from your program group BEES.

From CD-ROM. Install BEES by inserting the compact disc into your CD-ROM drive and running the BEES setup program, SETUP.EXE. Follow on-screen installation instructions. Once installation is complete, you are ready to run BEES 2.0 from your program group BEES.

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 % of the raw stone, gravel, and sand used globally each year, and 25 % of the virgin wood. Buildings also account for 40 % of the energy and 16 % 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 % 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 % of U.S. consumers worry about their home's environmental impact, only 18 % 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 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 BEES is to develop and implement a systematic methodology for selecting building products that achieve the most appropriate balance

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[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 % more for environmentally friendly products (Maurice Strong, Chairman, Earth Council Institute, "Closing Day *Engineering and Construction for Sustainable Development in the 21st Century,* Washington, DC, February 4-8, 1996, p 54)

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 13101, *Greening the Government Through Waste Prevention, Recycling, and Federal Acquisition*, 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 13101.

In 1999, the U.S. Department of Housing and Urban Development's (HUD) Partnership for Advancing Technology in Housing (PATH) Program began supporting the development of BEES data for residential building products. This year, PATH is supporting an effort to explore the technical and economic feasibility together with the most suitable framework for a residential version of BEES. This work is based on input from homebuilders, residential designers, and product suppliers. The purpose is to provide a useful tool for the residential sector.

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.

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 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,* International Standard 14040, 1997; ISO *Environmental Management--Life-Cycle Assessment—Goal and Scope Definition and Inventory Anslysis,* International Standard 14041, 1998; and ISO *Environmental Management--Life-Cycle Assessment—Life Cycle Impact Assessment,* International Standard 14042, 2000.

[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 1765-98, West Conshohocken, PA, 1998.

[5] American Society for Testing and Materials, *Standard Classification for Building Elements and Related Sitework--UNIFORMAT II,* ASTM Designation E 1557-97, West Conshohocken, PA, September 1997.

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 primary 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

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

relative, U.S. average economic scores to help the building community select environmentally and economically balanced building products.

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 to 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 m^2 (1 ft^2) of product service for 50 years.[8,9] Therefore, for example, the functional unit for the BEES roof covering alternatives is *covering 0.09* m^2 *(1* ft^2*) 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 6 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

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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 concrete paving is 0.76 cubic meters (1 cubic yard) of product service for 50 years.

[10] Ecobalance, Inc., DEAM™ 3.0: Data for Environmental Analysis and Management, Bethesda, MD, 1999.

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 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 400 inventory flow items included in BEES.

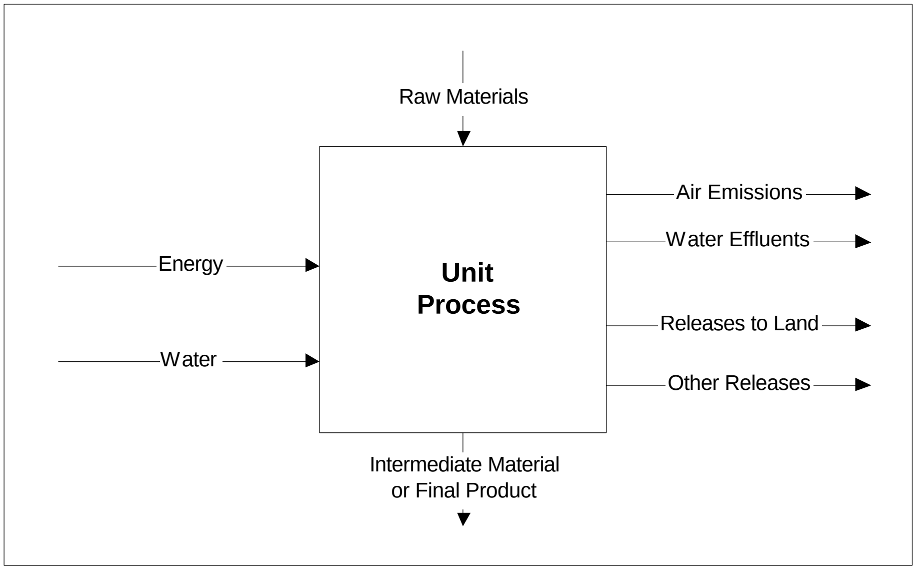

Figure 2.2 BEES Inventory Data Categories

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

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

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[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.

Environmental Strategies and Solutions (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 % of the data come directly from industry sources, with about 10 % 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:

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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.

- 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.

Ecological Scarcity (Switzerland). A more general approach has been developed by 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.

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[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.

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]

- 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.

The BEES model uses this classification/characterization approach because it enjoys some general consensus among LCA practitioners and scientists.[18] The following global and regional impacts are assessed using the classification/characterization approach: Global Warming Potential, Acidification Potential, Eutrophication Potential, and Natural Resource Depletion. Indoor Air Quality and Solid Waste impacts are also included in BEES, for a total of six impacts for most BEES products.

As part of its *Framework for Responsible Environmental Decisionmaking* project, EPA confirmed the validity of the six impacts included in BEES 1.0. In addition, EPA suggested that four additional impacts be pilot tested in BEES 2.0: Smog, Ecological Toxicity, Human Toxicity, and Ozone Depletion.[19] **For a select group of products, BEES 2.0 also assesses Smog and in some cases Ecological Toxicity, Human Toxicity, and Ozone Depletion as well. These "expanded impact" products are identified in table 4.1. Note that the data and science underlying measurement of these four impacts are less certain than for the original six BEES impacts.** The 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

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

[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.

[19] U.S. EPA, *Framework for Responsible Environmental Decisionmaking (FRED): Using Life Cycle Assessment to Evaluate Preferability of Products*, by Science Applications International Corporation, Research Triangle Institute, and EcoSense, Inc, Draft Report, 1999.

acidification) the method may result in an accurate description of the potential impact. For impacts dependent upon local conditions (e.g., smog, ecological toxicity, and human toxicity) it may result in an oversimplification of the actual impacts because the indices are not tailored to localities.

If the BEES user has important knowledge about other potential environmental impacts, it should be brought into the interpretation of the BEES results. The ten 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 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 environmental 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.[20] 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:

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

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[20] International Panel on Climate Change (IPCC*), IPCC Second Assessment—Climate Change 1995: A Report of the Intergovernmental Panel on Climate Change,* 1996.

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
Nitrous oxide	360

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 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:

$$\text{acidification index} = \Sigma_I\, w_i * AP_i, \text{ where}$$

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.[21]

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

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	0.050
Hydrogen Chloride	0.027

Eutrophication Potential. Eutrophication 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 eutrophication 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 eutrophication (in grams of phosphate ions per functional unit of product), representing the quantity of phosphate ions with the same potential nutrifying effect:

$$\text{eutrophication index} = \Sigma_i\ w_i \times EP_i, \text{ where}$$

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

EP_i = grams of phosphate ions with the same potential nutrifying effect as one grams of inventory flow i, as listed in Table 2.3.[22]

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.

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[22] CML, 1992.

Table 2.3 BEES Eutrophication Potential Equivalency Factors

Flow *(i)*	***EP_i*** *(phosphate-equivalents)*
Phosphates	1.00
Nitrogen Oxides	0.13
Ammonia	0.42
Nitrogenous Matter	0.42
Nitrates	0.10
Phosphorous	3.06
Chemical Oxygen Demand	0.02

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:

> 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.[23]

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:

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

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

where:

reserve_i = reserves (in kg) 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 kg/year) for natural resource i

w_i = the weight (in kg) 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 system. 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 50-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, and 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 m^3, or ft^3, of waste per functional unit of product) is derived as follows:

solid waste volume = $(\Sigma_i w_i)$ / density,

where:

w_i = weight (in kg) of non-recyclable solid waste inventory flow i, and

density = density of the product (in kg/0.0283 m^3, or kg/ ft^3), as listed in Table 2.5.

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 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

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)
All Asphalt Products	66 (145)
Roof and Wall Sheathing	
- Oriented Strand Board	18 (38)
- Plywood	13 (28)
Exterior Wall Finishes	
- Brick	60 (132)
- Stucco	55 (121)
- Cedar Siding	17 (37)
- Aluminum Siding	76 (168)
- PVC Siding	39 (87)
Interior Wall Finishes	
- Recycled Latex Paint	36 (80)
- Virgin Latex Paint	36 (80)
Batt Insulation	
- R-11 Fiberglass	0.23 (0.5)
- R-13 Fiberglass	0.36 (0.8)
- R-15 Fiberglass	0.68 (1.5)
- R-30 Fiberglass	0.23 (0.5)
Blown Insulation	
- R-13 Cellulose	0.73 (1.6)
- R-30 Cellulose	0.73 (1.6)
- R-12 Mineral Wool	0.98 (2.2)
- R-30 Mineral Wool	0.98 (2.2)
- R-30 Fiberglass	0.35 (0.75)
Roof Coverings	
- Asphalt Shingles	89 (196)
- Clay Tile	60 (132)
- Fiber Cement Shingles	44 (97)
Framing	
- Steel	224 (493)
- Wood	13 (29)
Floor Coverings	
- Ceramic Tile	61 (134)
- Linoleum	33 (73)
- Vinyl Composition Tile	59 (130)
- Composite Marble Tile	73 (161)
- Terrazzo	72 (159)
- Tile Carpet	6.3 (14)
- Broadloom Carpet	6.2 (14)

factors, a product's total volatile organic compound (VOC) emissions are 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, interior wall finishes, wall and roof sheathing, and wall and ceiling insulation. Other BEES building elements are primarily exterior or inert interior elements for which indoor air quality is not an issue.

Floor Coverings. BEES currently includes 17 floor covering products. Data for two components of their indoor air performance are considered—total VOC emissions from the products themselves and indoor air performance for their installation adhesives.

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. Ceramic tile, composite marble tile, and terrazzo are inert and emit no VOCs.[24] Total VOCs for all other BEES floor coverings are shown in Table 2.6.

Table 2.6 Volatile Organic Compound Emissions for BEES Floor Coverings

Floor Covering	***Total Volatile Organic Compound Emissions ($Mg/m^2/h$ at 24 h)***
Linoleum	1.667
Vinyl Composition Tile[a,b]	0.155
Carpet [c]	0.500

[a] 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.

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

[c] Carpet and Rug Institute (CRI) emissions standard for green labelling. Seventy-five percent of carpets tested meet these standards.

The second component of the BEES indoor air assessment for floor coverings is indoor air performance for their installation adhesives. Linoleum, vinyl composition tile, and carpets installed with traditional synthetic adhesives are assumed to be installed using a styrene-butadiene adhesive, and ceramic tile with recycled glass and composite marble tile using a styrene-butadiene cement mortar. Carpets installed with a low-VOC styrene-butadiene adhesive are assumed to have 17 %

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

the emissions of an equivalent quantity of traditional styrene-butadiene adhesive.[25] 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:

- linoleum—0.00878 kg/m^2 (0.00079 kg/ft^2)
- vinyl composition tile—0.00878 kg/m^2 (0.00079 kg/ft^2)
- ceramic tile with recycled windshield glass—0.00311 kg/m^2 (0.00028 kg/ft^2)
- composite marble tile—0.00311 kg/m^2 (0.00028 kg/ft^2)
- terrazzo—no installation adhesives
- wool broadloom carpet—1.30932 kg/m^2 (0.12164 kg/ft^2) traditional/ 0.22260 kg/m^2 (0.02068 kg/ft^2) low-VOC
- nylon broadloom carpet—3.27320 kg/m^2 (0.30409 kg/ft^2) traditional/ 0.55650 kg/m^2 (0.05170 kg/ft^2 low-VOC)
- PET broadloom carpet—3.27320 kg/m^2 (0.30409 kg/ft^2) traditional/ 0.55650 kg/m^2 (0.05170 kg/ft^2) low-VOC
- wool carpet tile—0.24779 kg/m^2 (0.02302 kg/ft^2) traditional/ 0.04209 kg/m^2 (0.00391 kg/ft^2) low-VOC
- nylon carpet tile—0.61946 kg/m^2 (0.05755 kg/ft^2) traditional/ 0.10527 kg/m^2 (0.00978 kg/ft^2) low-VOC
- PET carpet tile—0.61946 kg/m^2 (0.05755 kg/ft^2) traditional/ 0.10527 kg/m^2 (0.00978 kg/ft^2) low-VOC

To assess overall indoor air performance for BEES floor coverings, each product's performance data for product emissions and installation adhesives 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***	***Average***
Ceramic Tile w/ Glass	0	0.09	0.05
Linoleum	100.00	0.26	50.13
Vinyl Composition Tile	15.94	0.26	8.10
Composite Marble Tile	0	0.09	0.05
Terrazzo	0	0	0

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[25] Based on data reported in *Environmental Building News,* Vol. 3, No. 6, November/December 1994, p 4.

Wool Broadloom	44.52	40.00	42.26
Wool Broadloom & Low-VOC	44.52	6.80	25.66
Nylon Broadloom	44.52	100.00	72.26
Nylon Broadloom & Low-VOC	44.52	17.00	30.76
PET Broadloom	44.52	100.00	72.26
PET Broadloom & Low-VOC	44.52	17.0	30.76
Wool Tile	44.52	7.57	26.05
Wool Tile & Low-VOC	44.52	1.29	22.91
Nylon Tile	44.52	18.92	31.72
Nylon Tile & Low-VOC	44.52	3.22	23.87
PET Tile	44.52	18.92	31.72
PET Tile/Low-VOC	44.52	3.22	23.87

Interior Wall Finishes. BEES evaluates indoor air performance for interior wall finishes based on total VOC emissions. Total VOCs for virgin latex paint are estimated to be 100 g/L, and for recycled latex paint 125 g/L.[26] Both paints are initially applied by priming followed by two coats of paint. For both, one coat is reapplied every 4 years over the 50-year use phase. Based on these figures, virgin latex paint will emit 13.46 g of VOCs per 0.09 m^2 (1 ft^2) over 50 years of use, and recycled latex paint 16.58 g of VOCs per 0.09 m^2 (1 ft^2) over 50 years. These flows are directly used to assess indoor air performance for the two interior wall finishes.

Note that due to limitations of indoor air science, the BEES indoor air performance scores for floor coverings and interior wall finishes 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.

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

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[26] Based on data reported in *Environmental Building News*, Vol. 8, No. 2, February 1999, pp 12,18.

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.[27] 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.[28] 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.[29]

***Ozone Depletion* (assessed for a limited number of BEES products as described in this section under C*lassification/Characterization*).** The ozone layer is present in the stratosphere and acts as a filter absorbing harmful short wave ultraviolet light while allowing longer wavelengths to pass through. A thinning of the ozone layer allows more harmful short wave radiation to reach the Earth's surface, potentially causing changes to ecosystems as flora and fauna have varying abilities to cope with it. There may also be adverse effects on agricultural productivity. Effects on man can include increased skin cancer rates (particularly fatal melanomas) and eye cataracts, as well as suppression of the immune system. Another problem is the uncertain effect on the climate.

Since the late 1970s, a thinning of the ozone layer over the Antarctic has been observed during the Spring, which amounts to 80 % to 98 % removal of this layer (the ozone 'hole'). This "hole" over the Antarctic is created due to the unique chemistry present over the Poles. Under certain conditions chlorine and bromine (from chlorofluorocarbons—CFCs--and other sources) undergo complex reactions which result in ozone depletion.

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[27] Alex Wilson and Nadav Malin, "The IAQ Challenge: Protecting the Indoor Environment," *Environmental Building News,* Vol. 5, No. 3, May/June 1996, p 15.

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

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

A single index, expressed in grams of CFC-11 per functional unit of product, is derived to measure the quantity of CFC-11 with the same potential ozone depleting effect:[30]

Ozone Depletion index = $\sum_i ODP_i \times m_i$, where
m_i = mass (in grams) of inventory flow i, and ODP_i = grams of CFC-11 with the same ozone depleting potential as one gram of inventory flow i, as listed in table 2.8.

Table 2.8 BEES Ozone Depletion Potential Equivalency Factors

Flow	***Chemical Formula***	***ODP (CFC-11 equivalents)***
Methyl Bromide	CH_3Br	0.37
Carbon Tetrachloride	CCl_4	1.2
CFC 11	$CFCl_3$	1
CFC 113	$CF_2ClCFCl_2$	0.9
CFC 114	CF_2ClCF_2Cl	0.85
CFC 115	CF_3CF_2Cl	0.4
CFC 12	CCl_2F_2	0.82
Halon 1201	CHF_2Br	1.4
Halon 1202	CF_2Br_2	1.25
Halon 1211	CF_2ClBr	5.1
Halon 1301	CF_3Br	12
Halon 2311	$CF_3CHBrCl$	0.14
Halon 2401	CHF_2CF_2Br	0.25
Halon 2402	CF_2ClBr	7
HCFC 123	$CHCl_2CF_3$	0.012
HCFC 124	$CHClFCF_3$	0.026
HCFC 141b	$CFCl_2CH_3$	0.086
HCFC 142b	CF_2ClCH_3	0.043
HCFC 22	CHF_2Cl	0.034
HCFC 225ca	$C_3HF_5Cl_2$	0.017
HCFC 225cb	$C_3HF_5Cl_2$	0.017
Methyl Chloroform, HC-140a	CH_3CCl_3	0.11

This method is limited by the following factors:

1. The Ozone Depletion Potentials upon which the assessment method is based are subject to considerable uncertainty and regular modification.
2. Greenhouse gases can affect the level of ozone directly through chemical reactions or indirectly by contributing to global warming. At present, the influence of this factor is not incorporated due to the complex nature of the reactions involved.

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[30] World Meteorological Organization (WMO), *Scientific assessment of ozone depletion*, 1991. Updated with World Meteorological Organization (WMO), *Scientific Assessment of Ozone Depletion: 1998*, Report 44 (Global Ozone Research and Monitoring Project).

3. Concentrations of trace gases such as nitrogen oxides affect atmospheric levels of the hydroxyl radical (OH), which in turn can affect the atmospheric lifetime of hydrogenated halocarbons. This process can influence future ozone depletion rates. Thus, ozone depletion rates may vary with time.
4. ODPs are defined at steady state, and therefore do not represent transient effects. In reality, shorter-lived halocarbons will reach a "steady state" ability to destroy ozone before longer-lived compounds. ODPs are based on annually averaged global changes in ozone, which do not take into account the chemical reactions involving a change in state which occur specifically at the Poles. Consequently, ODP-derived concentrations tend to understate the damage to the ozone caused by the presence of chlorine and bromine in the atmosphere.

***Smog Formation* (assessed for a limited number of BEES products as described in this section under C*lassification/Characterization*).** Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level, where they react with sunlight to produce photochemical smog. One of the components of smog is ozone, which is not emitted directly, but rather produced through the interactions of volatile organic compounds (VOCs) and oxides of nitrogen (NO_x).

While NO_x availability ultimately limits the production of ozone, the reactivity of the VOC determines the rate at which ozone is produced. Thus, when attempting to quantify smog potential, not only must the reactivity of the VOC be considered, but also the environmental conditions (e.g., NO_x concentration).

There are a number of difficulties inherent in calculating VOC reactivities, not the least of which is the non-linear nature of the reactions that produce photochemical smog. This is typified by the properties of NO_x, which can either form ozone or inhibit its formation, depending on the overall environmental conditions. Additionally, scientists are still not certain of the exact mechanism underlying ozone formation.

One method that is used to quantify the ozone production potential of various VOCs is based on the incremental reactivity (IR) scale.[31] This scale gives factors for VOCs that indicate the change in ozone caused by adding a small amount of the compound to the emissions, divided by the amount added. The resulting factor is generally expressed in moles of ozone formed per gram of VOC emitted. For the reasons stated above, there are limits to the accuracy of the calculated IR factors. All the same, government bodies have generally accepted them.[32]

The US Environmental Protection Agency ranks volatile organic compounds as being either ‘negligibly reactive’ or ‘reactive’. These rankings are used for regulatory control purposes and

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[31] William P. Carter, "Development of Ozone Reactivity Scales for Volatile Organic Compounds", *Journal of the Air & Waste Management Association*, Vol. 44, July 1994, pp. 881-899

[32] Dr. Basil Dimitriades, a Senior Scientific Advisor at the Atmospheric Processes Research Division of the US EPA, stated that while the use of incremental reactivity (IR) factors is not officially sanctioned, when IR data are presented in reports, they are accepted as being accurate (August 26, 1997). Bart Croes of the California Air Resources Board (CARB) indicated that MIR factors were specifically used to develop legislation for California (August 26, 1997).

are based on the reactivity of a compound. Compounds with incremental reactivities less than that for ethane are considered ‘negligibly reactive’.[33] This is not to say that these compounds don’t form ozone, they do; they simply produce ozone in small enough amounts that their effect on overall ozone formation is considered to be inconsequential.

The Maximum Incremental Reactivity (MIR) index is calculated to measure smog formation potential as follows:

> $MIR = \sum_i m_i \times MIR_i$, where
> m_i = mass (in grams) of inventory flow i, and MIR_i = Maximum Incremental Reactivity for inventory flow i.

A partial listing of the 53 flows used in this calculation are shown in Table 2.9.

Table 2.9 Sampling of BEES Maximum Incremental Reactivity Equivalency Factors

Substance	***Chemical Formula***	***MIR (Maximum Incremental Reactivity)***
1-Butanol	$C_4H_{10}O$	3.324
2-Methyl 1-Butene	C_5H_{10}	5.543
Acetaldehyde	CH_3CHO	6.322
Benzene	C_6H_6	0.601
Methyl Bromide	CH_3Br	0.015
1-Butene	$CH_3CH_2CHCH_2$	10.68
Carbon Monoxide	CO	0.061
Cyclopentadiene	C_5H_6	12.51
Dibutyl Ether	$C_6H_{14}O$	2.809
1,3-Dimethyl Cyclohexane	C_8H_{16}	2.586
Ethane	C_2H_6	0.299
Ethyl Acetylene	C_4H_6	11.08
Formaldehyde	CH_2O	7.009
Glyoxal	$C_2H_2O_2$	2.209
Heptane	C_7H_{16}	1.045
Isobutyl Alcohol	$(CH_3)_2CHCH_2OH$	2.332
Methane	CH_4	0.016
Methyl Cyclopentane	C_6H_{12}	3.444
Methyl Glyoxal	$C_3H_4O_2$	14.32
1-Nonene	C_9H_{18}	3.06
3-Octene	C_8H_{16}	7.528
2-Pentene	$CH_3CH_2(CH)_2CH_3$	11.79
Styrene	$C_6H_5CHCH_2$	2.28
Toluene	$C_6H_5CH_3$	3.154
Trimethyl Amine	$(CH_3)_3N$	6.699

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[33] The incremental reactivity for ethane has been estimated to be 0.299 grams ozone per gram VOC.

n-Undecane	$C_{11}H_{24}$	0.619
Vinyl Acetate	$C_4H_6O_2$	6.96
m-Xylene	$C_6H_4(CH_3)_2$	8.82

***Ecological Toxicity* (assessed for a limited number of BEES products as described in this section under C*lassification/Characterization*).** Ecological toxicity impacts were not included in BEES 1.0. However, several approaches for ranking chemicals according to relative hazard have been developed in recent years, in support of waste minimization and pollution prevention[34,35,36] and the Clean Air Act,[37] which are potentially applicable in an LCA context. Research Triangle Institute (RTI) developed the method described below and used in BEES 2.0 after reviewing these sources.

The RTI method includes measurements of relative hazard (toxicity factors or benchmarks) and environmental fate and transport (persistence and biomagnification factors). The approach involves the following steps:

1. Screen inventory data by identifying chemical-specific inventory flows or general inventory flows that can be represented by a chemical-specific surrogate, and eliminate those that are within 15 % of one another.
2. Identify aquatic and terrestrial benchmarks for both acute and chronic toxicity.
3. Assign chemicals a default benchmark if data are missing. The geometric mean of the available benchmarks is used as the default.
4. Normalize benchmarks within each category based on the geometric mean.
5. Select the maximum normalized benchmark as the toxicity factor.
6. Identify persistence factors for pertinent environmental media.
7. Identify biomagnification factors.
8. Multiply toxicity, persistence, and biomagnification factors for each inventory flow within each environmental medium for the TPB score.
9. Multiply TPB scores by the inventory mass per functional unit.
10. Sum factors to derive the total terrestrial and aquatic ecological toxicity impact indicator (ETI).
11. Determine the percentage of each ETI relative to the total ETI and select inventory flows contributing 0.1 % or more.
12. Compare inventory impacts to total US emissions to determine relative significance.

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[34] United States Environmental Protection Agency. *Waste Minimization Prioritization Tool, Beta Test Version 1.0: User's Guide and System Documentation,* Draft, EPA 530-R-97-019, Office of Solid Waste, Office of Pollution Prevention and Toxics, Washington, DC, 1997.

[35] United States Environmental Protection Agency. *Chemical Hazard Evaluation for Management Strategies, A Method for Ranking and Scoring Chemicals by Potential Human Health and Environmental Impacts,* EPA/600/R-94/177, Office of Research and Development, Washington, DC., 1994.

[36] Research Triangle Institute. *A Multimedia Waste Reduction Management System for the State of North Carolina,* Final Report, Prepared for the North Carolina Department of Health, Environment, and Natural Resources, Pollution Prevention Program, April, 1993.

[37] United States Environmental Protection Agency. *Technical Background Document to Support Rulemaking Pursuant to the Clean Air Act - Section 112(g), Ranking of Pollutants with Respect to Hazard to Human Health,* EPA-450/3-92-010, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 1994.

Table 2.10 gives examples of the 152 RTI ecological toxicity potential equivalency factors used in BEES to evaluate ecological toxicity for a handful of building products.

Table 2.10 Sampling of Ecological Toxicity Potential Equivalency Factors

Flow *(i)*	***Ecotoxicity*** *(grams equivalent Ecotoxicity)*
Hydrocarbons	21.90
Nitrogen Oxides	7.30
Carbon Monoxide	7.30
Dioxins	$20.2 \mathrm{x} 10^8$
Hydrogen Chloride	10.95

***Human Toxicity* (assessed for a limited number of BEES products as described in this section under C*lassification/Characterization*).** One approach to developing human toxicity indicators has been reported by the U.S EPA in *Framework for Responsible Environmental Decision Making (FRED).*[38] The FRED approach is based on the belief that industrial systems often release substances into the environment which can have toxic effects on human beings. In order for actual effects to occur, exposure to the substance must occur, the substance must be assimilated, and the received dose to the individual must exceed the body's ability to detoxify it.

There are many potential toxic effects from exposure to industrial and natural substances, ranging from transient irritation to permanent disability and even death. Some substances have a wide range of different effects, and different individuals have a widely varying tolerance to different substances. Finally, of the millions of industrial chemicals, very few have been subjected to toxicological evaluation. All these factors make assessments of the human toxicity potential of given substances difficult at best. When evaluated on a life-cycle basis, evaluating their impact is even more problematic.

Nevertheless, because human toxicity is a real and important environmental issue, the FRED LCA system incorporated an indicator based on the recommendation of the International Life Sciences Institute (ILSI), which suggested that all life-cycle human toxicity indicators be based on "No Observable adverse Effect Levels" (NOELs) and "Lowest Observable Effect Levels" (LOELs). In other words, toxicity indicators are based on concentrations or doses of chemicals tested on humans or laboratory animals that caused no effect or minimal effect. Generally, the lower the NOEL or LOEL, the more toxic the chemical. This approach has been incorporated into the

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[38] U.S. EPA, *Framework for Responsible Environmental Decisionmaking (FRED): Using Life Cycle Assessment to Evaluate Preferability of Products*, Draft Report, by Science Applications International Corporation, Research Triangle Institute, and EcoSense, Inc, 1999.

Environmental Defense Fund (EDF) Scorecard developed in conjunction with University of California at Berkeley. The FRED methodology used the Environmental Defense Fund (EDF) Scorecard as an indicator of human toxicity. This indicator consists of a pair of measures, one for carcinogenic and one for non-carcinogenic effects:

Carcinogenic Effects Index = $\sum_i w_i \times TEP_i$, where

$w_i =$ weight of inventory flow i per functional unit of product, and
TEP_i = Toxic Equivalency Potential, estimated as the weight of benzene with the same potential cancer-causing effect as a unit weight of inventory flow i.

Non-Carcinogenic Effects Index = $\sum_i w_i \times TEP_i$, where

$w_i =$ weight of inventory flow i per functional unit of product, and
TEP_i = Toxic Equivalency Potential, estimated as the weight of toluene with the same potential toxic effect as a unit weight of inventory flow i.

Toxic Equivalency Potentials (TEPs) for some of the 174 BEES inventory flows used in this calculation are given in Table 2.11. In BEES, the human toxicity impact score is computed by weighting equally the normalized carcinogenic and non-carcinogenic effects indices.

Table 2.11 Sampling of Human Toxicity Potential Equivalency Factors

Flow to Air	***TEP(carcinogens) weight Benzene/ weight substance***	***TEP (non-carcinogens) weight Toluene/ weight substance***
Ammonia	0	3.2
Benzene	1	17
Formaldehyde	0.003	7
Lead	15	1,300,000
Phenolics	0	0.045
Flow to Water	***TEP(carcinogens) weight Benzene/ weight substance***	***TEP (non-carcinogens) weight Toluene/ weight substance***
Ammonia (NH_4 +, NH_3 as N)	0	0.041
Benzene	0.99	11
Phenols	0	0.0038

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 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 eutrophication. To compare the overall environmental performance of competing products, the performance measures for all impact categories may be synthesized. Note that in BEES 2.0, synthesis of impact measures is optional.

Synthesizing the impact category performance measures involves combining apples and oranges. Global warming potential is expressed in carbon dioxide equivalents, acidification in hydrogen equivalents, eutrophication in phosphate equivalents, and so on. 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.[39]

MADA first places all impact categories on the same scale by normalizing them. Within an impact category, each product's performance measure can be normalized by dividing by the highest measure for that category, as in the BEES model. 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 environmental 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 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:

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

Nine of the ten BEES impact categories were among the SAB lists of relative importance:[40]

- Relatively High-Risk Problems: global warming, indoor air quality, ecological toxicity, human toxicity, ozone depletion, smog

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[39] 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.

[40] 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.

- Relatively Medium-Risk Problems: acidification, eutrophication
- Relatively Low-Risk Problems: solid waste[41]

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.[42]

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).[43] 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 2.12 and 2.13 list the pairwise comparison values assigned to the SAB verbal importance rankings, and the resulting importance weights computed for the BEES impacts, respectively.

Table 2.12 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 2.13 Relative Importance Weights based on Science Advisory Board Study

	Relative Importance Weight (%)		
Impact Category	***6 Impacts***	***7 Impacts[a]***	***10 Impacts[a]***
Global Warming	27	21	13
Acidification	13	11	6

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

[42] 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.

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

Eutrophication	13	11	6
Natural Resource Depletion	13	11	6
Indoor Air Quality	27	21	13
Solid Waste	7	4	4
Smog		21	13
Ecological Toxicity			13
Human Toxicity			13
Ozone Depletion			13

[a]This set of expanded impacts is available for a limited number of BEES products, as identified in Table 4.1.

Harvard University Study. In 1992, an extensive study was conducted at Harvard University to establish the relative importance of environmental impacts.[44] 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.

Nine of the ten BEES impact categories were among the studied impacts. Table 2.14 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.[45]

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

Table 2.14 U.S. Rankings for Current and Future Consequences by Impact Category

Impact Category	***Current Consequences***	***Future Consequences***
Global Warming	Low	High
Acidification	High	Low
Eutrophication	Medium	Medium
Natural Resource Depletion[a]	Medium	Medium-Low
Indoor Air Quality	Medium	Low
Smog	High	Low
Ecological Toxicity	Medium-Low	Medium-Low
Human Toxicity	Medium-Low	Medium-Low
Ozone Depletion	Low	High

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

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[44] 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.

[45] 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.

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.[46] Table 2.15 lists the resulting importance weights for the ten 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 2.15 Relative Importance Weights based on Harvard University study

	Relative Importance Weight Set								
	Current (%)			***Future (%)***			***Combined (%)***		
Impact Category	***6***	***7[a]***	***10[a]***	***6***	***7[a]***	***10[a]***	***6***	***7[a]***	***10[a]***
Global Warming	8	6	5	38	35	22	28	25	16
Acidification	33	25	19	10	9	6	17	15	10
Eutrophication	16	12	9	19	18	11	18	16	10
Natural Resource Depletion	16	12	9	14	13	8	15	13	9
Indoor Air Quality	16	12	9	10	9	6	12	10	7
Solid Waste	11	8	7	9	8	5	10	8	6
Smog		25	19		7	5		13	10
Ecological Toxicity			9			8			8
Human Toxicity			9			9			9
Ozone Depletion			5			20			15

[a]This set of expanded impacts is available for a limited number of BEES products, as identified in table 4.1.

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[46] 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.

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, *2000 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 1999*, supplemented by industry interviews. 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.[47]

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 farther 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.

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[47] 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.

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 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.[48]

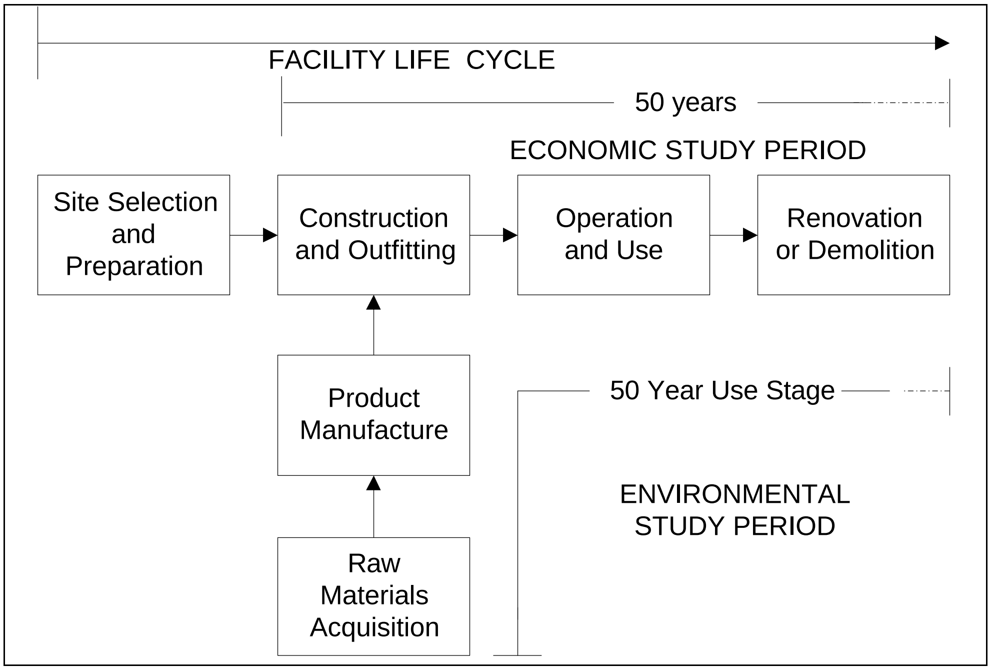

Figure 2.3 BEES Study Periods For Measuring Building Product Environmental And Economic Performance

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., 2000) 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 future costs are expressed in constant 2000 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 discount 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

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[48] 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.

same LCC results. The BEES model computes LCCs using constant 2000 dollars and a real discount rate. As a default, the BEES tool uses a real rate of 4.2 %, the 2000 rate mandated by the U.S. Office of Management and Budget (OMB) for most Federal projects.[49]

2.3 Overall Performance

The BEES overall performance score combines the environmental and economic results into a single score, as illustrated in Figure 2.4. 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 environmental and economic performance scores are combined into an overall score by weighting environmental and economic performance by their relative importance values. Overall scores are thereby placed on a scale from 0 to 100; if a product performs worst with respect to all environmental impacts *and* has the highest life-cycle cost, it would receive the worst possible overall score of 100. 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. 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 regulations, transportation distances, and labor and material markets may differ.[50] Furthermore, all products in an industry-average, generic product group, such as vinyl composition tile floor covering, are not created equal. Product composition, manufacturing methods, 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.

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[49] 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, February 2000.

[50] 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.

The BEES LCA uses selected inventory flows converted to selected local, 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. Ecological toxicity, human toxicity, ozone depletion, and smog impacts are included in BEES 2.0 for a select set of products (see table 4.1), but the science and data underlying their measurement are less certain. Finally, since BEES develops U.S. average results, some local impacts such as resource scarcity (e.g., water scarcity) 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, environmental impacts are optionally combined into a single environmental performance score using relative importance weights. These weights necessarily incorporate values and subjectivity. BEES users should routinely test the effects on the environmental performance scores 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. In rare instances, rank reversal, or a reordering of scores, is possible. 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 D has an environmental performance score of 40, Product D does not necessarily perform better than Product A (keeping in mind that lower performance scores are better). The same limitation relative to comparing environmental performance scores across building elements, of course, applies to comparing overall performance scores across elements.

There are inherent limits to comparing product alternatives without reference to the whole building design context. First, it 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

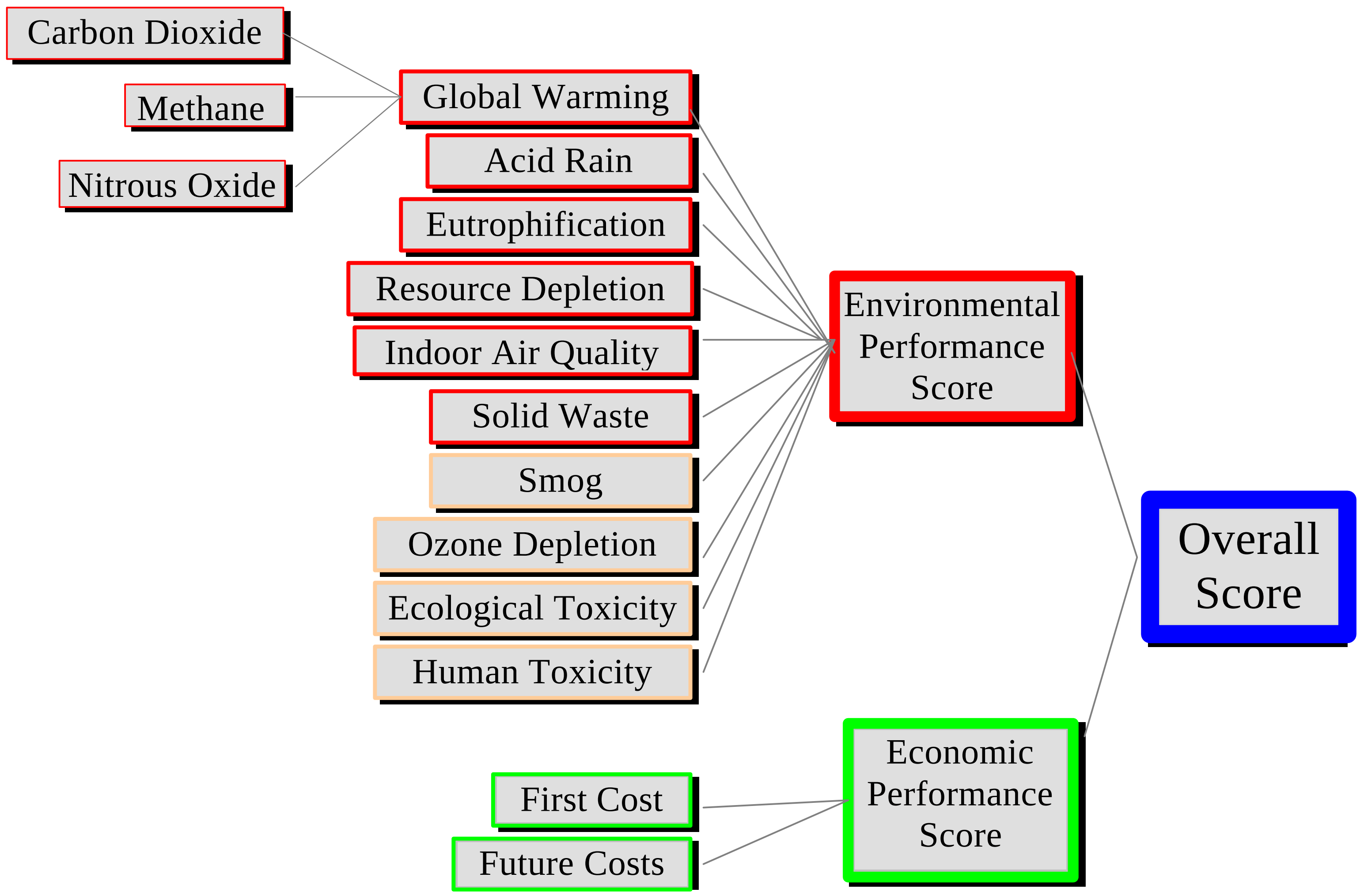

Figure 2.4 Deriving the BEES Overall Performance Score

technical performance requirements.[51] However, there may be significant differences in technical performance, such as acoustical performance, fire performance, or aesthetics, which may outweigh environmental and economic considerations.

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[51] Environmental and economic performance results for wall insulation, roof coverings and concrete beams and columns do consider technical performance differences. For wall insulation and roof coverings, BEES accounts for differential heating and cooling energy use. For concrete beams and columns, BEES accounts for different compressive strengths.

3. BEES Product Data

The BEES model uses the ASTM standard classification system, UNIFORMAT II,[52] to organize comparable building products into 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 Slabs, Walls, Beams, and Columns (BEES Codes A1030, A2020, B1011, B1012)

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 MPa to 138 MPa (100 psi to 20,000 psi), concrete for residential slabs and basements 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 MPa or 34 MPa (4000 psi or 5000 psi). Thus, concrete mixes modeled in the BEES software are limited to compressive strengths of 21 MPa, 28 MPa, and 34 MPa (3000 psi, 4000 psi, and 5000 psi).

To reduce cost, heat generation, and the environmental burden of concrete, ground granulated blast furnace slag (referred to as GGBFS or "slag") or fly ash may be substituted for a portion of the portland cement in the concrete mix. Fly ash is a waste material that results from burning coal to produce electricity. Slag is a waste material that is a result of steel production. When used in concrete, slag and fly ash are cementitious materials that can act in a similar manner as cement by facilitating compressive strength development.

BEES performance data apply to four building elements: 21 MPa (3000 psi) Slabs on Grade and Basement Walls; and 28 MPa or 34 MPa (4000 psi or 5000 psi) Beams and Columns. For each

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

building element, concrete alternatives with 100 % cement (no fly ash or slag), 15 %, and 20 % fly ash content (by weight of cement), and 20 %, 35 %, and 50 % slag content (by weight of cement) may be compared. While life-cycle costs differ among building elements, the environmental performance for a given slag or fly ash content and compressive strength rating is the same. The detailed environmental performance data for all concrete products except concrete paving[53] may be viewed by opening the following files under the File/Open menu item in the BEES software:

- A1030A.DBF—Concrete without supplementary cementitious materials
- A1030B.DBF—15 % Fly Ash Content Concrete
- A1030C.DBF—20 % Fly Ash Content Concrete
- A1030D.DBF—20 % Slag Content Concrete
- A1030E.DBF—35 % Slag Content Concrete
- A1030F.DBF—50 % Slag Content Concrete

Within each of these six environmental performance data files, there are three complete sets of environmental performance data corresponding to compressive strength ratings of 21 MPa, 28 MPa, and 34 MPa (3000 psi, 4000 psi, 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.[54]

BEES comparisons for slabs, basement walls, beams, and columns are limited to concrete products. Thus, for these building elements, 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 or slag content for the ignored life-cycle stages.

Figures 3.1 and 3.2 show the elements of concrete production with and without slag or 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 or slag are an equal replacement for cement. Quantities of constituent materials used in an actual project may vary.

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[53] The environmental performance of concrete paving products is discussed later in this section.

[54] Portland Cement Association, *Data Transmittal for Incorporation of Slag Containing Concrete Mixes into Version 2.0 of the BEES Software,* PCA R&D Serial No. 2168a, PCA Project 94-04, prepared by Construction Technology Laboratories, Inc. and JAN Consultants, May 2000; and 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.

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

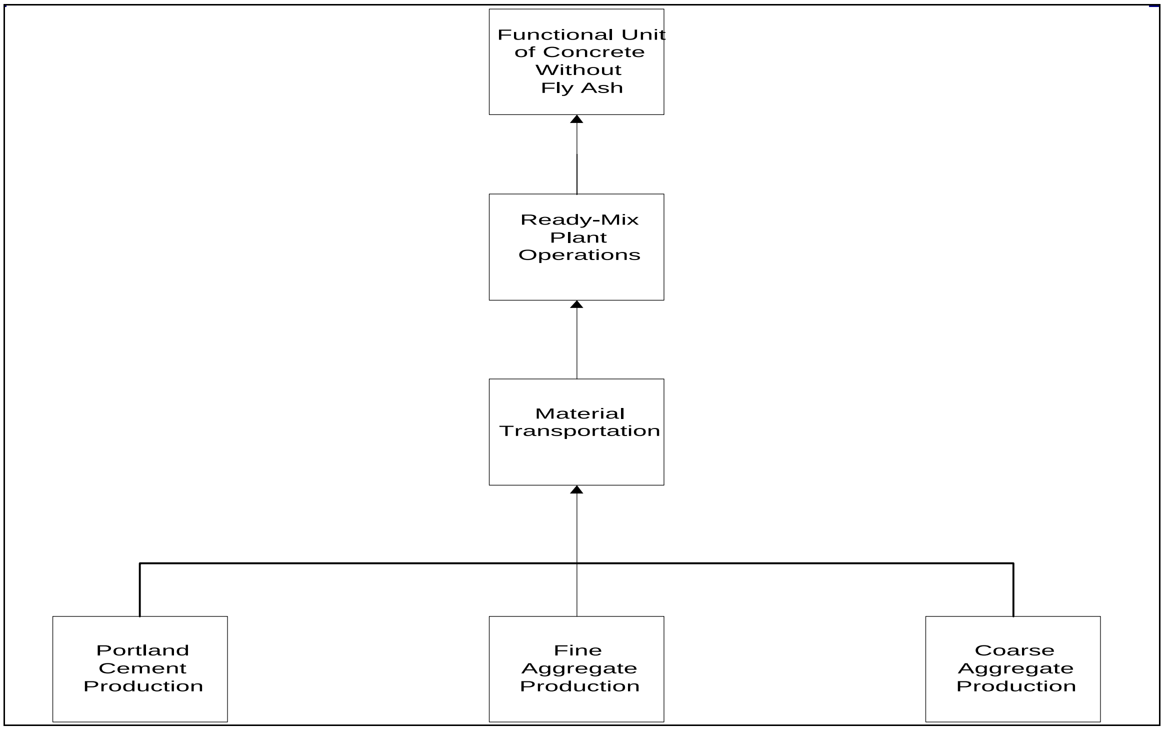

Figure 3.1 Portland Cement Concrete Without Fly Ash Flow Chart

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 % (by weight) of portland cement.

Aggregate. Aggregate is a general term that describes a filler material in concrete. Aggregate generally provides 60 % to 75 % of the concrete volume. Typically, aggregate consists of a

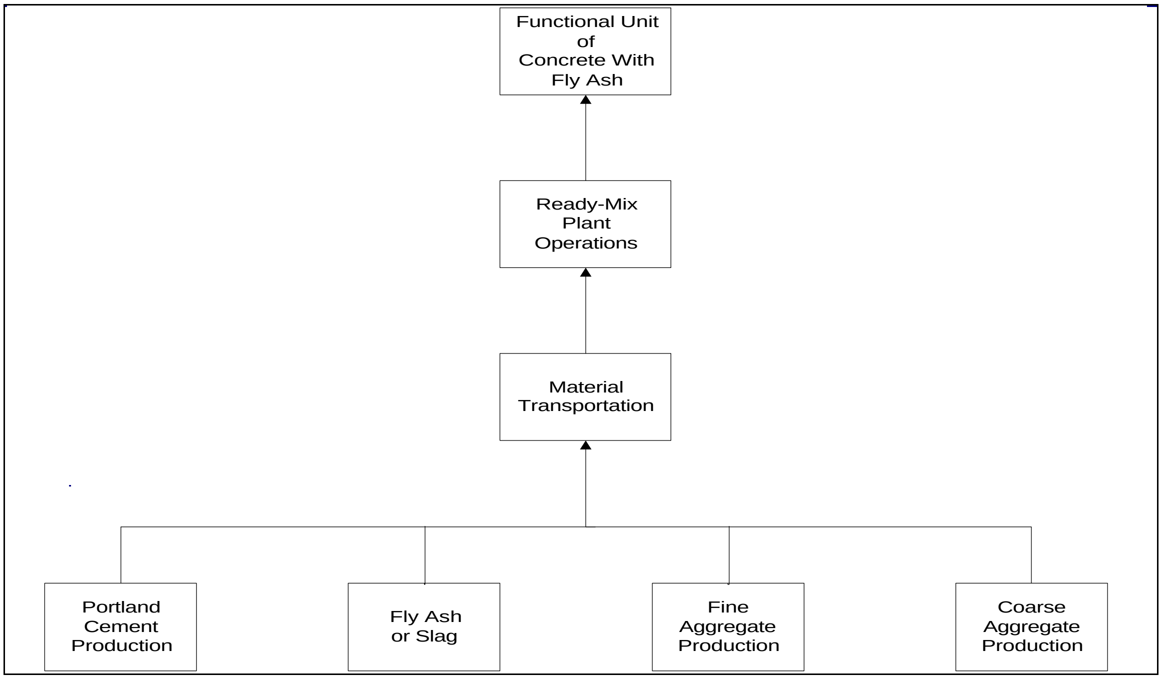

Figure 3.2 Portland Cement Concrete With Fly Ash or Slag Flow Chart

Table 3.1 Concrete Constituent Quantities by Compressive Strength of Concrete

Concrete Constituent	***Constituent Weight in kg per m^3 (lb/ yd^3)*** 21 MPa (3000 psi)	28 MPa (4000 psi)	34 MPa (5000 psi)
Cement and Fly Ash or Slag	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)

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 that results from 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.[55] However, transport of the fly ash to the ready mix plant is included.

Slag. Slag is a waste material, which is a result of the production of steel. Similar to fly ash, slag is an environmental outflow of steel production and an environmental inflow of concrete production. Therefore, slag is considered to be an environmentally “free” input material.[55] Unlike fly ash, slag must be processed prior to inclusion in concrete. Processing consists of quenching and granulating at the steel mill, transport to the grinding facility, and finish grinding. Transportation 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 preheater/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 or preheater/precalciner processes. As of 1995, the mix of production processes was 30 % wet, 27 % dry, 19 % preheater, and 24 % preheater/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

	Cement Manufacturing Process*				
Fuel Use	***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 % 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

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

and fine aggregate is assumed to be 155 kJ/kg of aggregate (66.8 Btu/lb).

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

Slag. Similar to fly ash, slag is a waste material and therefore does not include energy burdens associated with steel production. Because slag requires processing prior to incorporation into concrete, the energy use for granulation and grinding are included. Production energy is assumed to be 465 kJ/kg of slag (200 Btu/lb).

Round-trip distances for transport of concrete raw materials to the ready mix plant are assumed to be 97 km (60 mi) for portland cement and fly ash, 216 km (134 mi) for slag, and 80 km (50 mi) for aggregate. The method of transport is truck, consuming 1.18 kJ/kg$*$km (0.818 Btu/lb$*$mi).

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 MJ/m^3 of concrete (0.179 MBtu/yd^3, 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 oxides (SO_X), nitrogen oxides (NO_X), total hydrocarbons, and hydrogen chloride (HCl). Emissions vary for the eighteen different mixtures of compressive strength and fly ash or slag 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, 2000 *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 1999*, supplemented by industry interviews.

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

Concrete Product	Specification	BEES Code
0 % Fly Ash Content Slab on Grade	10.2cm-15.2cm (4"-6") thick	A1030,A0
15 % Fly Ash Content Slab on Grade	10.2cm-15.2cm (4"-6") thick	A1030,B0
20 % Fly Ash Content Slab on Grade	10.2cm-15.2cm (4"-6") thick	A1030,C0
0 % Fly Ash Content Basement Wall	20.3-38.1cm (8"-15") thick	A2020,A0
15 % Fly Ash Content Basement Wall	20.3-38.1cm (8"-15") thick	A2020,B0
20 % Fly Ash Content Basement Wall	20.3-38.1cm (8"-15") thick	A2020,C0
0 % Fly Ash Content Beams	3.0-7.6 m (10'-25') span	B1011,A0
15 % Fly Ash Content Beams	3.0-7.6 m (10'-25') span	B1011,B0
20 % Fly Ash Content Beams	3.0-7.6 m (10'-25') span	B1011,C0
0 % Fly Ash Content Columns	40.6-61.0cm (16"-24") diameter	B1012,A0

15 % Fly Ash Content Columns	40.6-61.0cm (16"-24") diameter	B1012,B0
20 % Fly Ash Content Columns	40.6-61.0cm (16"-24") diameter	B1012,C0

3.2 Roof and Wall Sheathing Alternatives (B1020, B2015)

3.2.1 Oriented Strand Board Sheathing (B1020A, B2015A)

Oriented strand board (OSB) is made from strands of low density wood. A wax, primarily a petroleum-based wax, is used to bind the strands. Resins, mainly phenolic resin with some Methylene Diphenyl Isocyanate (MDI) resin, are also used as a binder material in making most OSB. For the BEES system, 1.1 cm (7/16 in) thick OSB boards are studied. The flow diagram 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 B1020A.DBF under the File/Open menu item in the BEES software.

Raw Materials. Energy use for timber production is based on studies by Forintek and Procter & Gamble.[56] The average energy use reported is 200 MJ per 907 kg (95 Btu/lb) of greenwood produced, assumed to be in the form of diesel fuel for tractors. Tailpipe emissions from tractors and emissions associated with production of diesel fuel are included based on the Ecobalance LCA database.
BEES also accounts for the absorption of carbon dioxide by trees. The "uptake" of carbon dioxide during the growth of timber is assumed to be 1.74 kg of carbon dioxide per kg of greenwood harvested. The volume of wood harvested is based on an average density of 500 kg/m^3 (31 lb/ft^3), with aspen at 450 kg/m^3 (28 lb/ft^3) and Southern yellow pine at 550 kg/m^3 (34 lb/ft^3).

Transportation of Raw Materials to Manufacturing Plant. For transportation of raw materials to the manufacturing plant, BEES assumes truck transportation of 161 km (100 mi) for wood timber and truck transportation of 322 km (200 mi) for both the resins and the wax. The tailpipe

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[56] Ash, Knoblock, and Peters, *Energy Analysis of Energy from the Forest Options*, ENFOR Project P-59, 1990; B. N. Johnson, "Inventory of Land Management Inputs for Producing Absorbent Fiber for Diapers: A Comparison of *Forest Products Journal*, vol 44, no. 6, 1994.

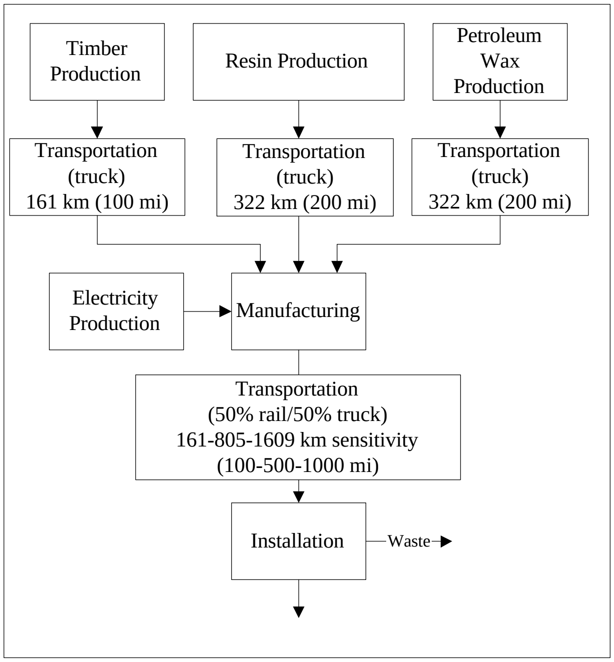

Figure 3.3 Oriented Strand Board Flow Chart

emissions from the trucks and the emissions from producing the fuel used in the trucks are taken into account based on the Ecobalance database.

Manufacturing. The components and energy requirements for OSB manufacturing are based on a study performed by the United States Department of Agriculture (USDA).[57] Table 3.4 shows the constituents of OSB production.

Table 3.4 Oriented Strand Board Sheathing Constituents

Component	***Input (kg/kg product)***	***In Final Product (kg/kg)***	***In Final Product (%)***
Wood	1.365	0.967	96.7
Resin	0.023	0.023	2.3
Wax	0.010	0.010	1.0
Total:	1.398	1	100

There is no waste from the OSB manufacturing process. All the input resin (mainly phenolic resin with some Methylene Diphenyl Isocyanate (MDI) resin) and the wax are assumed to go into the final product and the excess wood material is assumed to be burned on site for fuel.

The energy for the OSB manufacturing process is generated from burning the wood waste and from purchased electricity. The amount of electricity used is assumed to be 612 MJ/kg (263.2

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[57] Spelter H, Wang R, and Ince P, *Economic Feasibility of Products from Inland West Small-Diameter Timber*, United States Department of Agriculture, Forest Service (May 1996).

Btu/lb) of OSB produced.

The emissions from the OSB manufacturing process are based on a Forintek Canada Corporation Study, as reported in Table 3.5.[58] Since these emissions are assumed to be from combustion of the wood residue and any volatile organic compound (VOC) emissions from drying the OSB, the carbon dioxide (CO_2) emissions are all assumed to be biomass-based. VOC emissions are reduced by 30 % to account for process improvements over time. Electricity production emissions are based on a standard US electricity grid.

Table 3.5 Oriented Strand Board Manufacturing Emissions

Emission	***Value (per oven dry tonne of OSB)***
Carbon Dioxide	488 kg (1076 lb)
Carbon Monoxide	91 g (3.2 oz)
Methane	43 g (1.5 oz)
Nitrous Oxides	685 g (24.2 oz)
Sulfur Dioxide	159 g (5.6 oz)
Volatile Organic Compounds	161 g (5.7 oz)
Particulates	502 g (17.7 oz)

The resin used in OSB production is assumed to be 80 % phenolic resin and 20 % Methylene Diphenyl Isocyanate. Data representing the production of both resins are derived from the Ecobalance database.

The wax used in the production of OSB is assumed to be petroleum wax. Production of the petroleum wax is based on the Ecobalance database and includes the extraction, transportation, and refining of crude oil into petroleum wax.

Transportation from Manufacturing to Use. Transportation of OSB to the building site is modeled as a variable of the BEES system, with equal portions by truck and rail. Emissions associated with the combustion of fuel in the train and truck engines are included as are the emissions associated with producing the fuel, both based on the Ecobalance database.

Installation: Installation waste with a mass fraction of 0.015 is assumed.

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,A0—Oriented Strand Board Roof Sheathing

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[58] 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.

- B2015,A0—Oriented Strand Board Wall Sheathing

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, *2000 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 1999*, supplemented by industry interviews.

3.2.2 Plywood Sheathing (B1020B, B2015B)

Plywood sheathing is made from lower density wood. Phenol formaldehyde is used in the manufacturing process. For the BEES system, 1.3 cm (1/2 in) thick plywood boards are studied. The flow diagram shown in Figure 3.4 shows the major elements of 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 B1020B.DBF under the File/Open menu item in the BEES software.

Raw Materials. BEES accounts for energy use during timber production. Energy use was based on studies by Forintek and Procter & Gamble.[59] The average energy use reported was 200 MJ per 907 kg (95 Btu/lb) of greenwood produced, assumed to be in the form of diesel fuel for tractors. Tailpipe emissions from tractors and emissions associated with production of diesel fuel are included based on the Ecobalance LCA database.

BEES also accounts for the absorption of carbon dioxide by trees. The “uptake” of carbon dioxide during the growth of timber is assumed to be 1.74 kg of carbon dioxide per kilogram of greenwood harvested. The volume of wood harvested is based on an average density of 600 kg/m^3 (37.5 lb/ ft^3).

Transportation of Raw Materials to Manufacturing Plant. For transportation of raw materials to the manufacturing plant, BEES assumes truck transportation of 161 km (100 mi) for wood timber and truck transportation of 322 km (200 mi) for the resin. The tailpipe emissions from the trucks and the emissions from producing the fuel used in the trucks are taken into account based on the Ecobalance database.

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[59] Ash, Knoblock, and Peters, *Energy Analysis of Energy from the Forest Options*, ENFOR Project P-59, 1990; B. N. Johnson, “Inventory of Land Management Inputs for Producing Absorbent Fiber for Diapers: A Comparison of Cotton and Softwood Land Management,” *Forest Products Journal*, vol 44, no. 6, 1994.

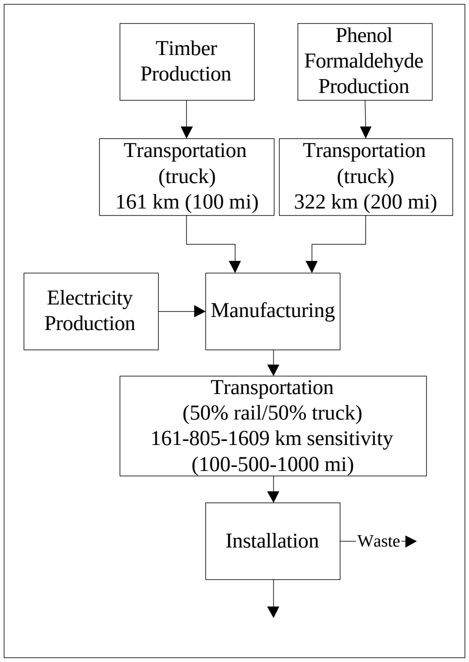

Figure 3.4 Plywood Sheathing Flow Chart

Manufacturing. The components and energy requirements for plywood manufacturing are based on a Forintek Canada Corporation study[60]. Table 3.6 shows the constituents of plywood production.

Table 3.6 Plywood Constituents

Constituent	***Input (kg/kg product)***	***In Final Product (kg/kg)***	***In Final Product (%)***
Wood	1.51	0.899	89.9
Resin	0.101	0.101	10.1
Total:	1.611	1	100

There is no waste from the plywood manufacturing process. All the input resin, phenol formaldehyde, is assumed to go into the final product and the residual wood material in the form of bark and wasted veneers is assumed to be burned on site for fuel (except for some waste veneer's cores, which are normally sold for landscaping timber or converted into chips for pulp).

The energy for the plywood manufacturing process is generated from burning the wood waste and from purchased electricity. The amount of electricity used is based on the Forintek study and is assumed to be 351 MJ per oven dry tonne (151 Btu/lb) of plywood produced. Electricity production emissions are based on a standard U.S. electricity grid. The emissions from the

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[60] 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.

plywood manufacturing process are based on the Forintek Canada Corporation study, as reported in Table 3.7.

Table 3.7 Plywood Manufacturing Emissions

Emission	***Amount (per oven dry tonne of plywood)***
Carbon Dioxide	500 kg (1102.3 lb)
Carbon Monoxide	112 g (3.95 oz)
Methane	35 g (1.2 oz)
Nitrous Oxides	668 g (23.6 oz)
Sulfur Dioxide	30 g (1.1 oz)
Volatile Organic Compounds	408 g (14.4 oz)
Particulates	699 g (24.7 oz)

Since emissions are assumed to be from combustion of the wood residue and any VOC emissions from drying the plywood, CO_2 emissions are all assumed to be biomass-based.

The glue used in bonding plywood consists of phenolic resin in liquid form combined with extender (dry fibers) assumed to be caustic soda. Data for the production of this glue are based on the Ecobalance database.

Transportation from Manufacturing to Use. Transportation of plywood to the building site is modeled as a variable of the BEES system, with equal portions by truck and rail. Emissions associated with the combustion of fuel in the train and truck engines are included as are the emissions associated with producing the fuel, both based on the Ecobalance database.

Installation. Installation waste with a mass fraction of 0.015 is assumed.

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,B0—Plywood Roof Sheathing
- B2015,B0—Plywood Wall Sheathing

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, *2000 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 1999*, supplemented by industry interviews.

3.3 Exterior Wall Finish Alternatives (B2011)

3.3.1 Brick and Mortar (B2011A)

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 (10 cm x 6.8 cm x 20 cm, or 4 in x 2-2/3 in x 8 in) 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 B2011A.DBF under the File/Open menu item in the BEES software.

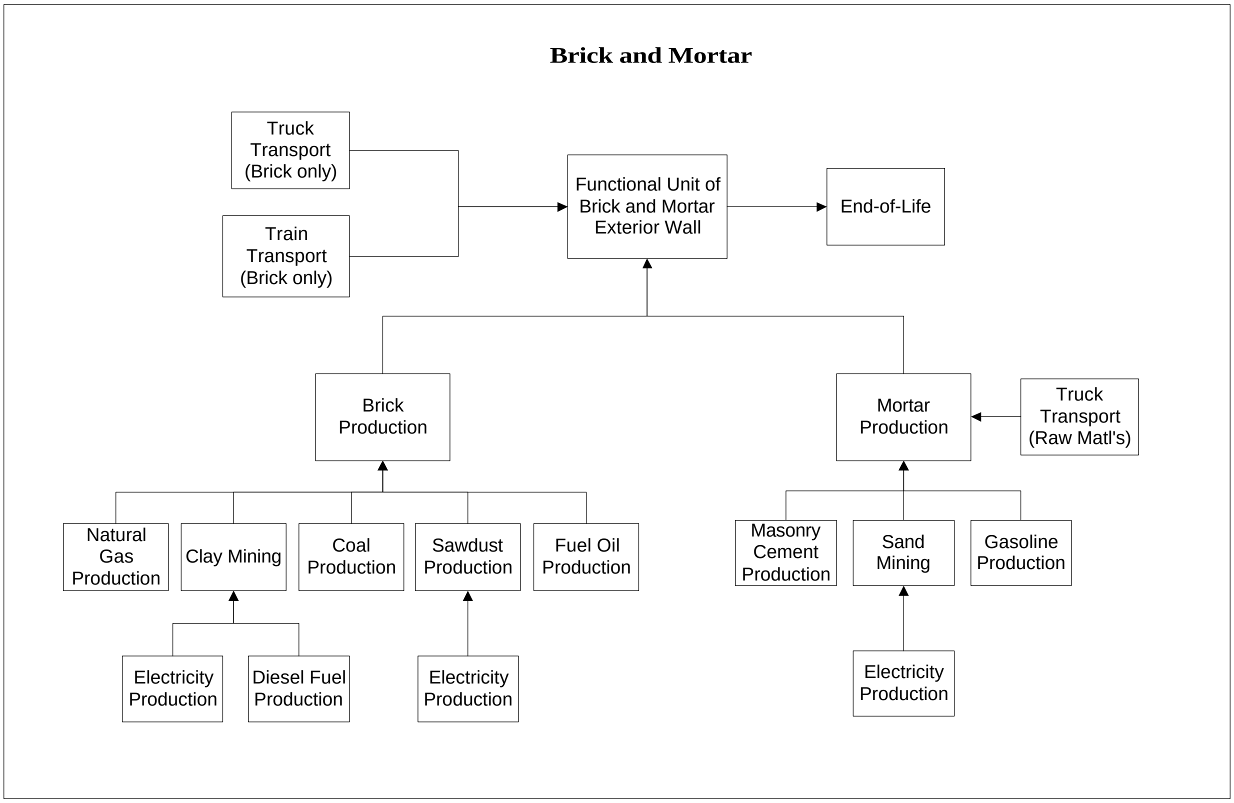

Figure 3.5 Brick and Mortar Flow Chart

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,[61] and 6.3 L (1.67 gal) of water. Masonry cement is modeled based on the assumptions outlined below for stucco exterior walls.

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

Energy Required. The energy requirements for brick production (drying and firing) are listed in Table 3.8. The production of the different types of fuel is based on the Ecobalance LCA database.

Table 3.8 Energy Requirements for Brick Manufacturing

Fuel Use	*Manufacturing Energy*
Total Fossil Fuel	2.88 MJ/kg (1,238 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 % tunnel kiln technology and 27 % periodic kiln technology.

The mortar is assumed to be mixed in a 5.9 kW (8 hp), gasoline powered mixer with a flow rate of 0.25 m^3 (9 ft^3) of mortar per hour, running for five minutes.

Emissions. Emissions are based on AP-42[62] 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 is 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 kg (6.5 lb) per brick. The density of the Type N mortar is assumed to be 2002 kg/m^3 (125 lb/ft^3). 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 100 years. Seventy-five percent of the bricks are assumed to be recycled after the 100 year use.

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, *2000 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 1999*, supplemented by industry interviews.

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[62] United States Environmental Protection Agency, *Clearinghouse for Inventories and Emission Factors,* Version 6.0, EPA 454/C-98-005, Emission Factor and Inventory Group, October 1998.

3.3.2 Stucco (B2011B)

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.

The detailed environmental performance data for stucco exterior walls may be viewed by opening the file B2011B.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 3.9.

Table 3.9 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 3.10.[63]

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

Production of sand, lime, and polyvinyl acetate is based on the Ecobalance database.

Energy Requirements. The energy requirements for masonry cement production are shown in Table 3.11.

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

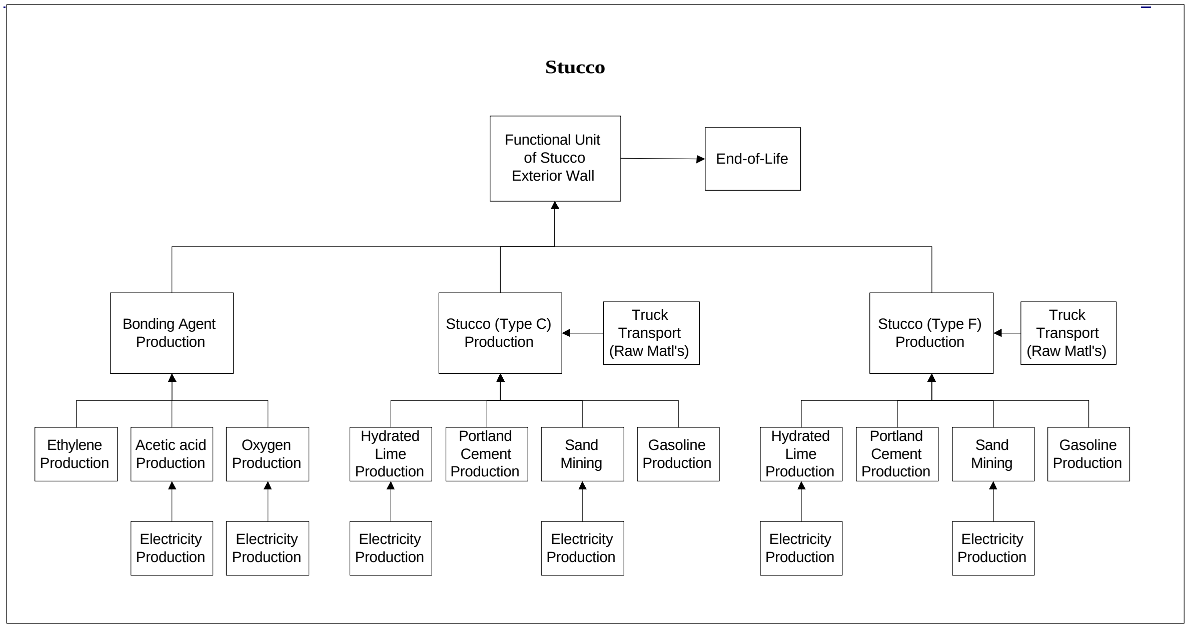

Figure 3.6 Stucco (Type C) Flow Chart

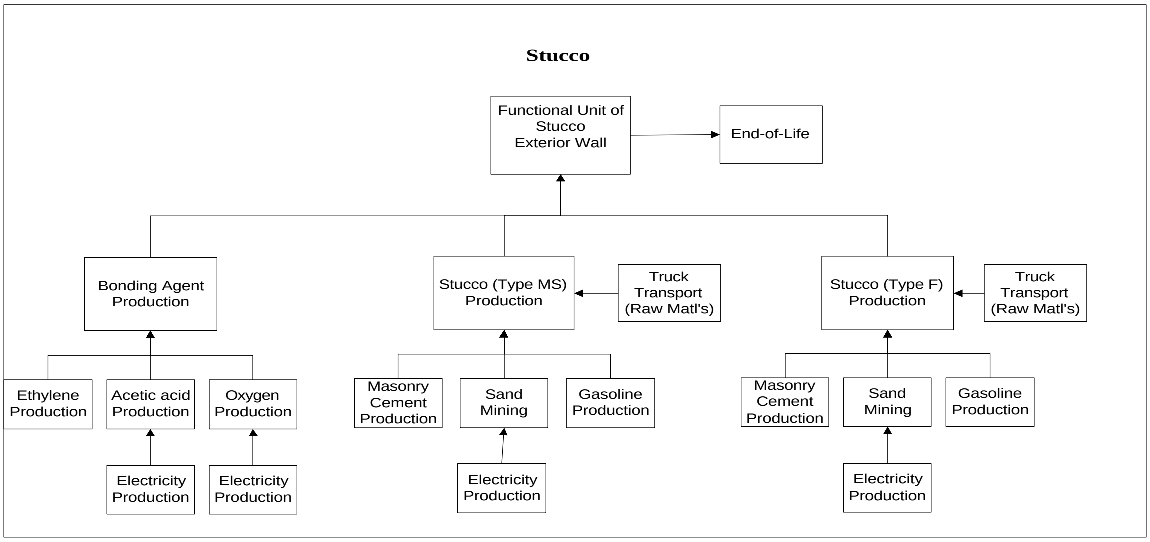

Figure 3.7 Stucco (Type MS) Flow Chart

Table 3.10 Stucco Constituents

	Cementitious Materials (parts by volume)			*Sand*
Type of Stucco	*Portland Cement*	*Masonry Cement*	*Lime*	*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

Table 3.11 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 an 5.9 kW (8 hp), gasoline powered mixer with a flow rate of 0.25 m^3 (9 ft^3) 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 cm (5/8 in) each. The densities of the different types of stucco are shown in Table 3.12.

Table 3.12 Density of Stucco by Type

Type of Stucco	Density kg/0.0283m^3 (lb/ ft^3)
Base Coat C	51.79 (114.18)
Finish Coat F	55.78 (122.97)
Base Coat MS	53.97 (118.98)
Finish Coat FMS	61.55 (135.69)

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, *2000 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 1999*, supplemented by industry interviews.

3.3.3 Aluminum Siding (B2011C)

Aluminum siding is a commonly-used exterior wall cladding. Aluminum siding is very attractive for its weight and durability, weighing less and lasting longer than traditional wood and vinyl siding. The manufacture of any aluminum product consists of many steps – crude oil production, distillation and desalting, hydrotreating of crude oil, salt mining, caustic soda manufacturing, limestone mining, lime manufacture, bauxite mining, alumina production, coal mining, coke production, aluminum smelting, and ingot casting. For the BEES system, 0.061 cm (0.024 in) thick, 20 cm (8 in) wide horizontal siding, is studied. The aluminum siding is assumed to be fastened with aluminum nails 41 cm (16 in) on center. The flow diagram in Figure 3.8 shows the major elements of aluminum siding production.

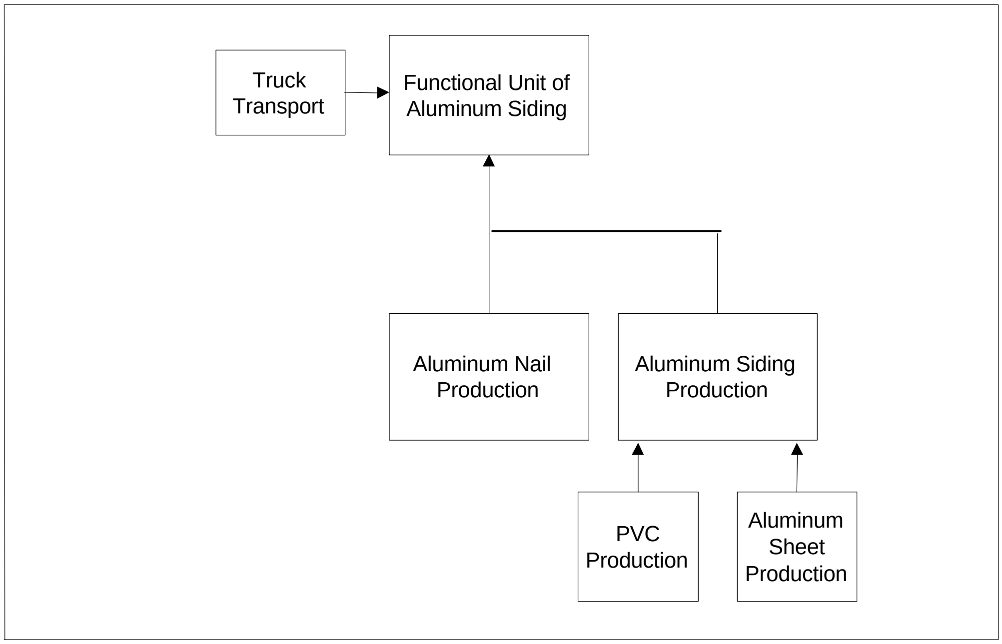

Figure 3.8 Aluminum Siding Flow Chart

Raw Materials. There are a number of aluminum siding products on the market, each with different proprietary ingredients. The product studied for the BEES system is manufactured as an aluminum sheet with a Polyvinyl Chloride (PVC) thermoset topcoat. Table 3.13 presents the major constituents of aluminum siding. Production requirements for these constituents are based on the Ecobalance LCA database.

Table 3.13 Aluminum Siding Constituents

Constituent	*Percent Weight %*
Aluminum Sheet	99
PVC Topcoat	1

Transportation. Transport of PVC from its production site to the aluminum siding manufacturing plant is taken into account. Transportation of manufactured aluminum siding by heavy-duty truck to the building site is modeled as a variable of the BEES system. Emissions associated with the combustion of fuel in the truck engines are included, as are the emissions associated with fuel production, both based on the Ecobalance LCA database.

Use. Installation waste with a mass fraction of 0.05 is assumed.

3.3.4 Cedar Siding (B2011D)

Cedar wood is ideal for exterior siding because it is a lightweight, low-density material that provides adequate weatherproofing. It also provides an attractive exterior wall finish. As with most wood products, cedar siding production consist of three major steps. First, roundwood is harvested from logging camps. Second, logs are sent to sawmills and planing mills where the logs are washed, debarked, and sawed into planks. The planks are edged, trimmed, and dried in a kiln. The dried planks are then planed and the lumber sent to a final trimming operation. Third, lumber from the sawmill is shaped into fabricated, milled wood products.

For the BEES system, beveled cedar siding 1.3 cm (½ in) thick and 15 cm (6 in) wide is studied. Cedar siding is assumed to be installed with galvanized nails 41 cm (16 in) on center and finished with one coat of primer and two coats of stain. Stain is reapplied every ten years. The flow diagram in Figure 3.9 shows the major elements of cedar siding production.

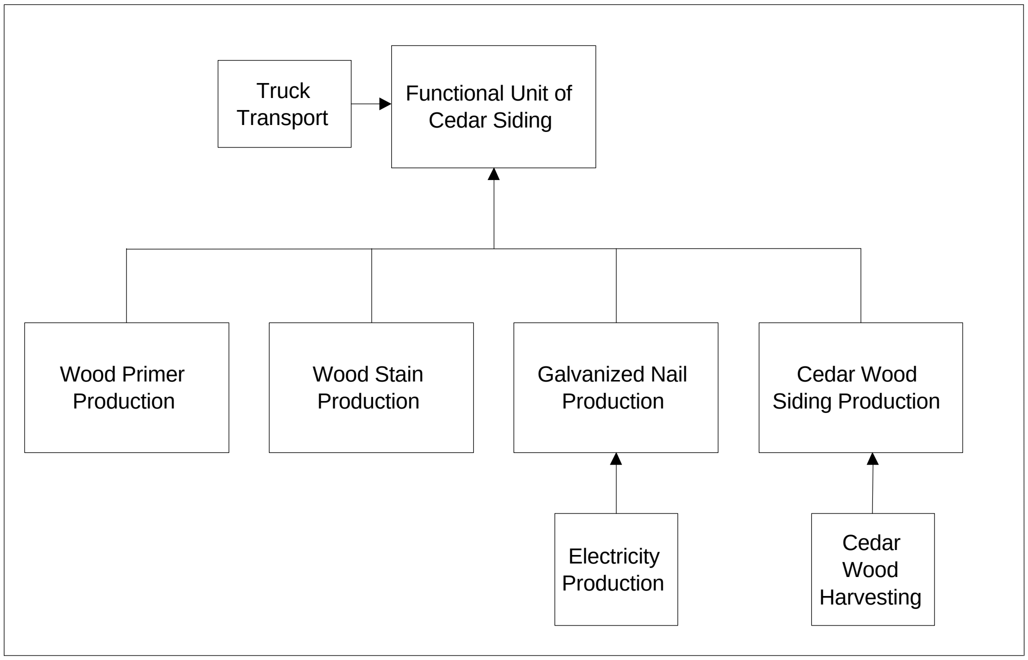

Figure 3.9 Cedar Siding Flow Chart

Raw Materials. Production data for cedar wood is derived from the Ecobalance LCA database.

Energy Requirements. The energy requirements for cedar siding manufacture are approximately

5.6 MJ/kg (2,413 Btu/lb) of cedar siding produced.[64] Table 3.14 shows the breakdown by fuel type. BEES data for production and combustion of the natural gas, heavy fuel oil, and liquid petroleum fuels used for cedar siding production are based on the Ecobalance database.

Table 3.14 Energy Requirements for Cedar Siding Manufacture

Fuel Use[65]	*Manufacturing Energy*
Total Fossil Fuel	5.6 MJ/kg (2,413 Btu/lb)
% Natural Gas	39.8
% Heavy Fuel Oil	4.1
% Liquid Petroleum Gas	4.1
% Hogfuel	52

Emissions. The hogfuel emissions from the cedar sawmill are listed in Table 3.15.

Table 3.15 Hogfuel Emissions[66]

Emission	*Amount g/MJ wood burned (oz/kWh)*
Carbon Dioxide (CO_2)	81.5 (10.35)
Carbon Monoxide (CO)	0.011 (0.0014)
Methane (CH_4)	0.008 (0.001)
Nitrogen Oxides (NO_X)	0.110 (0.014)
Sulfur Oxides (SO_X)	0.0002 (0.000025)
Volatile Organic Compounds (VOC)	0.039 (0.005)
Particulates	0.708 (0.09)

Transportation. Since sawmills are typically located close to the forested area, transportation of raw materials to the sawmill is not taken into account. Transport of primer and stain to the manufacturing plant is included. Transport of cedar siding by truck to the building site is modeled as a variable of BEES. Emissions associated with the combustion of fuel in the truck engine are included, as are the emissions associated with producing the fuel. Both sets of emissions data are based on the Ecobalance database.

Use. The density of cedar siding at 12 % moisture content is assumed to be 449 kg/ m^3 (28 lb/ ft^3). At installation, 5 % waste is assumed.

3.3.5 Vinyl Siding (B2011E)

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[64] *Building Materials in the Context of Sustainable Development – Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates for Structural Wood Products*, March 1993.

[65] Excluding electricity

[66] *Building Materials in the Context of Sustainable Development – Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates for Structural Wood Products*, op cit.

Vinyl siding is attractive for its low maintenance, and cost. Durability under exposure to a wide variety of weather conditions is another key attraction. Like all plastic materials, vinyl results from a series of processing steps that convert hydrocarbon-based raw materials (petroleum, natural gas, or coal) into polymers. The vinyl polymer is based in part on hydrocarbon feedstocks: ethylene obtained by processing natural gas or petroleum. The other part of the vinyl polymer is based on the natural element chlorine. Inherent in the vinyl manufacturing process is the ability to formulate products of virtually any color with any number of performance qualities--including ultraviolet light stabilization, impact resistance, and flexibility--in virtually any size, shape, or thickness.

Vinyl siding is manufactured in a wide variety of profiles, colors, and thickness' to meet different market applications. For the BEES system, 0.11 cm (0.0428 in) thick, 23 cm (9 in) wide horizontal vinyl siding installed with galvanized nail fasteners is studied. The fasteners are assumed to be placed 41 cm (16 in) on center. Figure 3.10 shows the major steps for vinyl siding production.

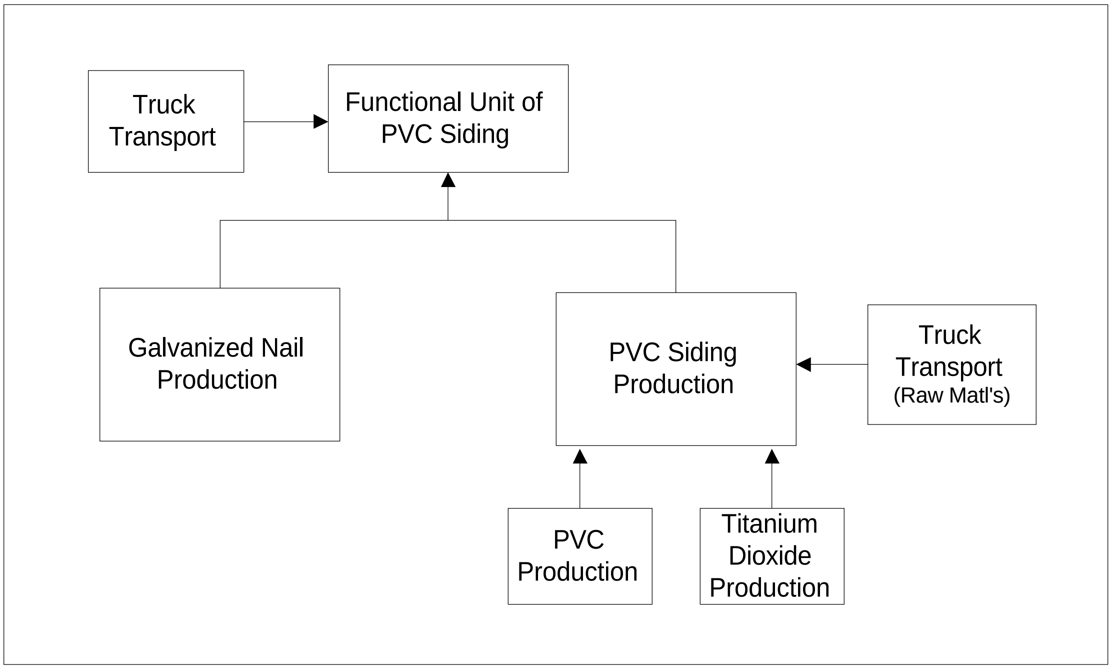

Figure 3.10 Vinyl Siding Flow Chart

Raw Materials. Polyvinyl chloride (PVC) is the main component in the manufacture of vinyl siding. Titanium dioxide (TiO_2) is a chemical additive that is used in the siding as a pigment or bleaching agent. Table 3.16 presents the proportions of PVC and titanium dioxide in the siding studied. Data representing the production of raw materials for vinyl siding are based on the Ecobalance database.

Table 3.16 Vinyl Siding Constituents

Constituent	*Percent by Weight (%)*
Polyvinyl Chloride (PVC)	80
Titanium Dioxide (TiO_2)	20

Transportation. Transportation of raw materials to the manufacturing plant is taken into account. Transportation of the manufactured siding to the building site by heavy-duty truck is modeled as a variable of BEES. Emissions associated with the combustion of fuel in the truck engine are included, as are emissions associated with fuel production. Emissions data are derived from the Ecobalance database.

Use. At installation, 5 % of the product is lost to waste.

3.4 Wall and Ceiling Insulation Alternatives (B2012, B3012)

3.4.1 Blown Cellulose Insulation (B2012A, B3012A)

Blown cellulose insulation is produced primarily from post-consumer wood pulp (newspapers), typically accounting for roughly 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 3.11 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 amount of cellulose insulation material used per functional unit is shown in Table 3.17, based on information from the Cellulose Insulation Manufacturers Association (CIMA).

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:

- B2012A.DBF—R-13 Blown Cellulose Wall Insulation
- B3012A.DBF—R-30 Blown Cellulose Ceiling Insulation
-

Transportation of Raw Materials to Manufacturing. Transport of raw materials to the manufacturing plant is taken into account, assuming truck transportation of 161 km (100 mi) for wastepaper and truck transportation of 322 km (200 mi) for both the ammonium sulfate and the boric acid. The tailpipe emissions from the trucks and the emissions from producing the fuel used in the trucks are based on the Ecobalance database.

Manufacturing. The constituents for cellulose insulation manufacture are based on information from CIMA, as shown in Table 3.18.

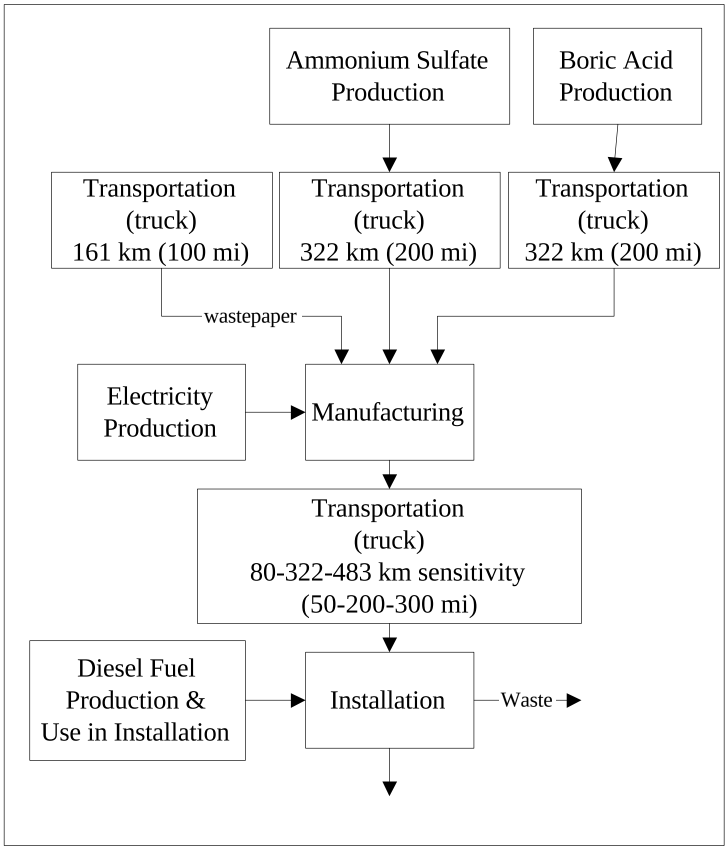

Figure 3.11 Blown Cellulose Insulation Flow Chart

Table 3.17 Blown Cellulose Mass by Application

Application	*Thickness cm (in)*	*Density kg/m^3 (lb/ft^3)*	*Mass per Functional Unit kg/m^2 (oz/ft^2)*
Wall (R-13)	8.9 (3.5)	25.6 (1.6)	2.26 (7.41)
Ceiling (R-30)	20.6 (8.1)	25.6 (1.6)	5.27 (17.28)

Table 3.18 Blown Cellulose Insulation Constituents

Constituent	*Input (kg/kg product)*	*In Final Product (%)*
Wastepaper	0.80	80
Ammonium Sulfate	0.155	15.5
Boric Acid	0.045	4.5
Total:	1.0	100

There are no wastes or water effluents from the manufacturing process. Manufacturing energy is assumed to come from purchased electricity. The amount of electricity used is based on CIMA data and a requirement of 0.35 MJ per kg (150 Btu per lb) of cellulose insulation produced. Electricity production emissions are based on the Ecobalance database and a standard U.S. electricity grid.

The only burdens for production of wastepaper are those associated with collection and transportation of wastepaper to the manufacturing facility.

Ammonium sulfate is assumed to be produced as a co-product of caprolactam production. The materials and energy used by the process are based on the Ecobalance database.

The boric acid used in the manufacture of cellulose insulation is assumed to be produced from borax. Production of boric acid is based on the Ecobalance database.

Transportation from Manufacturing to Use. Transport of cellulose insulation to the building site by truck is modeled as a variable of BEES, based on a range of likely distances (80 km, 322 km, and 483 km, or 50 mi, 200 mi, and 300 mi) provided by CIMA. Emissions associated with combustion of fuel in the truck engine are included as are the emissions associated with producing the fuel. Emissions data are derived from the Ecobalance database.

Since it is assumed that all three insulation materials studied (cellulose, fiberglass, and mineral wool) have similar packaging requirements, no packaging burdens are taken into account.

Installation. At installation, 5 % of the product is lost to waste. The energy required for blowing the insulation is included, assuming the insulation is blown at a rate of 1134 kg (2,500 lb) per hour using energy provided by a diesel truck. BEES accounts for emissions associated with burning diesel fuel in a reciprocating engine, as well as emissions associated with producing the diesel fuel.

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 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.[67] 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[68] and U.S. Department of Energy fuel price projections over the next 30 years[69] are used to compute the present value cost of operational energy per functional unit for each alternative R-value.

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,A0—R-13 Blown Cellulose Wall Insulation
- B3012,A0—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 USEECON.DBF. All other future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1999,* supplemented by industry interviews. First cost data are collected from the R.S. Means publication, 2000 *Building Construction Cost Data.*

3.4.2 Fiberglass Batt Insulation (B2012B, B2012C, B2012E, B3012B)

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 in Figure 3.12 shows the elements of fiberglass batt insulation production.

BEES performance data are provided for thermal resistance values of R-11, R-13, and R-15 for a wall application, and R-30 for a ceiling application. The amount of fiberglass insulation material used per functional unit is shown in Table 3.19. The detailed environmental performance data for this product may be viewed by opening the following files under the File/Open menu item in the BEES software:

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[67] 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.

[68] 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.

[69] 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.

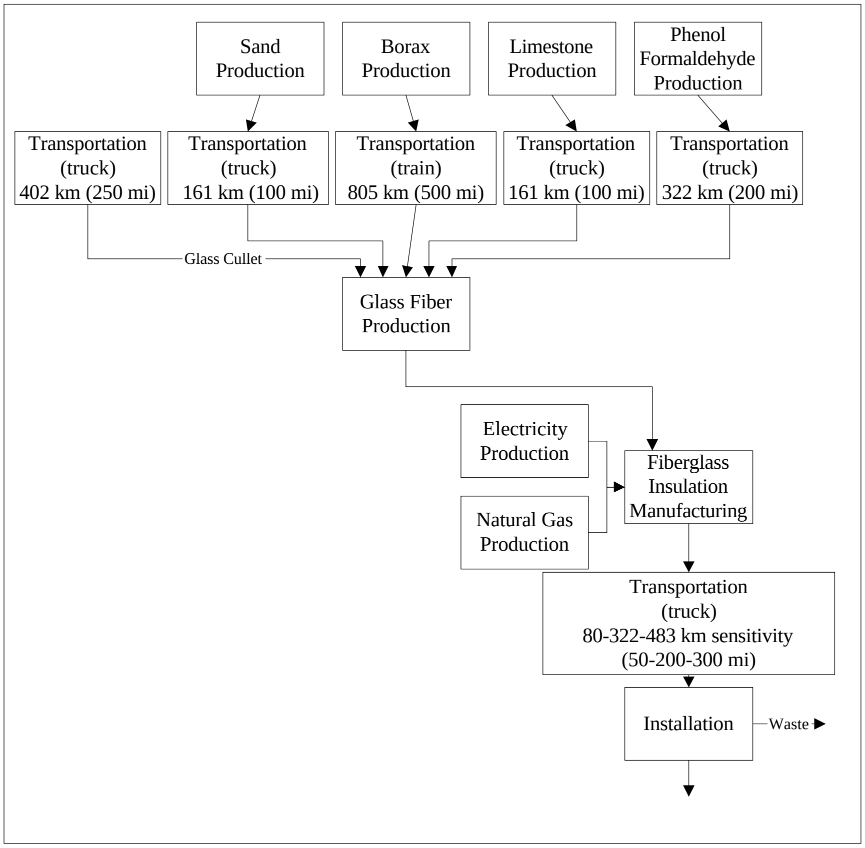

Figure 3.12 Fiberglass Batt Insulation Flow Chart

- B2012B.DBF—R-11 Fiberglass Batt Wall Insulation
- B2012E.DBF—R-13 Fiberglass Batt Wall Insulation
- B2012C.DBF—R-15 Fiberglass Batt Wall Insulation
- B3012B.DBF—R-30 Fiberglass Batt Ceiling Insulation

Table 3.19 Fiberglass Batt Mass by Application

Application	***Thickness cm (in)***	***Density kg/m^3 (lb/ft^3)***	***Mass per Functional Unit kg/m^2 (oz/ft^2)***
Wall--R-11	8.9 (3.5)	8.0 (0.5)	0.71 (2.33)
Wall--R-13	8.9 (3.5)	12.8 (0.8)	1.18 (3.88)
Wall--R-15	8.9 (3.5)	24.0 (1.5)	2.15 (7.05)
Ceiling--R-30	22.9 (9.0)	8.0 (0.5)	1.83 (6.0)

Raw Materials. Fiberglass batts are composed of the materials listed in Table 3.20. Production requirements for these materials are based on the Ecobalance LCA database.

Table 3.20 Fiberglass Batt Constituents

Constituent	***Physical Weight (%)***
Borax	6.9
Glass Cullet	6.2
Limestone	50
Phenol Formaldehyde	5.9
Sand	31

Fiberglass batt production involves the energy requirements as listed in Table 3.21.

Table 3.21 Energy Requirements for Fiberglass Batt Insulation Manufacturing

Fuel Use	***Manufacturing Energy***
Electricity	0.13 MJ/kg fiberglass (56 Btu/lb)
Natural Gas	6 MJ/kg fiberglass (2,580 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 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.[70] 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[71] and U.S. Department of

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[70] 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.

[71] 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.

Energy fuel price projections over the next 30 years[72] are used to compute the present value cost of operational energy per functional unit for each R-value.

When installing fiberglass batt insulation, approximately 2 % 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,B0—R-11 Fiberglass Batt Wall Insulation
- B2012,E0—R-13 Fiberglass Batt Wall Insulation
- B2012,C0—R-15 Fiberglass Batt Wall Insulation
- B3012,B0—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 USEECON.DBF. All other future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1999*, supplemented by industry interviews. First cost data are collected from the R.S. Means publication, *2000 Building Construction Cost Data.*

3.4.3 Blown Fiberglass Insulation (B3012D)

Blown fiberglass insulation is made by forming spun-glass fibers using the same method as for batts but leaving the insulation loose. 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

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The flow diagram in Figure 3.13 shows the elements of blown fiberglass insulation production.
BEES performance data are provided for a thermal resistance value of R-30 for a ceiling application. The amount of fiberglass insulation material used per functional unit is shown in Table 3.22. The detailed environmental performance data for blown fiberglass insulation may be viewed by opening the file B3012D.DBF under the File/Open menu item in the BEES software.

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[72] 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.

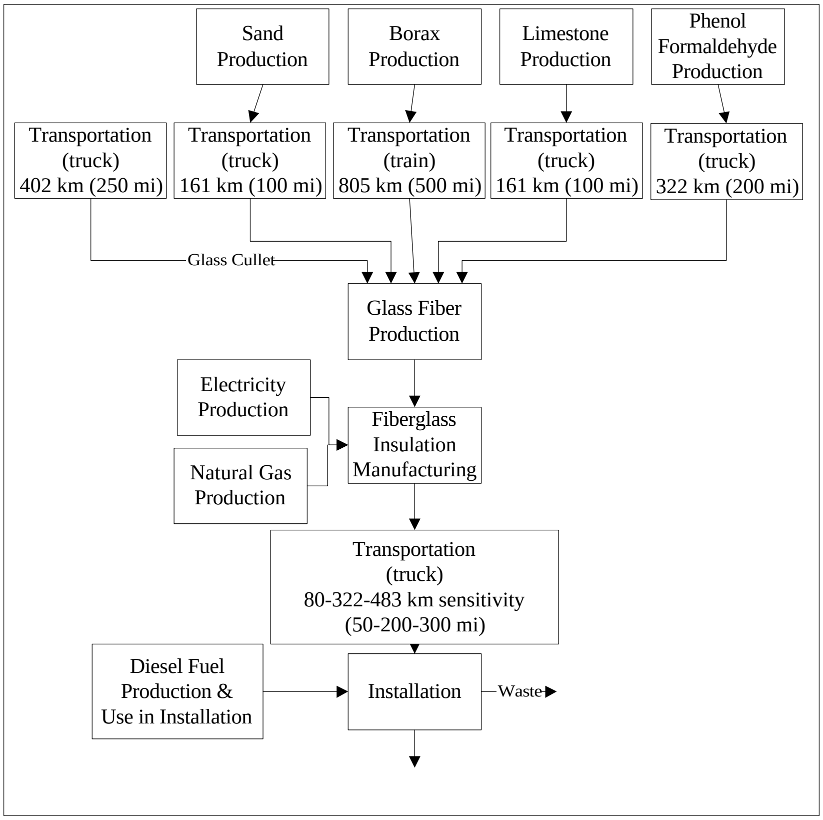

Figure 3.13 Blown Fiberglass Insulation Flow Chart

Table 3.22 Blown Fiberglass Mass

Application	*Thickness cm (in)*	*Density kg/m^3 (lb/ft^3)*	*Mass per Functional Unit kg/m^2 (oz/ft^2)*
Ceiling (R-30)	22.9 (9.0)	12.0 (0.75)	2.8 (9.17)

Raw Materials. Blown fiberglass is composed of the materials listed in Table 3.23.

Table 3.23 Blown Fiberglass Constituents

Constituent	*Physical Weight (%)*
Borax	6.9
Glass Cullet	6.2
Limestone	50
Phenol Formaldehyde	5.9
Sand	31

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

Fiberglass production involves the energy requirements as listed in Table 3.24.

Table 3.24 Energy Requirements for Fiberglass Insulation Manufacturing

Fuel Use	*Manufacturing Energy*
Electricity	0.13 MJ/kg fiberglass (56 Btu/lb)
Natural Gas	6 MJ/kg fiberglass (2,580 Btu/lb)

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

Use. It is important to recognize 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. However, since alternatives for ceiling insulation all have R-30 R-values, there are no thermal performance differences for this application.

When installing blown fiberglass 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. Energy for blowing the insulation is included, based on a 18 kW (25 hp) diesel engine blowing 1134 kg (2,500 lb) of fiberglass insulation per hour.

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 B3012,D0. 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). All other future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1999*, supplemented by industry interviews. First cost data are collected from the R.S. Means publication, *2000 Building Construction Cost Data.*

3.4.4 Blown Mineral Wool Insulation (B2012D, B3012C)

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 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 3.14 shows the elements of blown mineral wool insulation production**.**

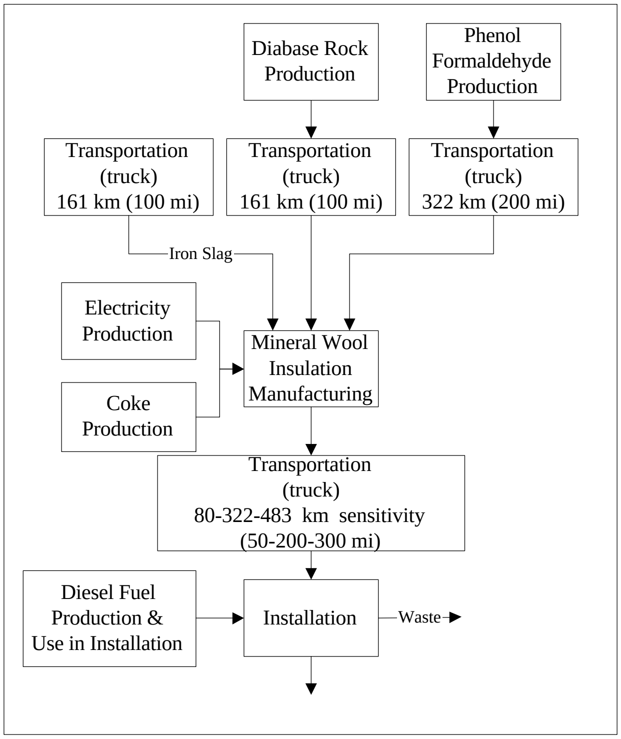

Figure 3.14 Blown Mineral Wool Insulation Flow Chart

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:

- B2012D.DBF—R-12 Blown Mineral Wool Wall Insulation
- B3012C.DBF—R-30 Blown Mineral Wool Ceiling Insulation

Raw Materials. Mineral wool insulation is composed of the materials listed in Table 3.25. Production requirements for the mineral wool constituents are based on the Ecobalance LCA database.

Table 3.25 Blown Mineral Wool Constituents

Mineral Wool Constituents	*Physical Weight (%)*
Phenol Formaldehyde	2.5
Iron-ore slag (North American)	78
Diabase/basalt	20

Mineral wool production involves the energy requirements listed in Table 3.26.

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

Table 3.26 Energy Requirements for Mineral Wool Insulation Manufacturing

Fuel Use	***Manufacturing Energy***
Electricity	1.0 MJ/kg (430 Btu/lb)
Coke	6.38 MJ/kg (2,743 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 R-values, thermal performance differences are at issue only for 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.[73] 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[74] and U.S. Department of Energy fuel price projections over the next 30 years[75] 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 kg/h (2,500 lb/h) with a 25 horsepower diesel engine. During installation, 5 % of the product is lost to waste.

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,D0—R-12 Blown Mineral Wool Wall Insulation
- B3012,C0—R-30 Blown 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,

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[73] 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.

[74] 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.

[75] 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 escalation factor is assumed to hold for years 31-50.

maintenance, and repair). Operational energy costs for wall insulation (discussed above under "Use") are found in the file USEECON.DBF. All other future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1999*, supplemented by industry interviews. First cost data are collected from the R.S. Means publication, *2000 Building Construction Cost Data.*

3.5 Framing Alternatives (B2013)

3.5.1 Steel Framing (B2013A)

Steel is an important construction framing material. Steel is made from iron, which in turn is made from iron ore, coal, and limestone in the presence of oxygen. The steel-making process includes the processing of iron ore, coal, and limestone prior to a blast furnace operation, which makes the raw material, iron. Other materials used in steel manufacturing processes include nickel, manganese, chromium, and zinc, as well as various lubricating oils, cleaning solvents, acids, and alkalines.

Cold-formed steel framing is manufactured from blanks sheared from sheets that are cut from coils or plates, or by roll-forming cold or hot-rolled coils or sheets. Both these forming operations are done at ambient temperatures. Light-gauge steel shapes are formed from flat-rolled 12- to 20-gauge carbon steel as either single bent shapes or bent shapes welded together. Two basic types of steel framing, nailable and nonnailable, are available in both punched and solid forms. Zinc chromate primer, galvanized, and painted finishes are available. Steel stud and joist systems have been adopted as an alternative to wood and masonry systems in most types of construction. Steel framing is also used extensively for interior partitions because it is fire-resistant, easy to erect, and makes installation of utilities more convenient. Light-gauge steel framing can be installed directly at the construction site or it can be prefabricated off- or on-site. The assembly process relies on a number of accessories usually made of steel, such as bridging, bolts, nuts, screws, and anchors, as well as devices for fastening units together, such as clips and nails.

In recent years, structural steel has increasingly been used for framing systems due to its fire resistance and high strength-to-weight ratio. For the BEES system, 18-gauge (1.1 mm, or 0.0428 in thick) steel studs and tracks are evaluated. Tracks are sized to fit the studs. Self-tapping steel screws, used as fasteners for the steel studs, are included. Figure 3.15 shows the elements of steel framing production. The detailed environmental performance data for this product may be viewed by opening the file B2013A.DBF under the File/Open menu item in the BEES software:

Raw Materials. Production of the raw materials necessary for steel stud manufacture is based on data from the American Iron and Steel Institute (AISI). Four North American steel companies provided primary data for the production of hot-rolled coil, while data for cold-rolled steel and

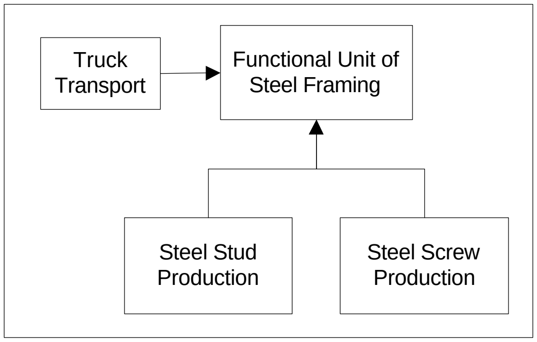

Figure 3.15 Steel Framing Flow Chart

hot dip galvanized steel came from three sites. Further primary data was collected for some upstream processes, such as iron ore mining and lime production. Secondary data were obtained from LCA databases and literature. The steel is assumed to be made of steel produced from the Basic Oxygen Furnace (BOF) process, which includes roughly 20 % recycled material.

Fasteners are produced largely from recycled material, and are produced primarily in Electric Arc Furnaces (EAF). European data are used for the production of steel fasteners[76].

Energy Requirements. Energy requirements for producing steel are based on the European data source listed above, combined with upstream U.S. energy production models in the Ecobalance LCA database.

Emissions. Emissions for steel stud and self-tapping screw production are based on the Ecobalance LCA database.

Transportation. Transport of steel raw materials to the manufacturing plant is included. Transport of steel framing by heavy-duty truck to the building site is a variable of the BEES model. Emissions associated with the combustion of fuel in the truck engine and with production of the fuel are included, based on the Ecobalance database.

Use. Use of steel framing for exterior walls without a thermal break such as rigid foam may increase thermal insulation requirements or otherwise adversely affect building thermal performance. While this interdependency of building elements is not accounted for in BEES 2.0, it will be considered in the future as the BEES system moves beyond building products to building systems and components.

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 *B2013*, product code *A0*. 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, *2000 Building Construction Cost Data*, and future cost data are

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[76] Swiss Federal Office of Environment, Forests and Landscape (FOEFL or BUWAL), *Environmental Series No. 250.*

based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1999*, supplemented by industry interviews.

3.5.2 Wood Framing (B2013B)

Wood framing is the most common structural system used for non-load-bearing and load-bearing interior walls, and includes lumber, constructed truss products, and specific applications of treated lumber. Floor framing consists of a system of sills, girders, subflooring, and joists or floor trusses that provide support for floor loads and walls. There are two types of interior partitions: bearing partitions, which support floors, ceilings, or roofs, and nonbearing partitions, which carry only their own weight. The sole plate and the top plate frame the wall structure of vertical studs, and sheathing or diagonal bracing ensures lateral stability. In general, dimensions for framing lumber are given in nominal inches (i.e., 2 x 4 x 6). Framing lumber must be properly grade-marked to be acceptable under the major building codes. Such grade marks identify the grade, species or species group, seasoning condition at time of manufacture, producing mill, and the grading rules-writing agency.

Wood studs are produced in a sawmill, where harvested wood is debarked and sawn into specific dimensions. The lumber is then dried in a controlled environment until the desired moisture content (between 12 % and 19 %) is reached. It is possible to treat framing lumber with preservatives in order to guard against insect attack, or to shield against surface moisture which might cause fungal decay.

The functional unit of comparison for BEES framing alternatives is 1 ft^2 of load bearing wall framing for 50 years. Preservative-treated pine wood studs, 5.08 cm x 10.16 cm (2 in x 4 in), with a moisture content of 12 % are studied. The preservative is assumed to be Type C Chromated Copper Arsenate (CCA), a common water-borne preservative used in the treatment of wood products. Galvanized nails used to fasten the studs together to form the wall framing are also studied. The flow diagram shown in Figure 3.16 shows the major elements of wood stud production. The detailed environmental performance data for this product may be viewed by opening the file B2013B.DBF under the File/Open menu item in the BEES software.

Raw Materials. For BEES, data were collected for the harvested trees used to produce the lumber necessary for framing load-bearing walls. Production of the other raw materials--steel for nails and chromated copper arsenate for preservative--is based on data from the Ecobalance LCA database.

Energy Requirements. The energy requirements for lumber manufacture are shown in Table 3.27. The energy is assumed to come primarily from burning wood waste. Other fuel sources, including natural gas and petroleum, are also used.

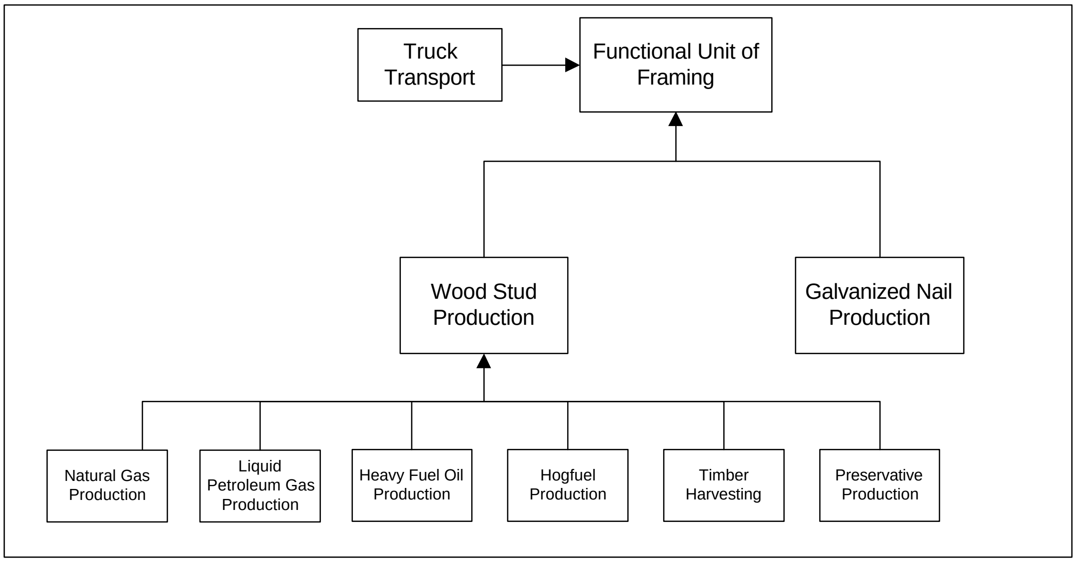

Figure 3.16 Wood Framing Flow Chart

Table 3.27 Energy Requirements for Lumber Manufacture[77]

Fuel Use[a]	***Manufacturing Energy MJ/kg (Btu/lb)***
Total Fossil Fuel	5.6 (2,413)
% Natural Gas	39.8
% Heavy Fuel Oil	4.1
% Liquid Petroleum Gas	4.1
% Hogfuel	52

[a]Excluding electricity

Emissions. The emissions from the lumber manufacturing process are shown in Table 3.28.

Table 3.28 Hogfuel Emissions[78]

Emission	***Amount g/MJ Wood burned (oz/kWh)***
Carbon Dioxide (CO_2)	81.5 (10.35)
Carbon Monoxide (CO)	0.011 (0.0014)
Methane (CH_4)	0.008 (0.001)
Nitrogen Oxides (NO_X)	0.110 (0.014)
Sulfur Oxides (SO_X)	0.0002 (0.000025)
Volatile Organic Compounds (VOC)	0.039 (0.005)
Particulates	0.708 (0.09)

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[77] 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.

[78] Forintek Canada Corporation, *op cit.*

Transportation. Since sawmills are often located close to tree harvesting areas, the transportation of lumber to the sawmill is not taken into account. However, truck transportation of 322 km (200 mi) is assumed for the preservative. The tailpipe emissions from the truck engine and the emissions that result from the production of the fuel used in the truck are taken into account based on the Ecobalance database. Transportation of framing lumber by heavy-duty truck to the construction site is a variable of the BEES model.

Use. The density of pine at 12 % moisture content (seasoned wood) is assumed to be 449 kg/m^3 (28 lb/ft^3). Retention of CCA in lumber is assumed to be 6.4 kg/m^3 (0.40 lb/ft^3). It is assumed that wood studs are placed 41 cm (16 in) on center and are fastened with galvanized steel nails. At installation, 5 % of the product is lost to waste.

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 *B2013*, product code *B0*. 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, *2000 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 1999*, supplemented by industry interviews.

3.6 Roof Covering Alternatives (B3011)

3.6.1 Asphalt Shingles (B3011A)

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 asphalt shingles with a 20 year life, roofing felt, and galvanized nails is analyzed. The flow diagram shown in Figure 3.17 shows the elements of asphalt shingle production**.** The detailed environmental performance data for this product may be viewed by opening the file B3011A.DBF under the File/Open menu item in the BEES software.

Filler is assumed to be 50 % dolomite and 50 % 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 kg (fifteen lb) felt consists of asphalt and organic felt as listed in Table 3.30. The organic felt is assumed to consist of 50 % recycled cardboard and 50 % 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

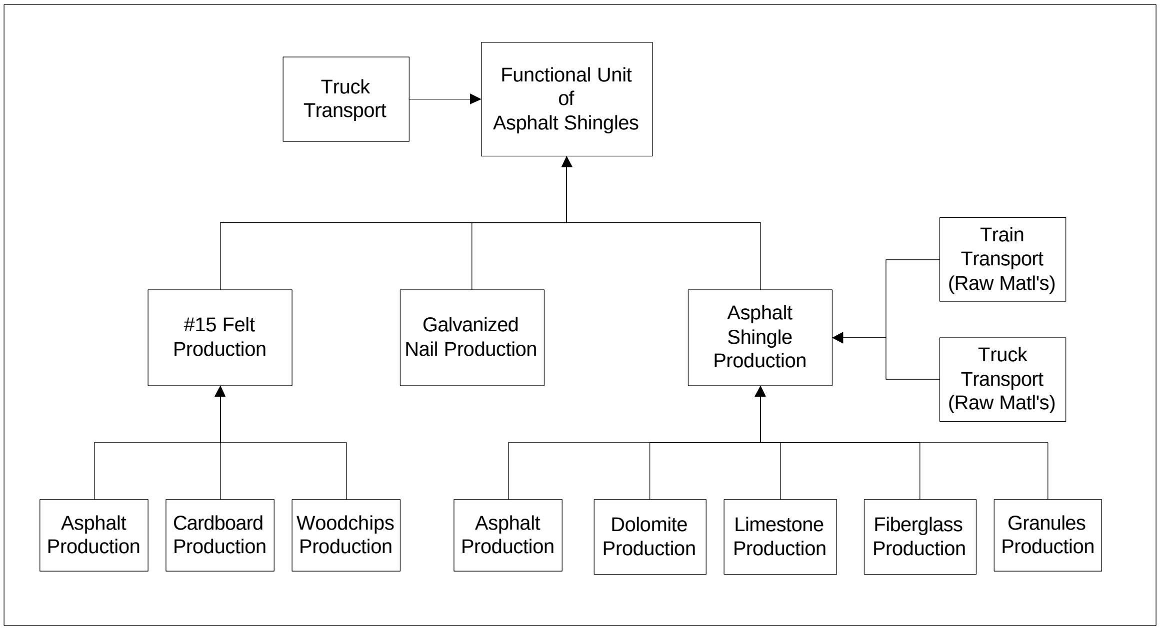

Figure 3.17 Asphalt Shingles Flow Chart

33 MJ/m^2 of natural gas (2,843 Btu/ft^2) of shingles.

Raw Materials. Asphalt shingles are composed of the materials listed in Table 3.29.

Table 3.29 Asphalt Shingle Constituents

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

Table 3.30 Seven Kg (15 lb) Roofing Felt Constituents

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

Emissions. Emissions associated with manufacturing asphalt shingles and roofing felt are taken into account based on AP-42 data for asphalt shingle 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. It is important to consider solar reflectivity differences among roof coverings of different materials and colors when assessing the environmental and economic performance of roof covering alternatives. "Cool" roofs reflect and emit solar radiation well, and thus stay cooler in the sun than less reflective, less emissive materials. The cool temperature results in building-scale cooling energy savings ranging from 2 % to 60 %.[79] A much less significant rise in building heating energy costs also occurs. BEES accounts for solar reflectivity performance in computing energy-related LCA inventory flows and building energy costs over the 50 year use stage for roof covering products.

For roof coverings, thermal performance differences are separately assessed for 16 U.S. cities spread across a range of Sunbelt climate and fuel cost zones. When selecting roof covering alternatives for use in Sunbelt climates,[80] the BEES user chooses 1) the roof covering material and color, 2) the U.S. Sunbelt climate city closest to the building location, 3) the building type (new or existing), 4) its heating and cooling system (electric air-source heat pump or gas furnace/central air conditioning heating and cooling systems), and 5) its duct placement (uninsulated attic ducts or ducts in the conditioned space), so that thermal performance differences may be customized to these important contributors to building energy use. Energy use data provided to the National Institute of Standards and Technology by Lawrence Berkeley National Laboratory (and which LBL developed for the U.S. EPA Energy Star Roof Products program), tailored to these five parameters, are used to estimate 50 year heating and cooling requirements per functional unit of roof covering.[81] BEES environmental performance results account for the energy-related inventory flows resulting from these energy requirements (stored in USEFLOWS.DBF), and BEES economic performance results account for the present value cost resulting from these energy requirements (stored in USEECON.DBF).

Asphalt shingle and roofing felt installation is assumed to require 47 nails/ m^2 (440 nails/square). Installation waste from scrap is estimated at 5 % 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.

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[79] Memorandum from Sarah Bretz/Lawrence Berkeley National Laboratory to Barbara Lippiatt/National Institute of Standards and Technology, 12/18/98.

[80] In cold climates, the amount of roof insulation is more important to thermal performance than the color of the roof covering.

[81] LBL data were developed for BEES by LBL's Sarah Bretz, based on Konopacki and Akbari, *Simulated Impact of Roof Surface Solar Absorptance, Attic, and Duct Insulation on Cooling and Heating Energy Use in Single-Family New Residential Buildings*, LBNL-41834, Lawrence Berkeley National Laboratory, Berkeley, CA, 1998, and on Parker *et al*., "Measured and Simulated Performance of Reflective Roofing Systems in Residential *ASHRAE Transactions*, SF-98-6-2, Vol. 104, 1998, p. 1.

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 *A0*. 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 roof coverings in U.S. Sunbelt climates (discussed above under "Use") are found in the file USEECON.DBF. First cost data are collected from the R.S. Means publication, 2000 *Building Construction Cost Data*, and other future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1999*, supplemented by industry interviews.

3.6.2 Clay Tile (B3011B)

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 the weight of the tile and its relatively long useful life, 14 kg (30 lb) felt and copper nails are used. The flow diagram shown in Figure 3.18 shows the elements of clay tile production. The detailed environmental performance data for this product may be viewed by opening the file B3011B.DBF under the File/Open menu item in the BEES software.

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

Fourteen kg (30 lb) felt consists of asphalt and organic felt as listed in Table 3.31. The organic felt is assumed to consist of 50 % recycled cardboard and 50 % wood chips. The production of these materials, and the asphalt, is based on the Ecobalance LCA database.

Table 3.31 Fourteen Kg (30 lb) Roofing Felt Constituents

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

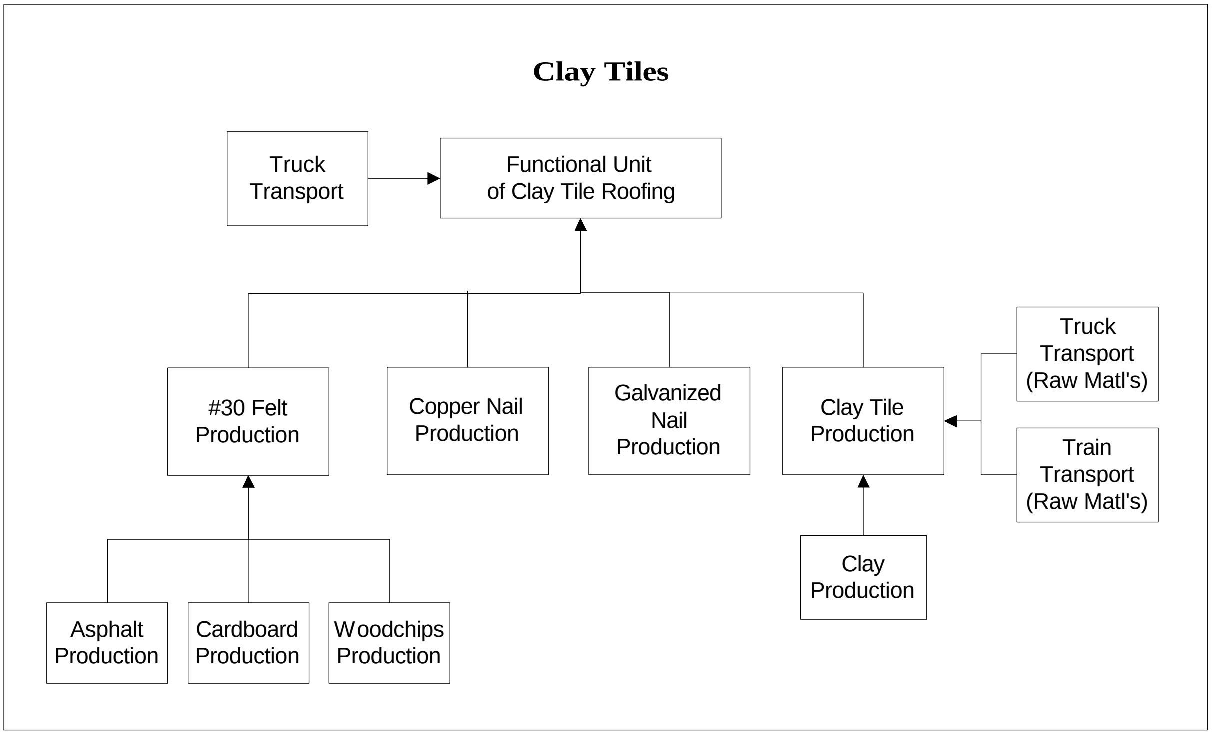

Figure 3.18 Clay Tile Flow Chart

Energy Requirements. The energy required to fire clay tile is 6.3 MJ per kg (2,708 Btu per lb) 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. It is important to consider solar reflectivity differences among roof coverings of different materials and colors when assessing the environmental and economic performance of roof covering alternatives. “Cool” roofs reflect and emit solar radiation well, and thus stay cooler in the sun than less reflective, less emissive materials. The cool temperature results in building-scale cooling energy savings ranging from 2 % to 60 %.[82] A much less significant rise in building heating energy costs also occurs. BEES accounts for solar reflectivity performance in computing energy-related LCA inventory flows and building energy costs over the 50 year use stage for roof covering products.

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[82] Memorandum from Sarah Bretz/Lawrence Berkeley National Laboratory to Barbara Lippiatt/National Institute of Standards and Technology, 12/18/98.

For roof coverings, thermal performance differences are separately assessed for 16 U.S. cities spread across a range of Sunbelt climate and fuel cost zones. When selecting roof covering alternatives for use in Sunbelt climates,[83] the BEES user chooses 1) the roof covering material and color, 2) the U.S. Sunbelt climate city closest to the building location, 3) the building type (new or existing), 4) its heating and cooling system (electric air-source heat pump or gas furnace/central air conditioning heating and cooling systems), and 5) its duct placement (uninsulated attic ducts or ducts in the conditioned space), so that thermal performance differences may be customized to these important contributors to building energy use. Energy use data provided to the National Institute of Standards and Technology by Lawrence Berkeley National Laboratory (and which LBL developed for the U.S. EPA Energy Star Roof Products program), tailored to these five parameters, are used to estimate 50 year heating and cooling requirements per functional unit of roof covering.[84] BEES environmental performance results account for the energy-related inventory flows resulting from these energy requirements (stored in USEFLOWS.DBF), and BEES economic performance results account for the present value cost resulting from these energy requirements (stored in USEECON.DBF).

Clay tile roofing is assumed to require two layers of 14 kg (30 lb) roofing felt, 13 galvanized nails/m^2 (120/square) for underlayment, and 37 copper nails/m^2 (342/square) for the tile (2 copper nails/tile). Installation waste from scrap is estimated at 5 % 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 *B0*. 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 roof coverings in U.S. Sunbelt climates (discussed above under “Use”) are found in the file USEECON.DBF. First cost data are collected from the R.S. Means publication, 2000 *Building Construction Cost Data*, and other future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1999*, supplemented by industry interviews.

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[83] In cold climates, the amount of roof insulation is more important to thermal performance than the color of the roof covering.

[84] LBL data were developed for BEES by LBL’s Sarah Bretz, based on Konopacki and Akbari, *Simulated Impact of Roof Surface Solar Absorptance, Attic, and Duct Insulation on Cooling and Heating Energy Use in Single-Family New Residential Buildings*, LBNL-41834, Lawrence Berkeley National Laboratory, Berkeley, CA, 1998, and on Parker *et al*., “Measured and Simulated Performance of Reflective Roofing Systems in Residential *ASHRAE Transactions*, SF-98-6-2, Vol. 104, 1998, p. 1.

3.6.3 Fiber Cement Shingles (B3011C)

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 3.19 shows the elements of fiber cement shingle production**.** The detailed environmental performance data for this product may be viewed by opening the file B3011C.DBF under the File/Open menu item in the BEES software.

Raw Materials. Fiber cement shingles are composed of the materials listed in Table 3.32. The filler is sand, and the organic fiber is wood chips. The weight of fiber cement shingles is assumed to be 16 kg/m^2 (325 lb/square), based on 36 cm x 76 cm x 0.4 cm (14 in x 30 in x 5/32 in) size shingles.

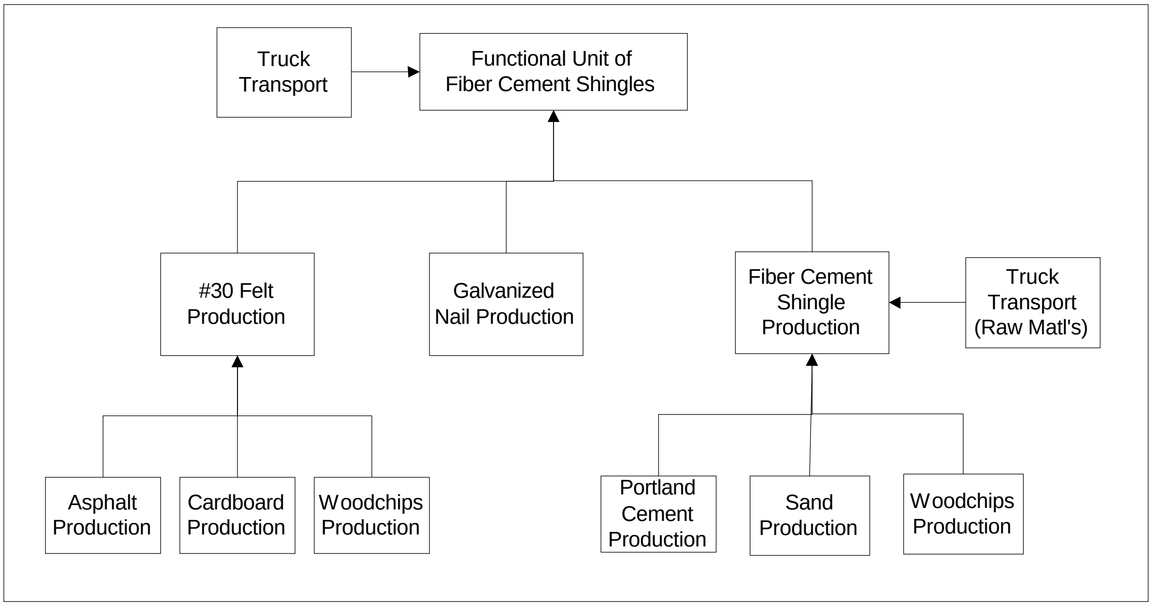

Figure 3.19 Fiber Cement Shingles Flow Chart

Table 3.32 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 a stucco exterior wall finish. Fourteen kg (30 lb) 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/m^2 of natural gas and 11 MJ/m^2 of electricity (2843 Btu/ft^2 of natural gas and 948 Btu/ft^2 of electricity) 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. It is important to consider solar reflectivity differences among roof coverings of different materials and colors when assessing the environmental and economic performance of roof covering alternatives. "Cool" roofs reflect and emit solar radiation well, and thus stay cooler in the sun than less reflective, less emissive materials. The cool temperature results in building-scale cooling energy savings ranging from 2 % to 60 %.[85] A much less significant rise in building heating energy costs also occurs. BEES accounts for solar reflectivity performance in computing energy-related LCA inventory flows and building energy costs over the 50 year use stage for roof covering products.

For roof coverings, thermal performance differences are separately assessed for 16 U.S. cities spread across a range of Sunbelt climate and fuel cost zones. When selecting roof covering alternatives for use in Sunbelt climates, [86] the BEES user chooses 1) the roof covering material and color, 2) the U.S. Sunbelt climate city closest to the building location, 3) the building type (new or existing), 4) its heating and cooling system (electric air-source heat pump or gas furnace/central air conditioning heating and cooling systems), and 5) its duct placement (uninsulated attic ducts or ducts in the conditioned space), so that thermal performance differences may be customized to these important contributors to building energy use. Energy use data provided to the National Institute of Standards and Technology by Lawrence Berkeley National Laboratory (and which LBL developed for the U.S. EPA Energy Star Roof Products program), tailored to these five parameters, are used to estimate 50 year heating and cooling requirements per functional unit of roof covering.[87] BEES environmental performance results account for the energy-related inventory flows resulting from these energy requirements (stored in USEFLOWS.DBF), and BEES economic performance results account for the present value cost resulting from these energy requirements (stored in USEECON.DBF).

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[85] Memorandum from Sarah Bretz/Lawrence Berkeley National Laboratory to Barbara Lippiatt/National Institute of Standards and Technology, 12/18/98.

[86] In cold climates, the amount of roof insulation is more important to thermal performance than the color of the roof covering.

[87] LBL data were developed for BEES by LBL's Sarah Bretz, based on Konopacki and Akbari, *Simulated Impact of Roof Surface Solar Absorptance, Attic, and Duct Insulation on Cooling and Heating Energy Use in Single-Family New Residential Buildings*, LBNL-41834, Lawrence Berkeley National Laboratory, Berkeley, CA, 1998, and on Parker *et al*., "Measured and Simulated Performance of Reflective Roofing Systems in Residential *ASHRAE Transactions*, SF-98-6-2, Vol. 104, 1998, p. 1.

Fiber cement shingle roofing requires one layer of 14 kg (30 lb) felt underlayment, 13 nails/m^2 (120 nails/square) for the underlayment, and 32 nails/m^2 (300 nails/square) for the shingles. Installation waste from scrap is estimated at 5 % 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 *C0*. 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 roof coverings in U.S. Sunbelt climates (discussed above under "Use") are found in the file USEECON.DBF. First cost data are collected from the R.S. Means publication, 2000 *Building Construction Cost Data*, and other future cost data are based on data published by Whitestone Research in *The Whitestone Building Maintenance and Repair Cost Reference 1999*, supplemented by industry interviews.

3.7 Interior Finishes (C3012)

3.7.1 Paints – General Information

Conventional paints are generally classified into two basic categories: water-based (in which the solvent is water) and oil-based (in which the solvent is an organic liquid, usually derived from petrochemicals). Oil-based paints are sometimes referred to as solvent-based. Paints essentially consist of a resin or binder, pigments, and a carrier in which these are dissolved or suspended. Once the paint is applied to a surface, the carrier evaporates, leaving behind a solid coating. In oil-based paints the carrier is a solvent consisting of volatile organic compounds (VOCs), which can adversely affect indoor air quality and the environment. As a result, government regulations and consumer demand are forcing continuing changes in paint formulations. These changes have led to formulations containing more paint solids and less solvent, and a shift away from oil-based paints to waterborne or latex paints.

Paint manufacture essentially consists of combining the ingredients, less some of the solvent, in a steel mixing vessel. In some cases the mixing is followed by a grinding operation to break up the dry ingredients, which tend to clump during mixing. Finally, additional solvents or other liquids are added to achieve final viscosity, and supplemental tinting is added. The paint is then strained, put into cans, and packaged for shipping.

Because they do not use solvents as the primary carrier, latex paints emit far fewer volatile organic compounds (VOCs) upon application. They also do not require solvents for cleaning of the tools and equipment. Water with a coalescing agent is the carrier for latex paints. The coalescing agent is typically a glycol or glycol ether. The binder is synthetic latex made from polyvinyl acetate and/or acrylic polymers and copolymers. Titanium dioxide is the primary pigment used to impart hiding properties in white or light-colored paints. A range of pigment extenders may be added. Other additives include surfactants, defoamers, preservatives, and fungicides.

BEES considers two latex-based paint alternatives, virgin latex paint and latex paint with a 35 % recycled content. The two alternatives are applied the same way. The surface to be painted is first primed and then painted with two coats of paint. One coat of paint is then applied every 4 years. The characteristics of both the paint and the primer are displayed in Table 3.33.

Table 3.33 Characteristics of BEES Paints and Primer

Characteristic	*Primer*	*Paint (recycled or virgin)*
Spread rate of the coat m^2/L (ft^2/gal)	7.4 (300)	8.6 (350)
Density of product kg/L (lb/gal)	1.26 (10.5)	1.28 (10.7)

3.7.2 Virgin Latex Interior Paint (C3012A)

Major virgin latex paint constituents are resins (binder), titanium dioxide (pigment), limestone (extender), and water (thinner), which are mixed together until they form an emulsion. Figure 3.20 displays the system under study for virgin latex paint.

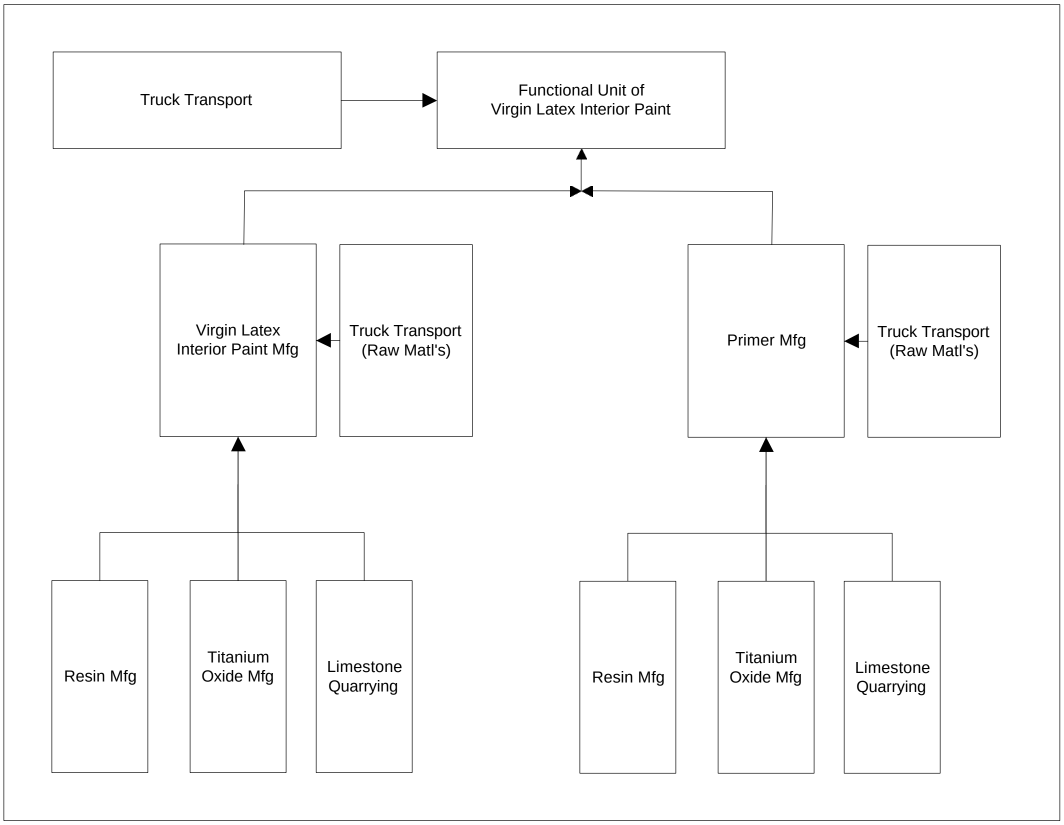

Figure 3.20 Virgin Latex Interior Paint Flow Chart

Raw Materials. The average composition of the virgin latex paint/primer system modeled in BEES is listed in Table 3.34.

Table 3.34 Virgin Latex Paint and Primer Constituents

Constituent	***Paint (Weight %)***	***Primer (Weight %)***
Resin	25	25
Titanium dioxide	12.5	7.5
Limestone	12.5	7.5
Water	50	60

Table 3.35 displays the market shares for the resins used for interior latex paint and primer.

Table 3.35 Market Shares of Resins

Resin type	***Market share (%)***
Vinyl Acrylic	40
Polyvinyl Acetate	40
Styrene Acrylic	20

Table 3.36 shows the components of the three types of resin as modeled in BEES. The production of the monomers used in the resins is based on the Ecobalance LCA database.

Table 3.36 Components of Paint Resins

Resin Type	***Components***
Vinyl Acrylic	Vinyl acetate (50 %) Butyl acrylate (50 %)
Polyvinyl Acetate	Vinyl acetate (100 %)
Styrene Acrylic	Styrene (50 %) Butyl acrylate (50 %)

Emissions. Emissions associated with paint manufacturing, such as particulates to the air, are based on AP-42 emission factors.

Transportation. Truck transportation of raw materials to the paint manufacturing site is assumed to average 402 km (250 mi) for titanium dioxide and limestone, and 80 km (50 mi) for the resins.

Use. Refer to Section 2.1.3, *Impact Assessment*, for a discussion of indoor air quality scoring for paints.

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 C3012, product code A0. 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, *2000 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 1999*, supplemented by industry interviews.

3.7.3 Recycled Latex Interior Paint (C3012B)

Figure 3.21 displays the BEES flow chart for recycled latex paint.

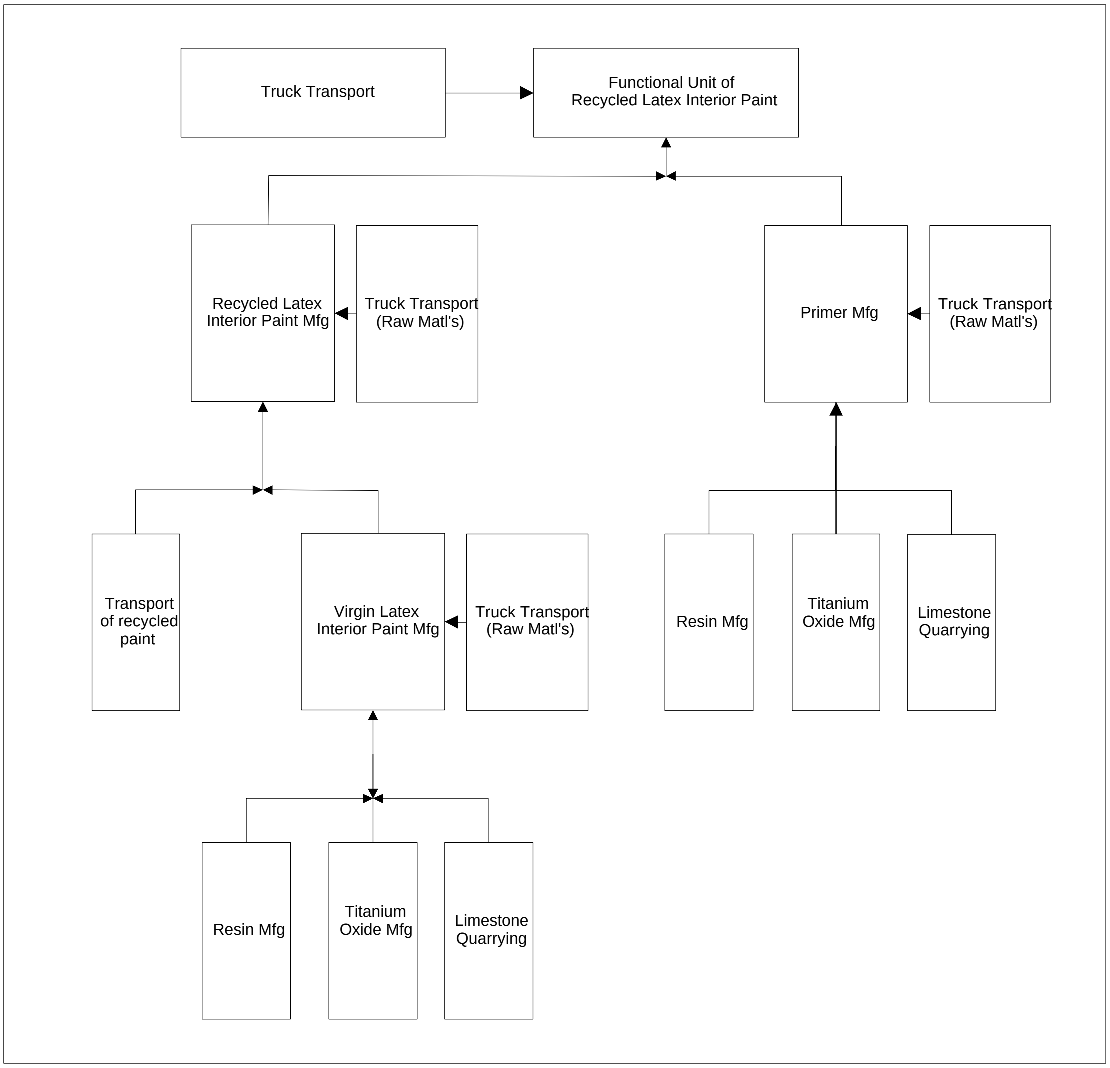

Figure 3.21 Recycled Latex Interior Paint Flow Chart

Raw Materials. The latex paint under study has a 65 % recycled content, or a 35 % content of virgin materials. The recycled content of the paint consists of leftover paint that is collected. After being pre-sorted at the collection site, recycled paints are sorted again at the "re-manufacturing" site. It is assumed that 10 % of the collected paint imported to the "re-manufacturing" site must be discarded (paint contaminated with texture material such as sand). The recycled paint is environmentally “free”, but its transportation to the paint manufacturing site is taken into account. The virgin materials in the recycled paint consist of either virgin paint ingredients (resin, titanium dioxide, and limestone) or virgin paint as a whole.

Transportation. Transport of collected paint from the collection point to the re-manufacturing site is assumed to average 80 km (50 mi) by truck.

Emissions. Emissions associated with paint manufacturing, such as particulates to the air, are based on AP-42 emission factors.

Use. Refer to Section 2.1.3, *Impact Assessment*, for a discussion of indoor air quality scoring for paints.

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 C3012, product code B0. 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, *2000 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 1999*, supplemented by industry interviews.

3.8 Floor Covering Alternatives (C3020)

3.8.1 Ceramic Tile with Recycled Windshield Glass (C3020A)

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 % recycled windshield glass content, installed using a latex-cement mortar, is studied. The flow diagram shown in Figure 3.22 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 C3020A.DBF under the File/Open menu item in the BEES software.

Raw Materials. For a 15 cm x 15 cm x 1.3 cm (6 in x 6 in x ½ in) ceramic tile with 75 % recycled glass content, clay and glass are found in the quantities listed in Table 3.37.

Table 3.37 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)

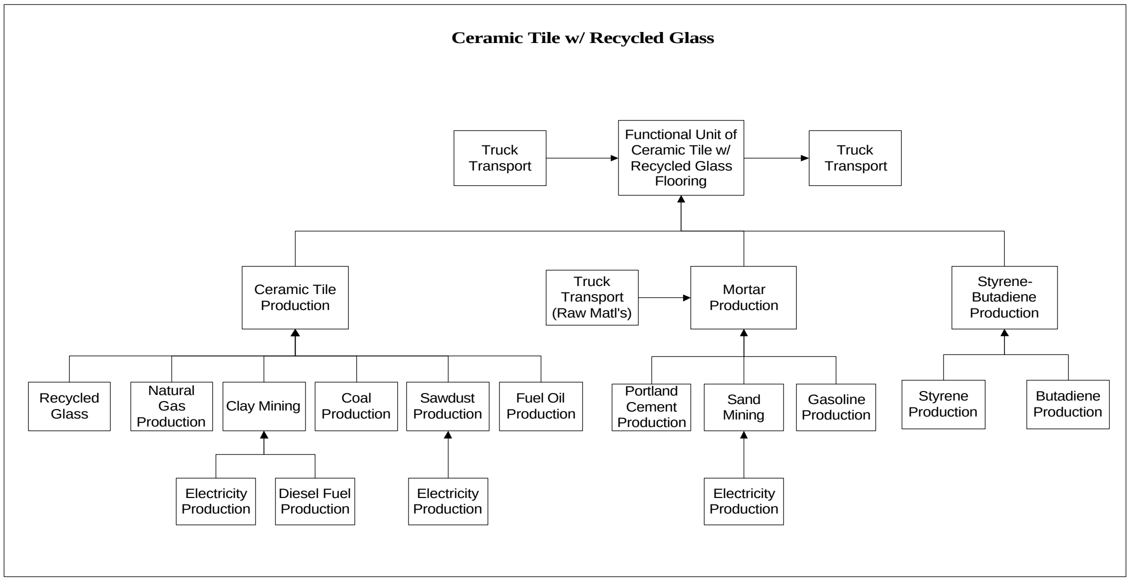

Figure 3.22 Ceramic Tile with Recycled Glass Flow Chart

Production requirements for clay are based on the Ecobalance LCA database. The recycled windshield glass material is environmentally "free." Burdens associated with glass production should be allocated to the product with the first use of the glass (vehicle windshields). The transportation of the glass to the tile facility and the processing of the glass are taken into account.

The production of mortar (1 part portland cement, 5 parts sand) and styrene-butadiene are 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 3.38.

Table 3.38 Energy Requirements for Ceramic Tile with Recycled Glass Manufacturing

Fuel Use	*Manufacturing Energy*
Total Fossil Fuel	4.19 MJ/kg (1,801 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 AP-42 emission factors.

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

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 *A0*. 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, 2000 *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 1999*, supplemented by industry interviews.

3.8.2 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 mm (0.098 in) 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 3.23 shows the elements of linoleum flooring production. The detailed environmental performance data for this product may be viewed by opening the file C3020B.DBF under the File/Open menu item in the BEES software.

Raw Materials. Table 3.39 lists the constituents of 2.5 mm (98 mil) linoleum and their proportions.

Table 3.39 Linoleum Constituents

Constituent	***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.

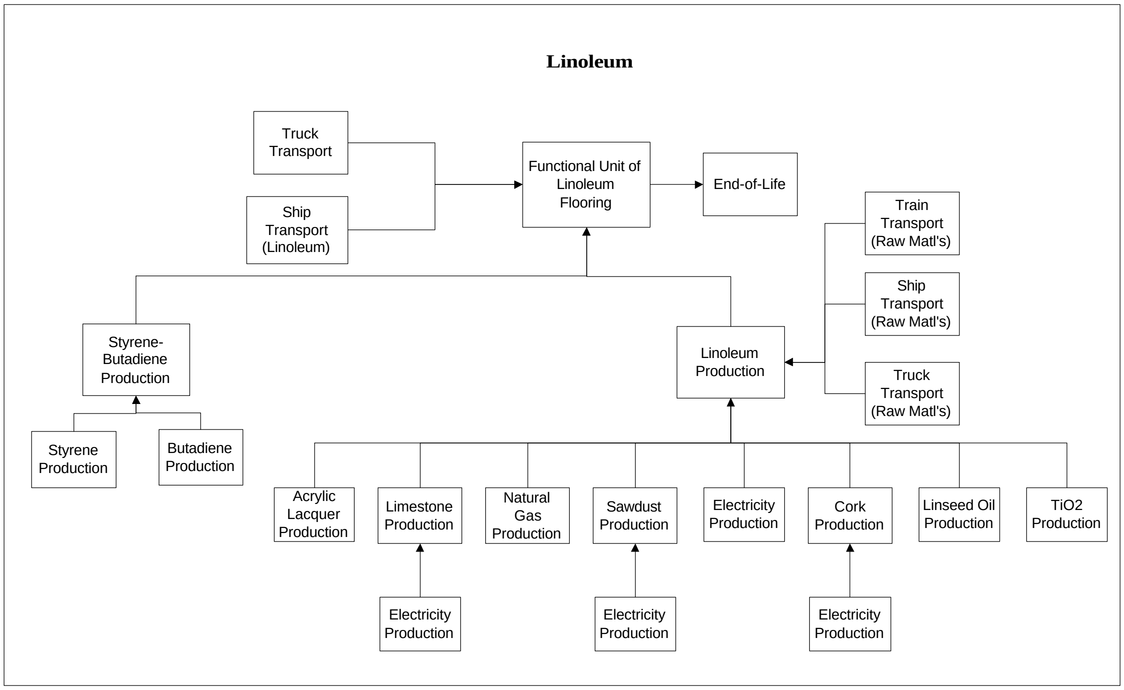

Figure 3.23 Linoleum Flow Chart

The cultivation of linseed is based on a United States agricultural model which estimates soil erosion and fertilizer run-off,[88] with the following inputs:[89]

- Fertilizer: 35 kg nitrogen fertilizer per 10,000 m^2 (31 lb/acre), 17 kg phosphorous fertilizer per hectare (15 lb/acre), and 14 kg potassium fertilizer per 10,000 m^2 (12 lb/acre)
- Pesticides: 0.5 kg active compounds per hectare (0.4 lb/acre), with 20 % lost to air
- Diesel farm tractor: 0.65 MJ per kg (279 Btu per lb) linseed
- Linseed yield: 600 kg/10,000 m^2 (536 lb/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 Ecobalance LCA data for cultivated forestry, with inventory flows allocated between pine rosin and its coproduct, turpentine. The production of limestone is based on Ecobalance data for open pit limestone quarrying and processing. 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.

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[88] Ecobalance, Sheehan, J. et al., Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus, NREL/SR-580-24089, prepared for USDA and U.S DoE, May 1998.

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

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 (66 %). Allocation is necessary because linseed cake is a co-product 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 3.40.

Table 3.40 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 3.41.

Table 3.41 Energy Requirements for Linoleum Manufacturing

Fuel Use	*Manufacturing Energy*
Electricity	2.3 MJ/kg (989 Btu/lb)
Natural Gas	5.2 MJ/kg (2,235 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 (66 %).

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)
- Particulates: 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 3.42.[90]

Table 3.42 Linoleum Raw Materials Transportation

Raw Material	*Distance*	*Mode of Transport*
linseed oil	4,350 km (2,703 mi)	Ocean Freighter
	1,500 km (932 mi)	Train
pine rosin	2,000 km (1,243 mi)	Ocean Freighter
limestone	800 km (497 mi)	Train
wood flour	600 km (373 mi)	Train
cork flour	2,000 km (1,243 mi)	Ocean Freighter

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

pigment	500 km (311 mi)	Diesel Truck
backing (jute)	10,000 km (6,214 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. 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 *B0*. 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, *2000 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 1999*, supplemented by industry interviews.

3.8.3 Vinyl Composition Tile (C3020C)

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 3.24 shows the elements of vinyl composition tile production. The detailed environmental performance data for this product may be viewed by opening the file C3020C.DBF under the File/Open menu item in the BEES software.

Raw Materials. Table 3.43 lists the constituents of 30 cm x 30 cm x 0.3 cm (12 in x 12 in x 1/8 in) 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 mm (0.98 mils). The production of these raw materials, and the styrene-butadiene adhesive, is based on the Ecobalance LCA database.

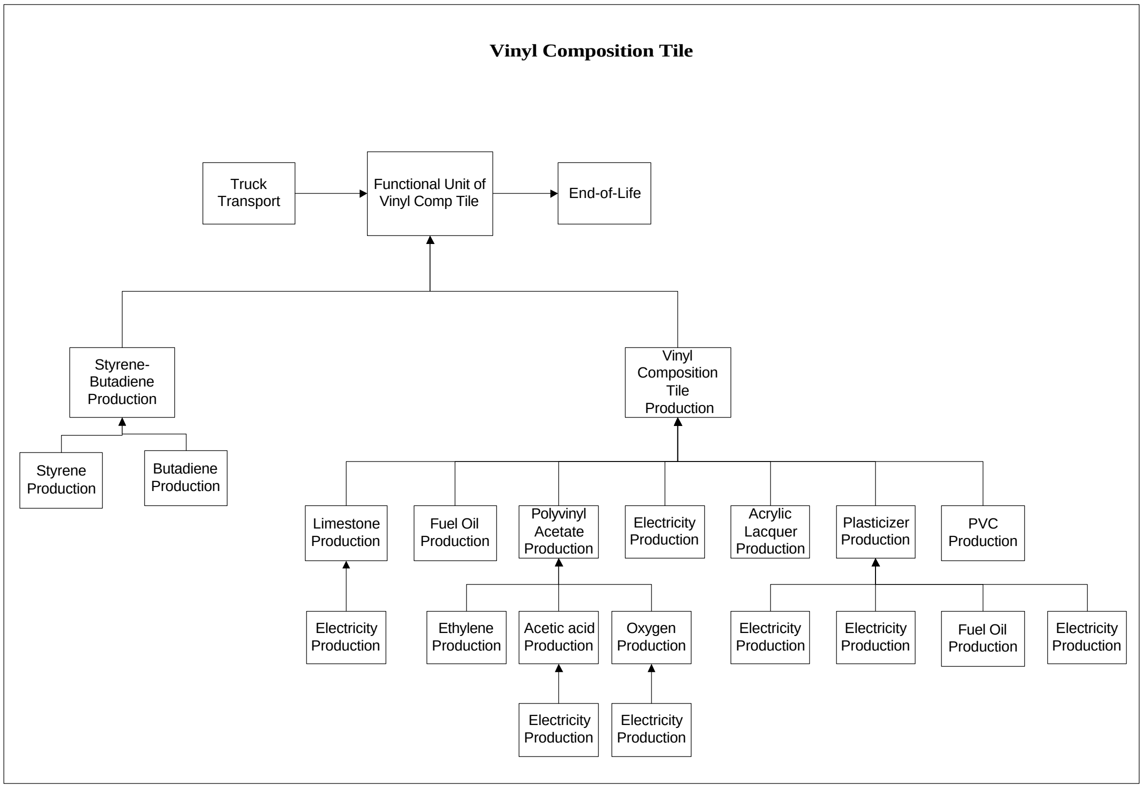

Figure 3.24 Vinyl Composition Tile Flow Chart

Table 3.43 Vinyl Composition Tile Constituents

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

Energy Requirements. Energy requirements for the manufacturing process (mixing, folding/calendaring, finish coating, and die cutting) are listed in Table 3.44.

Table 3.44 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 mm

(0.10 mils) thick. 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 *C0*. 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, *2000 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 1999*, supplemented by industry interviews.

3.8.4 Composite Marble Tile (C3020D)

Composite marble tile is a type of composition flooring. It is a mixture of polyester resin and matrix filler that is colored for marble effect and poured into a mold. The mold is then vibrated to release air and level the matrix. After curing and shrinkage the part is removed from the mold, trimmed, and polished if necessary. For the BEES system, a 30 cm x 30 cm x 0.95 cm (12 in x 12 in x 3/8 in) tile, installed using a latex-cement mortar, is studied. The flow diagram in Figure 3.25 shows the elements of composite marble tile production. The detailed environmental performance data for this product may be viewed by opening the file C3020D.DBF under the File/Open menu item in the BEES software.

Raw Materials Table 3.45 gives the constituents involved in the production of the marble matrix and their proportions. It is assumed there is no loss of weight during casting.

Table 3.45 Composite Marble Tile Constituents

Constituent	*Physical Weight (%)*
Resin	23.1
Filler	75.2
Catalyst (MEKP)	0.2
Pigment (TiO2)	1.5

The resin percentage is an average based on data from four sources ranging from 19 % to 26 % resin content. The remainder of the matrix is composed of filler, catalyst, and pigment. The filler is the largest portion of the matrix. Since calcium carbonate is the typical filler used for U.S. composite marble tile production, it is the assumed filler material in the BEES model. The filler is composed of coarse and fine particles with a ratio of two parts coarse to one part fine. Filler production involves the mining and grinding of calcium carbonate.

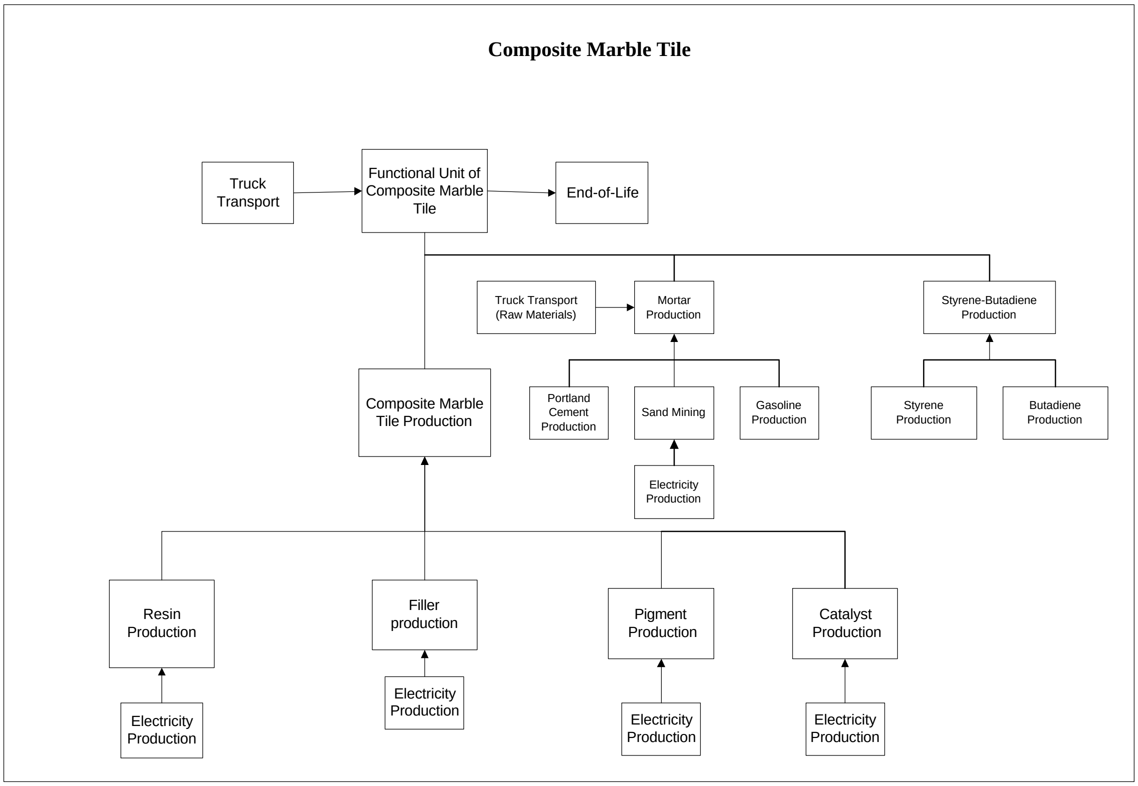

Figure 3.25 Composite Marble Tile Flow Chart

Resin is the second-most important ingredient used for the marble matrix. It is an unsaturated polyester resin cross-linked with styrene monomer. The styrene content is assumed to range from 35 % to 55 %.

The main catalyst used in the United States for the marble matrix is Methyl Ethyl Ketone Peroxide (MEKP). This catalyst is used as a solvent in the mixture of resin and filler, so is consumed in the process. Its amount is assumed to be about 1 % of the resin content, or 0.235 % of the total marble matrix.

A colorant may be used if necessary. The quantity depends on the color required. The colorant is usually added to the mixture before all the filler has been mixed. For the BEES study, titanium dioxide at 1 % to 2 % is assumed.

Energy Requirements. Electricity is the only energy consumed in producing and casting the resin-filler mixture for composite marble tile. Table 3.46 shows electricity use for composite marble tile manufacturing.

Table 3.46 Energy Requirements for Composite Marble Tile Manufacturing

Fuel Use	***Manufacturing Energy***
Electricity	0.047 MJ/kg (20.25 Btu/lb)

Emissions. The chief emission from composite marble tile manufacturing is fugitive styrene, which arises from the resin constituent and is assumed to be 2 % of the resin input. There could be some emissions from the solvent, but most manufacturers now use water-based solvents, which do not release any pollutants.

Use. Installing composite marble tile requires a sub-floor of a compatible type, such as concrete. A layer of mortar is used at 2.26 kg/0.09 m^2 (4.98 lb/ft^2), assuming a 1.3 cm (1/2 in) thick layer. It is assumed that composite marble tile has a useful life of 75 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 *C3020*, product code *D0*. 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, *2000 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 1999*, supplemented by industry interviews.

3.8.5 Terrazzo (C3020E)

Epoxy terrazzo is a type of composition flooring. It contains a high proportion of inorganic filler (principally marble dust and chips), a pigment for aesthetic purposes, and epoxy resin. The materials are mixed and installed directly on site and, when dry, are carefully polished. Figure 3.26 shows the elements of terrazzo flooring production. The detailed environmental performance data for this product may be viewed by opening the file C3020E.DBF under the File/Open menu item in the BEES software.

Raw Materials Table 3.47 lists the constituents of epoxy terrazzo and their proportions.

Table 3.47 Terrazzo Constituents

Terrazzo Constituents	*Physical Weight (%)*
marble dust	22
epoxy resin	77
pigment (titanium dioxide)	1

The finished floor is assumed to be 9.5 mm (3/8 in) thick. Typical amounts of raw materials used are as follows: 1.5 kg (3.3 lb) of marble dust and 0.23 kg (0.5 lb) of marble chips per 0.09 m^2 (1 ft^2), 3.8 L (1 gal) of epoxy resin to cover 0.8 m^2 (8.5 ft^2) of surface, and depending on customer selection, from 1 % to 15 % of the total content is pigment.

The production of these raw materials, including the quarrying of marble, is based on the Ecobalance LCA database. Note that because marble dust is assumed to be a coproduct rather than a waste byproduct of marble production, a portion of the burdens of marble quarrying is allocated to marble dust production.

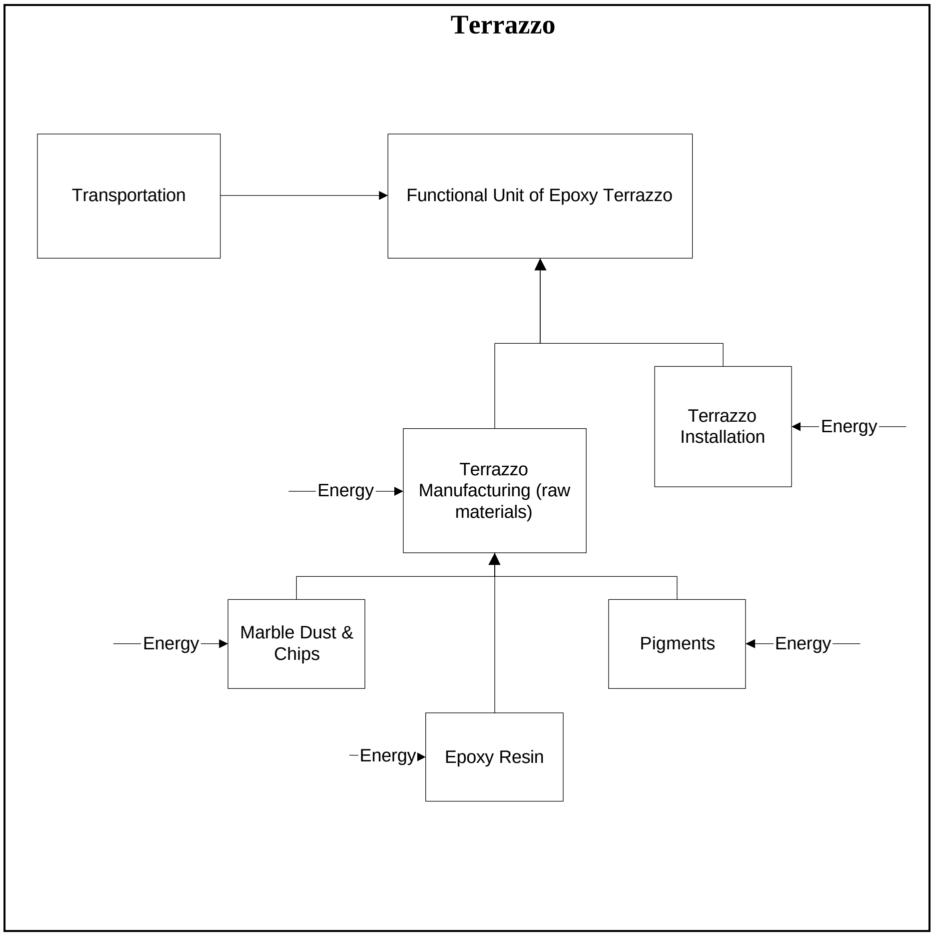

Figure 3.26 Epoxy Terrazzo Flow Chart

Energy Requirements. The energy requirements for the on-site "manufacturing" process involve mixing in an 8hp gasoline-powered mixer (a 0.25 m^3, or 9 ft^3 mixer running for 5 min).

Emissions. Emissions associated with the mixing process arise from the combustion of gasoline and are based on AP-42 emission factors.

Use. Installing epoxy terrazzo requires a sub-floor of a compatible type, such as concrete. It is assumed that epoxy terrazzo flooring has a useful life of 75 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 *C3020*, product code *E0*. 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, *2000 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 1999*, supplemented by industry interviews.

3.8.6 Carpeting – General Information

Carpets are composed of a facing and a backing, which are attached during manufacture. Before assembly, most carpets fibers are dyed. Adhesives are typically used for commercial installations. Each of these components is discussed in turn, followed by a discussion of the manufacturing process.

Carpet facing. Carpets are manufactured from a variety of fibers, usually nylon, polyester, olefin, or wool.

Carpet dyes. Dyes are applied to textile fibers in a number of ways, depending on the properties of the fiber, the dye, and the final product. The types of dyes used include inorganic, moralized organic, acid, dispersed, premetallized, and chrome dyes.

Carpet backing.

- Primary backing – usually made of either woven slit-film polypropylene or synthetic nonwoven polyester or polyester/nylon.

- Secondary backing – usually a woven or nonwoven fabric reinforcement laminated to the back of tufted carpeting (often with a styrene butadiene latex adhesive) to enhance dimensional stability, strength, stretch resistance, lie-flat stiffness, and handling. Most secondary backings are woven jute, woven polypropylene, or nonwoven polypropylene, although some manufacturers use propylene-polyethylene and polyvinyl chloride backings. The term "secondary backing" is sometimes used in a broader sense to include an attached cushion and other polymeric back coatings. Because secondary backing is visible in finished carpeting (while primary backing is concealed under the pile yarn), most dealers and installers refer to the secondary backing simply as "backing".

Carpet adhesives. Two types of carpet adhesive comprise most of the commercial market – latex and pressure sensitive adhesives. Low-VOC styrene butadiene latex adhesives are thought to be an environmentally-friendly adhesive alternative.

Carpet manufacture and fabrication. Carpet manufacture consists of a number of steps, including formation of the synthetic fibers; dyeing of the fibers; and construction, treatment, and finishing of the carpet.

- Forming synthetic fibers – nylon, olefin, and polyester are all thermoplastic, melt-spun synthetic fibers. Synthetic fibers are extruded and solidify as they cool. Post-treatments generally enhance the physical properties of the fiber. The bundle of fibers is then put through a crimping or texturizing process, after which it is either chopped into staple fiber or wound into bulk continuous filament yarn. The yarn may be heat-set to improve its ability to withstand the stresses of dyeing, finishing, and traffic wear. Heat-setting is performed either by the autoclave method, in which batches of the yarn are treated with pressurized steam, or the continuous method, in which the yarn is heat-set in an ongoing manner.

- Dyeing fibers – polymer, fiber, or yarn can be dyed before carpet is manufactured by applying the color through one of several processes:
    1. Solution dyeing – involves adding color pigments to the molten polymer prior to extrusion;
    2. Stock dyeing – cut staple fiber is packed into a large kettle after which dye liquid is forced through the fibers continuously as the temperature is increased. This process is often used to dye wool fiber;
    3. Package dyeing – yarn is wound onto a special perforated cone; or
    4. Space dyeing – involves knitting plain circular-knit tubing, which is then printed with dyestuffs in a multicolored pattern, steamed, washed, extracted, dried, and then unraveled and rewound into cones.

- Construction, treatment and finishing techniques – several different techniques are used to attach yarn to the carpet backing. Tufting is by far the most widespread, with weaving, knitting, fusion bonding, and custom tufting also in use.
    1. Tufting – the yarn is stitched through a fabric backing, creating a loop called a tuft;
    2. Weaving – carpet looms weave colored pile yarns and backing yarns into a carpet, which then gets a back coating, usually of latex, for stability;
    3. Knitting – carpet knitting machines produce facing and backing simultaneously, with three sets of needles to loop pile yarn, backing yarn, and stitching yarn together;
    4. Fusion bonding – the yarn is embedded between two parallel sheets of adhesive-coated backing, and the sheets are slit, forming two pieces of cut pile carpet; and
    5. Custom tufting – special designs are created using motorized hand tools called single-handed tufters and pass machines.

Commercial-grade carpet for medium traffic is evaluated for the BEES system. Two applications are studied: broadloom and carpet tile. The tufting manufacturing process is assumed for all carpet alternatives. Three face fiber materials are studied: wool, nylon, and recycled polyester (from soft drink PET bottles). The primary backing for all carpets is comprised of a plastic compound into which the face yarn is inserted by tufting needles. Also, a coating is applied to the back of the carpet to secure the face yarns to the primary backing. As carpet manufacturing and installation are assumed to be similar for the three face fiber options, the corresponding modeling is displayed only once in this general carpet information section.

Energy Requirements. Table 3.48 displays the energy requirements for tufting carpet.[91]

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[91] J. Potting and K. Blok, *Life Cycle Assessment of Four Types of Floor Covering* , Utrecht University, The Netherlands, 1994.

Table 3.48 Energy Requirements for Carpet Manufacturing

Fuel Type	***Manufacturing Energy***
Electricity	1.80 MJ/m^2 (0.046 kW∗h/ft^2)
Natural gas	8.2 MJ/m^2 (0.21 kW∗h /ft^2)

Emissions. Emissions associated with fuel combustion for carpet manufacture are based on AP-42 emission factors.

Use. Glue is typically used for commercial carpet installations. Two glue alternatives are evaluated: traditional latex glue and low-VOC latex glue. Details on these carpet installation parameters are given in Table 3.49.

Table 3.49 Carpet Installation Parameters

Parameter	***Broadloom***	***Tile***[92]
Glue application (applies to both traditional and low-VOC glues)	2 layers:[93] • one full layer of glue, spread rate of 1.77 m^2/L (8 yd^2/gal) • spots of glue (10 % of full spread of glue with spread rate of 4.42 m^2/L, or 20 yd^2/gal)	1 layer at 8.8 square m^2/L (40 yd^2/gal)
Cutting waste	5.7 %	2 %

Data for production of the traditional and low-VOC glues are based on the Ecobalance LCA database.

3.8.7 Wool Carpet (C3020G,C3020J,C3020M,C3020P)

A 1.13 kg (40 oz) wool carpet with a 25 year life is included in BEES. Figure 3.27 displays the system under study for wool carpet manufacture. The detailed environmental performance data for this product may be viewed by opening the following files under the File/Open menu item in the BEES software:

- C3020G.DBF — Wool Carpet Tile with Traditional Glue
- C3020J.DBF — Wool Carpet Tile with Low-VOC Glue
- C3020M.DBF — Wool Broadloom Carpet with Traditional Glue
- C3020P.DBF — Wool Broadloom Carpet with Low-VOC Glue

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[92] Note that wool carpet tile is not currently manufactured on industrial lines.

[93] Spread rates for glue as recommended by the Carpet and Rug Institute.

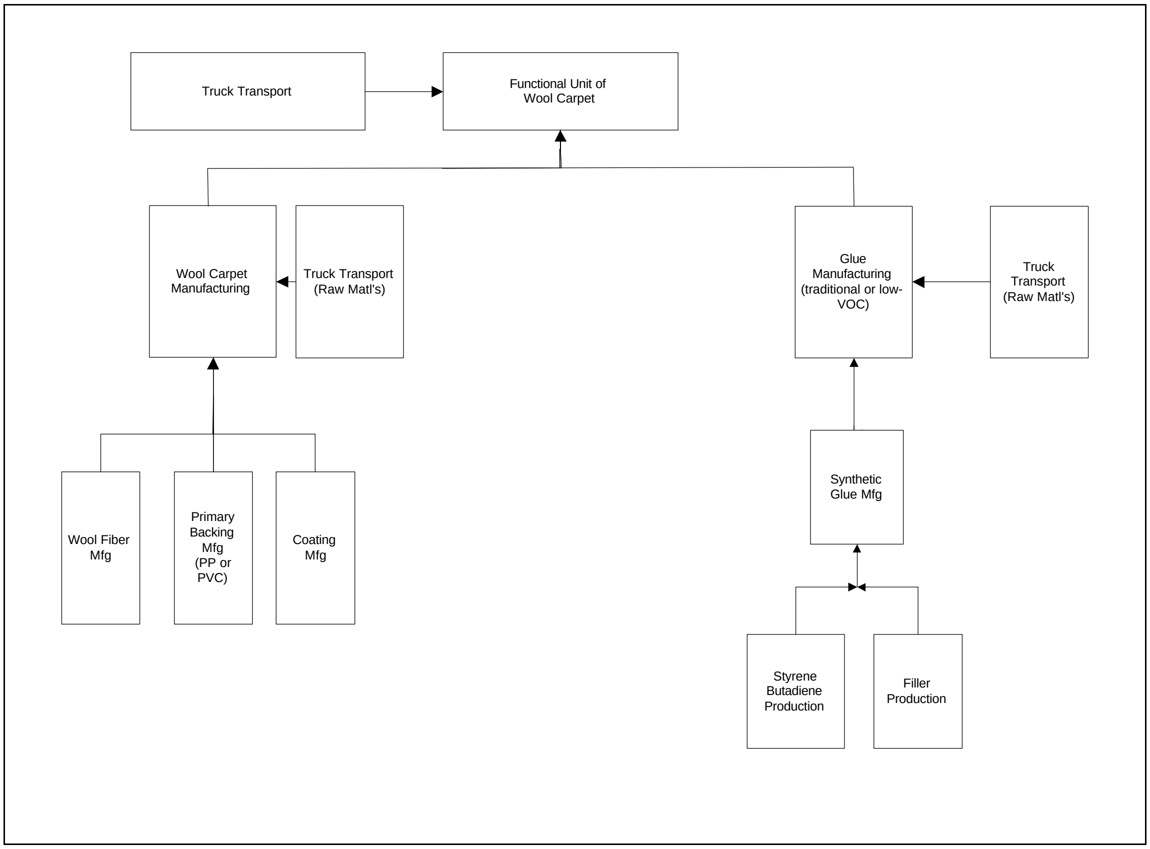

Figure 3.27 Wool Carpet Flow Chart

Raw materials. Table 3.50 lists the constituents of wool carpet and their amounts.

Table 3.50 Wool Carpet Constituents

Constituent	*Material*	*Amount g/m^2 (oz/ft^2)*
Face fiber	Wool	1400 (4.59)
Backing	Polypropylene for broadloom, PVC for tile	130 (0.43)
	Styrene butadiene latex	950 (3.11), including 710 g (25.04 oz) of limestone as a filler

The production of the plastic compound for backing, either polypropylene or PVC, and the production of the styrene butadiene latex are based on the Ecobalance LCA database.

The wool fiber is produced in New Zealand, following the major production steps displayed in Figure 3.28.

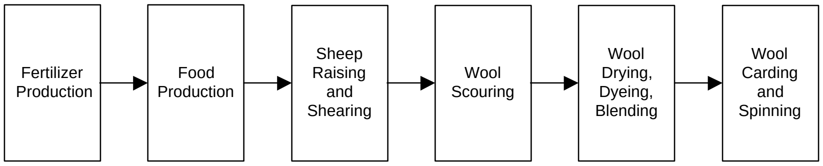

Figure 3.28 Wool Fiber Production

The material flows included for the production of raw wool are displayed in Table 3.51.[94]

Table 3.51 Raw Wool Material Flows

Flow	***Amount***
Inputs:	
- Nitrogen supply (ammonium nitrate)	29 g of nitrogen/kg raw wool (0.46 oz/lb)
- Phosphate supply (P_2O_5)	770 g of P_2O_5/kg raw wool (12.32 oz/lb)
Outputs:	
- Raw wool	5.5 kg (12.13 lb) of raw wool / 8 month period
- Methane emissions (enteric fermentation)	8.8 kg (19.4 lb) / head / year

[a] Average of data reported in two sources: International Panel on Climate Change for methane, 1993, reports 9.62 kg/head/y and AP-42, Table 14-4-2, gives 8 kg/head/yr.

The fertilizer inputs correspond to the production of food for the sheep. Fertilizer production is based on the Ecobalance LCA database.

Raw wool is greasy and carries debris that needs to be washed off in a process called "scouring." The amount of washed wool per kg of raw wool is 80 %, as shown in Table 3.52 along with other raw wool constituents.

Table 3.52 Raw Wool Constituents

Constituent	***Weight (%)***
Clean fiber (ready to be carded and spun)	80
Grease	6
Suint salts	6
Dirt	8

Grease is recovered at an average recovery rate of 40 %.[95] The scoured fiber is then dried, carded, and spun. Table 3.53 lists the main inflows and outflows for the production of wool yarn from raw wool.[96] The data for raw wool processing are from the Wool Research Organisation of New Zealand (WRONZ).

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[94] J.Potting and K.Blok, *Life Cycle Assessment of Four Types of Floor Covering*, Utrecht University, The Netherlands, 1994.

[95] The non-recovered grease exits the system (e.g., as sludge from water effluent treatment).

[96] These requirements also include processes such as dyeing and blending which take place at this stage.

Table 3.53 Wool Yarn Production Requirements

Flow	***Amount***
Input:	
- Natural Gas	4.3 MJ/kg (1849 Btu/lb)
- Electricity	0.56 MJ/kg (241 Btu/lb)
- Lubricant	0.05 kg/kg (0.05 oz/oz)
- Water	30 L/kg (3.59 gal/lb)
Output:	
- Wool yarn (taking into account material losses through drying, carding, and spinning)	0.75 kg/kg (0.75 oz/oz)
-Water emissions corresponding to scouring:	
BOD	3.3 g/kg (0.053 oz/lb)
COD	9.3 g/kg (0.15 oz/lb)

Most of the required energy is used at the scouring step. As grease is a co-product of the scouring process, a mass-based allocation is used to determine how much of the energy entering this process is actually due to the production of washed wool alone.[97] One-fourth of the required energy (about 1MJ, or 948 Btu) is used for drying.[98] Energy requirements with regard to wool carding and spinning are negligible. Water consumption is assumed to be 20 L/kg to 40 L/kg (2.4 gal/lb to 4.8 gal/lb) of greasy wool. Lubricant is added for blending, carding, and spinning. Some lubricant is incorporated into the wool.

Transportation. Backing and coating raw materials are assumed to travel 402 km (250 mi) to the carpet manufacturing plant. Wool yarn comes from New Zealand. Table 3.54 displays the transportation modes and distances the wool travels before being used in the tufting process.

Table 3.54 Wool Transportation

Mode of Transportation	***Distance***
Sea Freighter	11112 km (6,000 nautical miles)
Truck	805 km (500 mi)

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

Cost. Purchase and installation costs for wool carpet vary by application (broadloom or tile) and glue type (traditional or low-VOC). The detailed life-cycle cost data may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under the following codes

- C3020, G0—Wool Carpet Tile with Traditional Glue

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[97] This allocation is also applied to the non-energy flows for this process.

[98] Including dyeing and blending.

- C3020, J0—Wool Carpet Tile with Low-VOC Glue
- C3020, M0—Wool Broadloom Carpet with Traditional Glue
- C3020, P0—Wool Broadloom Carpet with Low-VOC Glue

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, *2000 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 1999, supplemented by industry interviews.

3.8.8 Nylon Carpet (C3020F,C3020I,C3020L,C3020O)

A 0.68 kg (24 oz) nylon carpet with an 11 year life is included in BEES. Figure 3.29 displays the system under study for nylon carpet manufacture. The detailed environmental performance data for this product may be viewed by opening the following files under the File/Open menu item in the BEES software:

- C3020F.DBF—Nylon Carpet Tile with Traditional Glue
- C3020I.DBF—Nylon Carpet Tile with Low-VOC Glue
- C3020L.DBF—Nylon Broadloom Carpet with Traditional Glue
- C3020O.DBF—Nylon Broadloom Carpet with Low-VOC Glue

Raw Materials. Table 3.55 lists the constituents of nylon carpet and their amounts.

Table 3.55 Nylon Carpet Constituents

Constituent	***Material***	***Amount*** ***g/m^2 (oz/ft^2)***
Face fiber	Nylon 6,6	810 (2.65)
Backing	Polypropylene for broadloom, PVC for tile	130 (0.43)
	Styrene butadiene latex	930 (3.05), including 710 g (25.04 oz) of limestone as a filler

The production of the plastic compound for backing (either polypropylene or PVC), the styrene butadiene latex, and the nylon fiber are based on the Ecobalance LCA database.

The spinning of nylon fiber is based on melt extrusion, for which the Association of Plastic Manufacturers in Europe (APME) is the data source for energy requirements and AP-42 the data source for emissions. The inputs and outputs of the nylon yarn manufacturing process are displayed in Table 3.56.

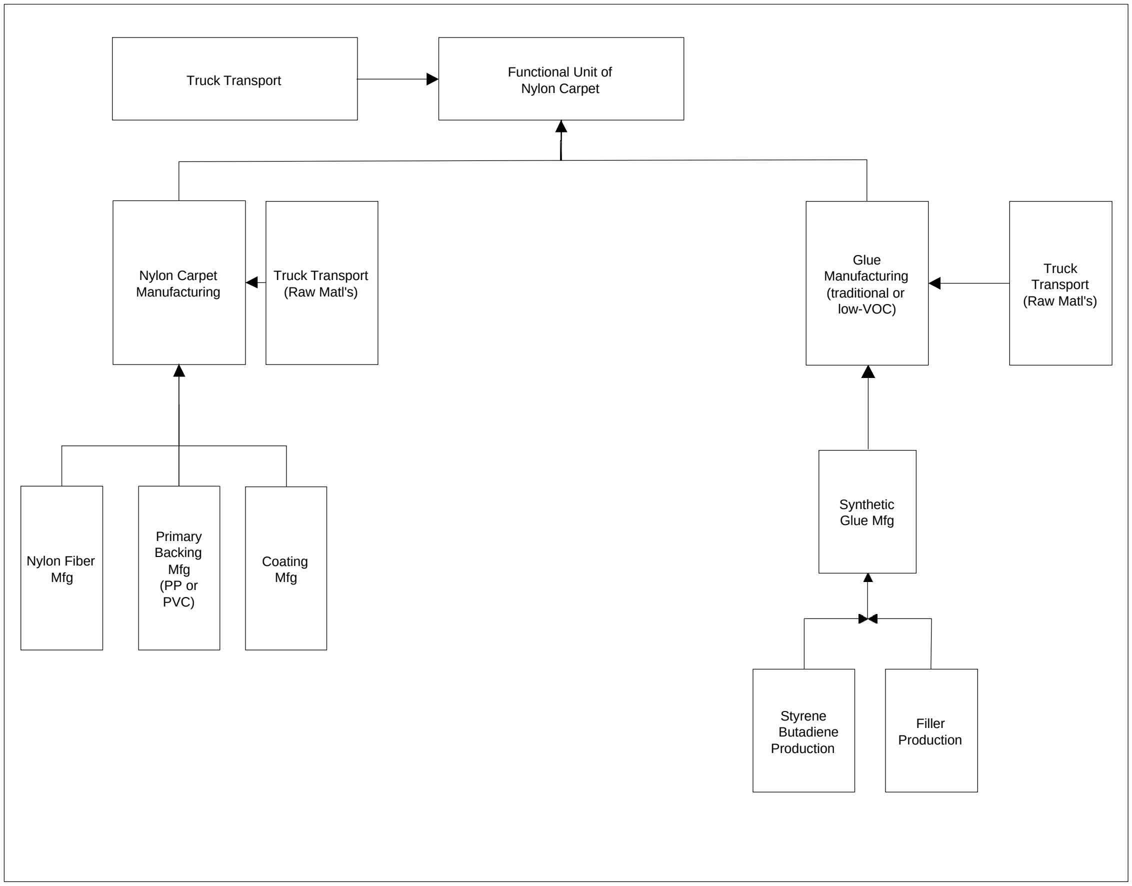

Figure 3.29 Nylon Carpet Flow Chart

Table 3.56 Nylon Yarn Production Requirements

Flow	***Amount***
Input:	
- Electricity	1.8 MJ/kg (774 Btu/lb)
- Fuel Oil	0.7 MJ/kg (301 Btu/lb)
- Natural gas	0.2 MJ/kg (86 Btu/lb)
Output (emissions to the air):	
- Hydrocarbons except methane	2.3 g/kg (0.037 oz/lb)
- Particulates	0.6 g/kg (0.0096 oz/lb)

Transportation. Transport of raw materials to the carpet manufacturing plant is assumed to require 402 km (250 mi) by truck.

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

Cost. Purchase and installation costs for nylon carpet vary by application (broadloom or tile) and glue type (traditional or low-VOC). The detailed life-cycle cost data may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under the following codes:

- C3020,F0—Nylon Carpet Tile with Traditional Glue
- C3020,I0—Nylon Carpet Tile with Low-VOC Glue
- C3020,L0—Nylon Broadloom Carpet with Traditional Glue
- C3020,O0—Nylon Broadloom Carpet with Low-VOC Glue

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, *2000 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 1999, supplemented by industry interviews.

3.8.9 Recycled Polyester Carpet (C3020H,C3020K,C3020N,C3020Q)

A 0.68 kg (24 oz) carpet with polyester fiber recycled from soft drink bottles (PET) and with an 8 year life is included in BEES. Figure 3.30 displays the system under study for recycled polyester carpet manufacture. The detailed environmental performance data for this product may be viewed by opening the following files under the File/Open menu item in the BEES software:

- C3020H.DBF—Recycled Polyester Carpet Tile with Traditional Glue
- C3020K.DBF— Recycled Polyester Carpet Tile with Low-VOC Glue
- C3020N.DBF—Recycled Polyester Broadloom Carpet with Traditional Glue
- C3020Q.DBF—Recycled Polyester Broadloom Carpet with Low-VOC Glue

Raw materials. Table 3.57 lists the constituents of recycled polyester carpet and their amounts.

Table 3.57 Recycled Polyester Carpet Constituents

Constituent	*Material*	*Amount* g/m^2 (oz/ft^2)
Face fiber	Recycled PET	810 (2.65)
Backing	Polypropylene for broadloom, PVC for tile	130 (0.43)
	Styrene butadiene latex	930 (3.05), including 710 g (25.04 oz) of limestone as a filler

The production of the plastic compound for backing (either polypropylene or PVC), the styrene butadiene latex, and the recycled PET fiber are based on the Ecobalance LCA database. The recycling of PET is modeled as shown in Figure 3.31.

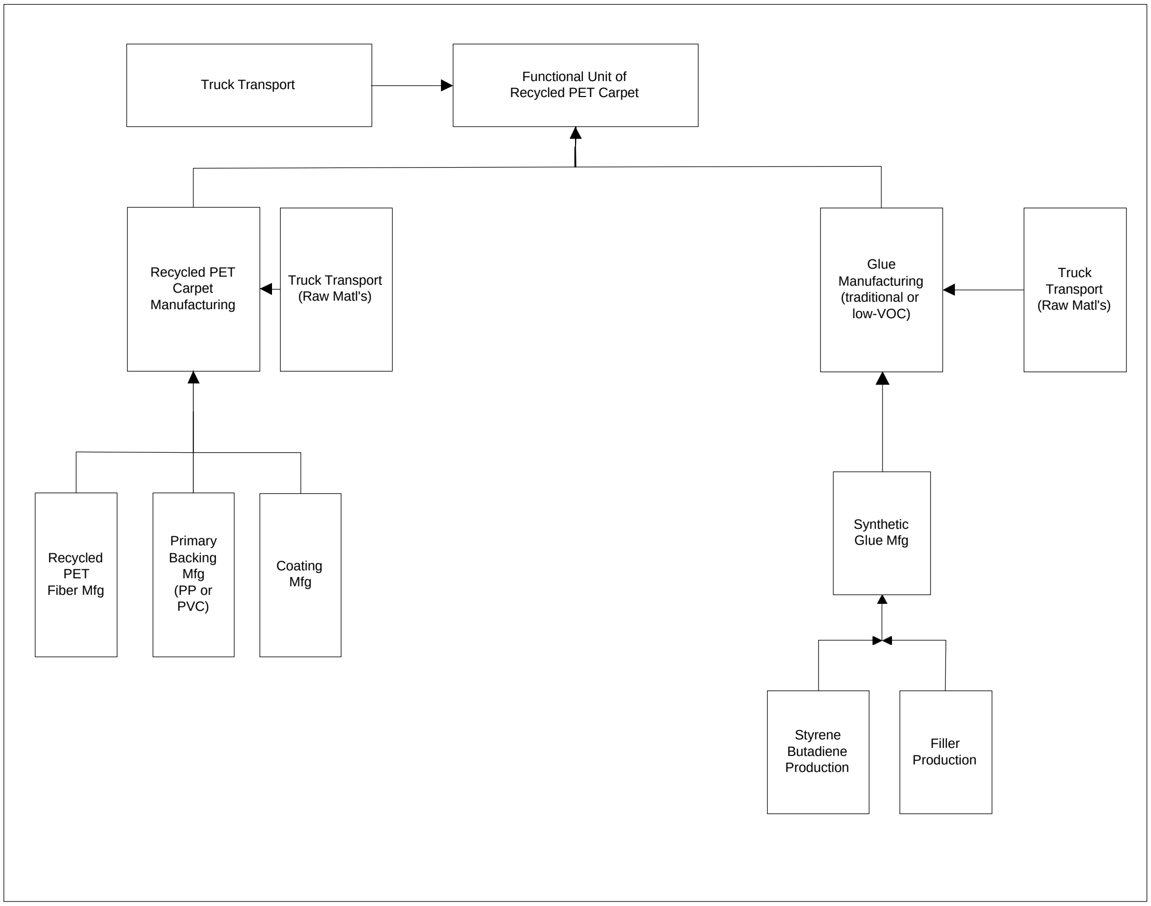

Figure 3.30 Recycled Polyester Carpet Flow Chart

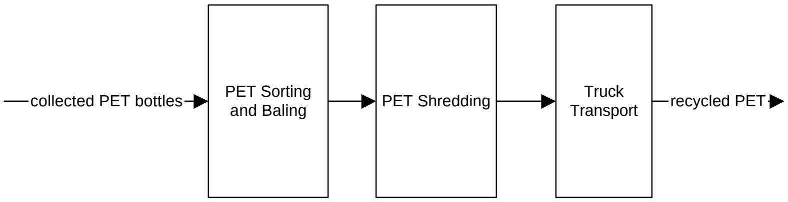

Figure 3.31 Handling and Reclamation of PET

The spinning of the PET fiber is based on melt extrusion, for which the Association of Plastic Manufacturers in Europe (APME) is the data source for energy requirements and AP-42 the data source for emissions. The inputs and outputs of the recycled PET yarn manufacturing process are displayed in Table 3.58.

Table 3.58 Recycled PET Yarn Production Requirements

Flow	*Amount*
Input:	
- Electricity	1.8 MJ/kg (774 Btu/lb)
- Fuel Oil	0.7 MJ/kg (301 Btu/lb)
- Natural Gas	0.2 MJ/kg (86 Btu/lb)

Output (emissions to the air):	
- Hydrocarbons except methane	0.05 g/kg (0.0008 oz/lb)
- Particulates	0.03 g/kg (0.00048 oz/lb)

Transportation. Transport of raw materials to the carpet manufacturing plant is assumed to require 402 km (250 mi) by truck. Another 274 km (170 mi) is added for transport of the recycled PET from the materials recovery facility to the recycled yarn processing site.

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

Cost. Purchase and installation costs for recycled PET carpet vary by application (broadloom or tile) and glue type (traditional or low-VOC). The detailed life-cycle cost data may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under the following codes:

- C3020,H0—Recycled Polyester Carpet Tile with Traditional Glue
- C3020,K0— Recycled Polyester Carpet Tile with Low-VOC Glue
- C3020,N0—Recycled Polyester Broadloom Carpet with Traditional Glue
- C3020,Q0—Recycled Polyester Broadloom Carpet with Low-VOC Glue

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, *2000 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 1999, supplemented by industry interviews.

3.9 Parking Lot and Driveway Paving Alternatives (G2022,G2031)

3.9.1 Concrete Paving (G2022A, G2022B, G2022C, G2031A, G2031B, G2031C)

For the BEES system, concrete paving consists of a 15 cm (6 in) layer of concrete poured over a 20 cm (8 in) base layer of crushed stone. The three concrete paving alternatives have varying degrees of fly ash in the portland cement (0 %, 15 %, and 20 % fly ash). Section 3.1 describes the production of concrete. For the paving alternatives, a compressive strength of 21 MPa (3000 psi) is used. The flow diagram shown in Figure 3.32 shows the elements of concrete paving. The detailed environmental performance data for concrete paving may be viewed by opening the following files under the File/Open menu item in the BEES software:

- G2022A.DBF—0 % Fly Ash Content Concrete
- G2022B.DBF—15 % Fly Ash Content Concrete
- G2022C.DBF—20 % Fly Ash Content Concrete

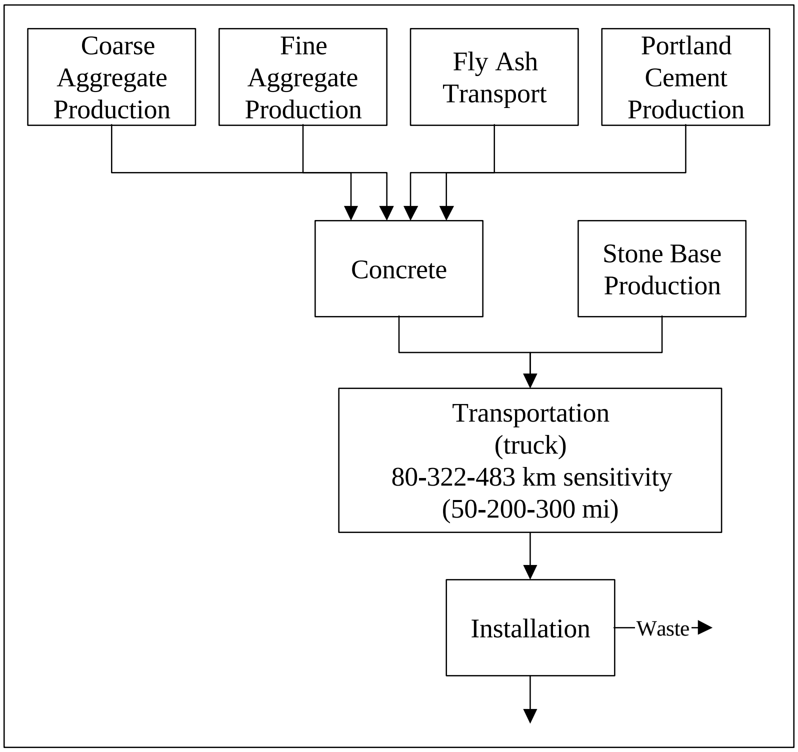

Figure 3.32 Concrete Paving Flow Chart

Raw Materials. The materials required to produce concrete are given in Section 3.1. The amount of material used per functional unit (0.09 m^2, or 1 ft^2 of paving for 50 years) is 32.9 kg (72.5 lb) of concrete and 33.3 kg (73.3 lb) of crushed stone.

Energy Requirements. The energy requirements for concrete production are outlined in Section 3.1. The energy required for site preparation and placement of crushed stone is 0.7 MJ/ ft^2 of paving, and the energy required for concrete placement is included in transportation to the site.

Emissions. Emissions associated with the manufacture of concrete are based on primary data from the portland cement industry as described in Section 3.1. In addition, for the concrete paving option, upstream emissions data for the production of fuels and electricity are added to the industry emissions data.

Transportation. Transport of raw materials is taken into account. Transport of the concrete to the building site is a variable of the BEES model.

Use. A light-colored paving material, such as concrete, will contribute less to the "urban heat island" effect than a dark-colored paving material, such as asphalt. These differences are not accounted for in BEES, but should be factored into interpretation of the results.

Cost. The detailed life-cycle cost data for concrete paving may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under the following codes:

- G2022,A0—0 % Fly Ash Content Concrete Parking Lot Paving
- G2022,B0—15 % Fly Ash Content Concrete Parking Lot Paving
- G2022,C0—20 % Fly Ash Content Concrete Parking Lot Paving
- G2031,A0—0 % Fly Ash Content Concrete Driveways
- G2031,B0—15 % Fly Ash Content Concrete Driveways
- G2031,C0—20 % Fly Ash Content Concrete Driveways

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, *2000 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 1999*, supplemented by industry interviews.

3.9.2 Asphalt Parking Lot Paving with GSB88 Asphalt Emulsion Maintenance (G2022D)

For the BEES system, asphalt parking lot paving consists of a 22 cm (8.75 in) thick layer of asphalt (a 6 cm , or 2.5 in, wearing course over a 16 cm, or 6.25, in binder course) over a 20 cm (8 in) layer of crushed stone with maintenance over 50 years.[99] The GSB88 Emulsified Sealer-Binder produced by Asphalt Systems, Inc. of Salt Lake City, Utah is one of two maintenance alternatives studied. GSB88 Emulsifier Sealer-Binder is a high-resin-content emulsifier made from naturally occurring asphalt. This maintenance product is applied to the base asphalt every four years to prevent oxidation and cracking. The flow diagram in Figure 3.33 shows the elements of asphalt paving with GSB88 emulsion maintenance. The detailed environmental performance data for this product may be viewed by opening the file G2022D.DBF under the File/Open menu item in the BEES software.

Raw Materials. The materials required to produce the asphalt layer are shown in Table 3.59. The production of the raw materials required for the pavement and the emulsifier is based on the Ecobalance database.

The amount of material used per functional unit (0.09 m^2, or 1 ft^2 of paving for 50 years) is 48 kg (106 lb) of asphalt , 33.3 kg (73.3 lb) of crushed stone, and 12 installments of the GSB88 emulsion maintenance at 0.374 kg (0.82 lb) each (for a total of 4.48 kg, or 9.8 lb of GSB88

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[99] While the combined asphalt binder and wearing course is thicker than commonly used, BEES asphalt paving specifications are structurally equivalent to those for BEES concrete paving to which it is compared. Equivalent thicknesses provided by Scott Tarr, Construction Technology Laboratories, Inc., May 2000 and based on American Association of State Highway and Transportation Officials (AASHTO) design equations.

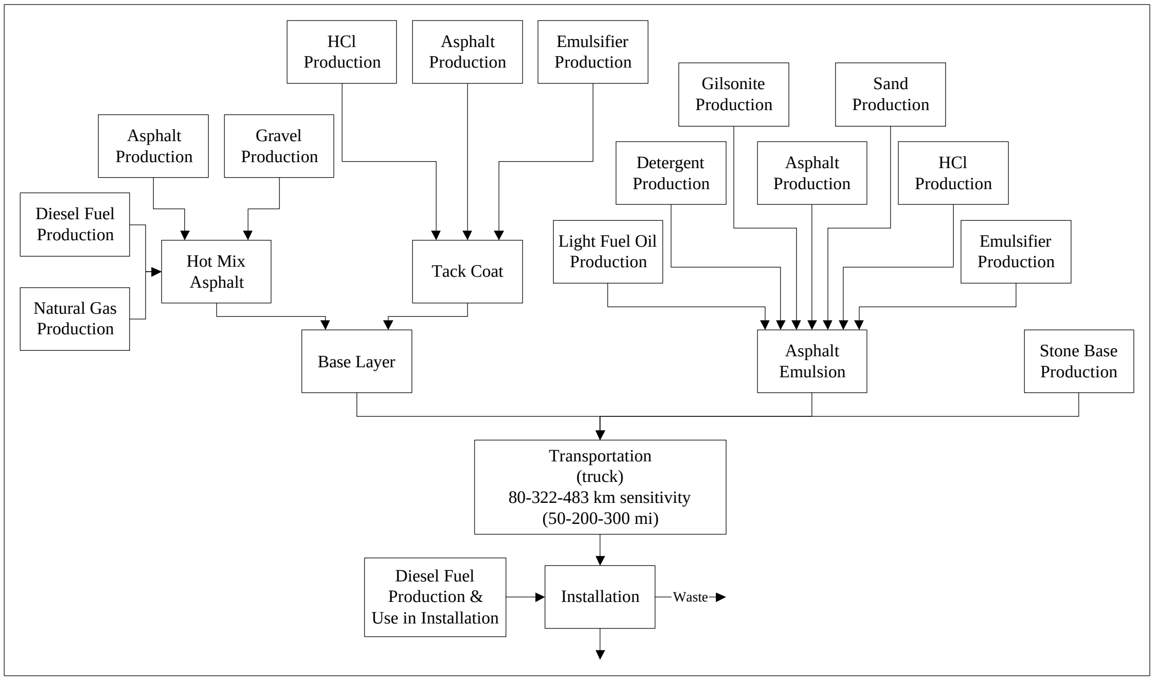

Figure 3.33 Asphalt with GSB88 Emulsion Maintenance Flow Chart

Table 3.59 Raw Materials for Asphalt Base Layer

Constituent	*Percent of Base Layer (by weight)*	*Percent of Component (by weight)*
- Hot Mix Asphalt (binder course)	71.4	
- Gravel		95
- Asphalt		5
- Hot Mix Asphalt (wearing course)	28.5	
- Gravel		94
- Asphalt		6
- Tack Coat	0.1	
- Asphalt		66
- Water		33
- Emulsifier		1.1
- HCl		0.2

asphalt emulsion maintenance over 50 years).

Energy Requirements. The energy requirements for producing the base layer's hot mix asphalt, for installing the base layer, and for applying the GSB88 emulsion maintenance are listed in Table 3.60.

Table 3.60 Energy Requirements for Asphalt Paving with GSB88 Emulsion Maintenance

Fuel Use	***Energy Use***
Hot Mix Asphalt Production:	
- Diesel	0.017 MJ/kg (7.3 Btu/lb)
- Natural Gas	0.29 MJ/kg (124.7 Btu/lb)
Site Prep. and Stone Base Placement	
- Diesel	0.7 MJ/ ft^2
Asphalt (binder course) Installation:	
- Diesel	0.96 MJ/ ft^2
Asphalt (wearing course) Installation:	
- Diesel	0.48 MJ/ ft^2
Emulsion Maintenance:	
- Diesel	0.000945 MJ/ ft^2

Emissions. Emissions associated with the manufacture of hot mix asphalt are based on U.S. EPA AP-42 emission factors. Emissions from the production of the upstream materials and energy carriers are from the Ecobalance database.

Transportation. Transport of the raw materials is taken into account. Transport of asphalt to the building site is a variable of the BEES model.

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 G2022, product code D0. 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, *2000 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 1999*, supplemented by industry interviews.

3.9.3 Asphalt Parking Lot Paving with Asphalt Cement Maintenance (G2022E)

For the BEES system, asphalt parking lot paving consists of a 22 cm (8.75 in) thick layer of asphalt (a 6 cm , or 2.5 in, wearing course over a 16 cm, or 6.25, in binder course) over a 20 cm (8 in) layer of crushed stone with maintenance over 50 years.[100] Asphalt cement maintenance is one of two maintenance alternatives studied. Asphalt cement maintenance involves milling the existing 6 cm (2.5 in) asphalt wearing course then topping with a fresh 6 cm (2.5 in) layer of asphalt cement every 8 years. The flow diagram shown in Figure 3.34 shows the elements of asphalt paving with asphalt cement maintenance. The detailed environmental performance data

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[100] While the combined asphalt binder and wearing course is thicker than commonly used, BEES asphalt paving specifications are structurally equivalent to those for BEES concrete paving to which it is compared. Equivalent thicknesses provided by Scott Tarr, Construction Technology Laboratories, Inc., May 2000 and based on American Association of State Highway and Transportation Officials (AASHTO) design equations.

for this product may be viewed by opening the file G2022E.DBF under the File/Open menu item in the BEES software.

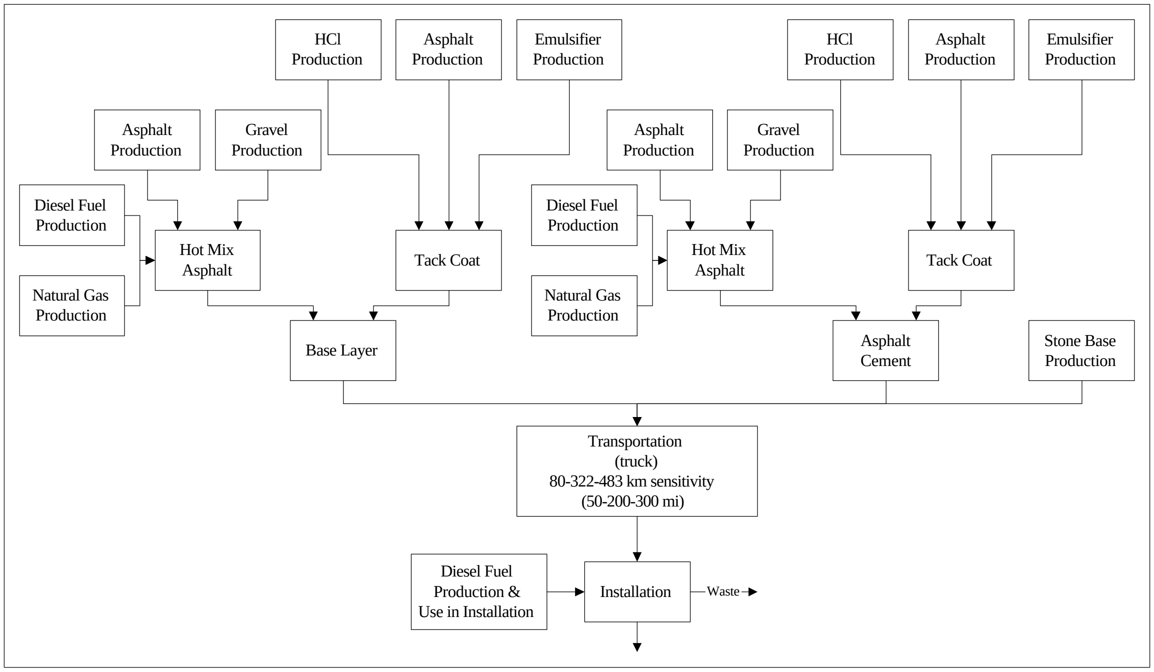

Figure 3.34 Asphalt with Asphalt Cement Maintenance Flow Chart

Raw Materials. The materials required to produce the asphalt base layer are identical to those given in the previous section. The materials required to produce the asphalt cement maintenance product are shown in Table 3.61.

The production of the raw materials required for both the pavement and its maintenance is based on the Ecobalance database.

Table 3.61 Raw Materials for Asphalt Cement Maintenance

Constituent	*Percent of Base Layer (by weight)*	*Percent of Component (by weight)*
Asphalt Cement:		
- Hot Mix Asphalt	99.4	
- Gravel		95
- Asphalt		5
- Tack Coat	0.6	
- Asphalt		66
- Water		33
- Emulsifier		1.1
- HCl		0.2

The amount of material used per functional unit (0.09 m^2, or 1 ft^2 of paving for 50 years) is 48 kg (106 lb) of asphalt, 33.3 kg (73.3 lb) of crushed stone, and 6 installments of the asphalt cement maintenance at 13.7 kg (30.3 lb) each (for a total of 82.4 kg, or 181.8 lb of asphalt cement maintenance over 50 years).

Energy Requirements. The energy requirements for producing and installing the original layer of hot mix asphalt over a crushed stone base are shown in Table 3.60. The energy requirements for the asphalt cement maintenance are listed in Table 3.62.

Table 3.62 Energy Requirements for Asphalt Cement Maintenance

Fuel Use	***Energy***
Diesel	0.72 MJ/ ft^2

Emissions. Emissions associated with the manufacture of hot mix asphalt are based on U.S. EPA AP-42 emission factors. Emissions from the production of the upstream materials and energy carriers are from the Ecobalance database.

Transportation. Transport of the raw materials is taken into account. Transport of asphalt to the building site is a variable of the BEES model.

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 G2022, product code E0. 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, *2000 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 1999*, supplemented by industry interviews.

3.9.4 Asphalt Driveway Paving with Sealer Maintenance (G2031D)

For the BEES system, asphalt driveway paving consists of a 22 cm (8.75 in) thick layer of asphalt (a 6 cm , or 2.5 in, wearing course over a 16 cm, or 6.25, in binder course) over a 20 cm (8 in) layer of crushed stone with maintenance over 50 years.[101] Asphalt driveway sealer maintenance involves adding a coat of sealer every 4 years. The flow diagram shown in Figure 3.35 shows the elements of asphalt paving with sealer maintenance. The detailed environmental performance data for this product may be viewed by opening the file G2031D.DBF under the File/Open menu item in the BEES software.

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[101] While the combined asphalt binder and wearing course is thicker than commonly used, BEES asphalt paving specifications are structurally equivalent to those for BEES concrete paving to which it is compared. Equivalent thicknesses provided by Scott Tarr, Construction Technology Laboratories, Inc., May 2000 and based on American Association of State Highway and Transportation Officials (AASHTO) design equations.

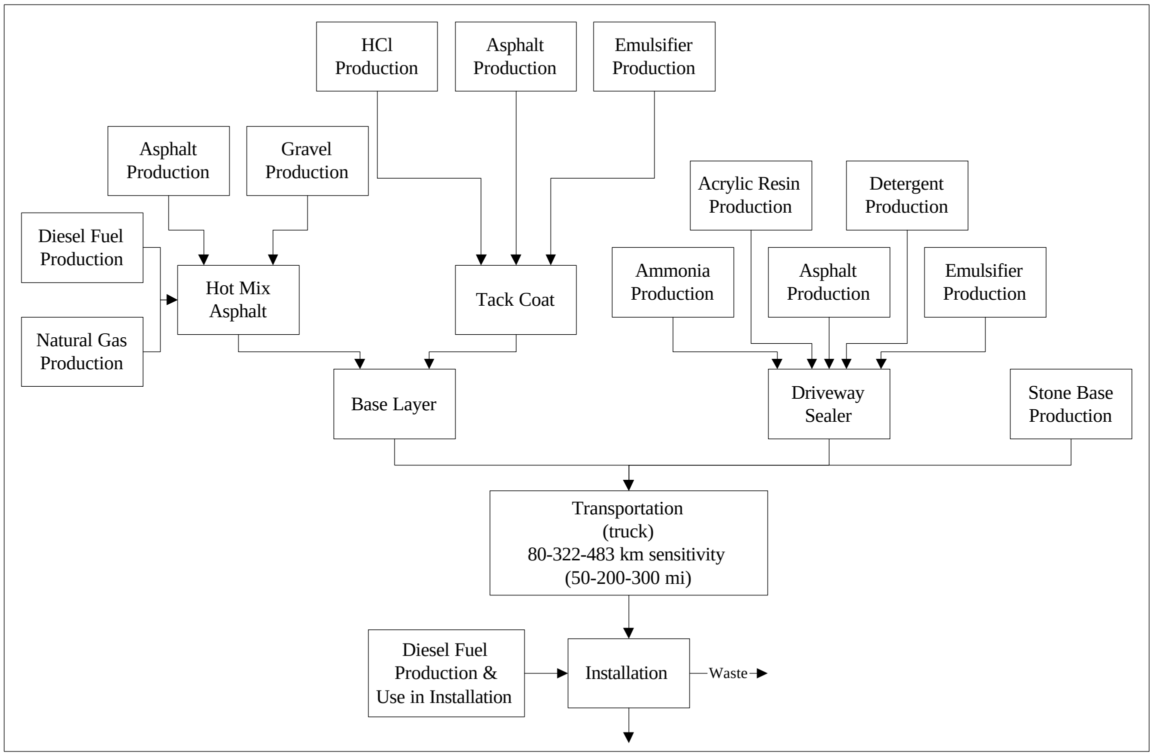


Figure 3.35 Asphalt with Sealer Maintenance Flow Chart

Raw Materials. The materials required to produce the asphalt base layer are identical to those shown in the section above, *Asphalt Parking Lot Paving with Asphalt Emulsion Maintenance*. The materials required to produce the driveway sealer are shown in Table 3.63.

Table 3.63 Raw Materials for Driveway Sealer

Constituent	*Percent of Sealer (by weight)*
- Asphalt	47.5
- Water	39.6
- Acrylic Resin	11
- Detergent	0.6
- Emulsifier	0.6
- Ammonia	0.1

The production of the raw materials required for both the asphalt base layer and the sealer are based on the Ecobalance database.

The amount of material used per functional unit (0.09 m^2, or 1 ft^2 of paving for 50 years) is 48 kg (106 lb) of asphalt, 33.3 kg (73.3 lb) of crushed stone, and 12 installments of the driveway sealer maintenance at 0.054 kg (0.12 lb) each (for a total of 0.65 kg, or 1.4 lb of driveway sealer maintenance over 50 years).

Energy Requirements. The energy requirements for producing and installing the base layer's hot mix asphalt are listed in Table 3.60. The energy required for installing the asphalt sealer is shown in Table 3.64.

Table 3.64 Energy Requirements for Asphalt Sealer Maintenance

Fuel Use	***Energy***
Diesel	0.000945 MJ/ ft^2

Emissions. Emissions associated with the manufacture of hot mix asphalt are based on U.S. EPA AP-42 emission factors. Emissions from the production of the upstream materials and energy carriers are from the Ecobalance database.

Transportation. Transport of the raw materials is taken into account. Transport of the asphalt to the building site is a variable of the BEES model.

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 G2031, product code D0. 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, *2000 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 1999*, 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.

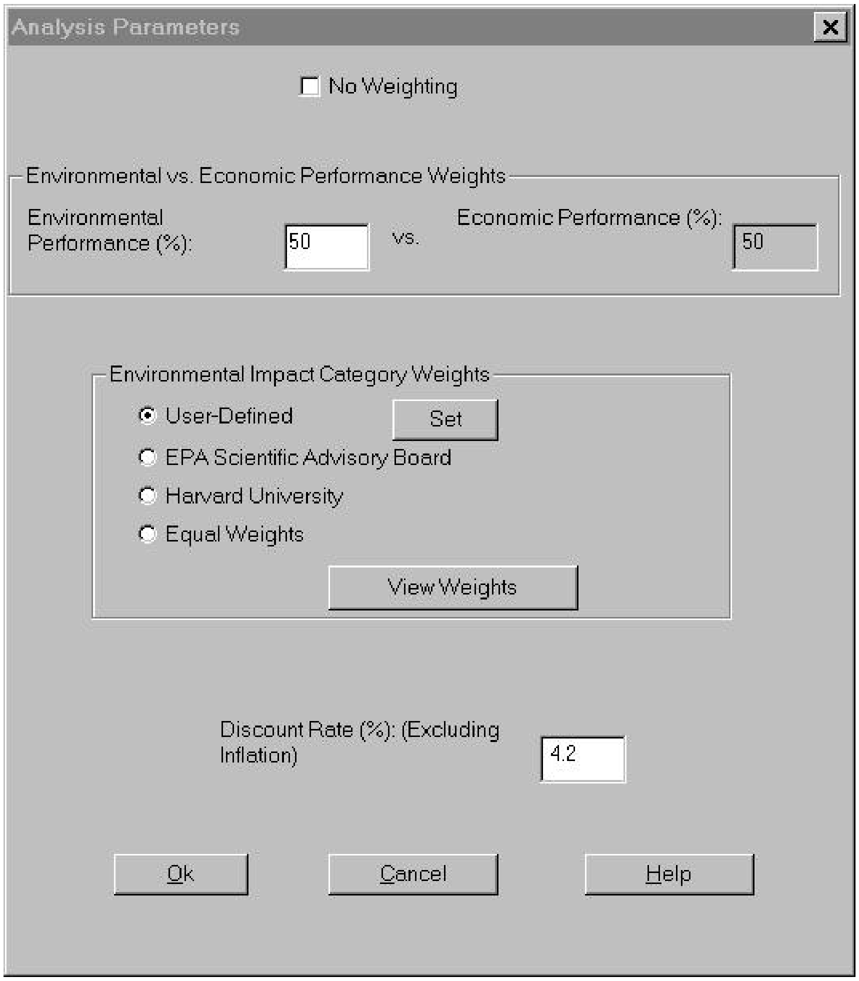
3. View the BEES results to compare the overall environmental/economic performance balance for your alternatives.

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.

BEES uses importance weights to combine environmental and economic performance measures into a single performance score. If you prefer not to weight the environmental and economic performance measures, select the “no weighting” option. In this case, BEES will compute and display only disaggregated performance results.

Assuming you have chosen to weight BEES results, you are asked to enter 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 environmental impact categories included in the BEES environmental performance score: Global Warming Potential, Acidification Potential, Eutrophication Potential, Natural Resource Depletion, Indoor Air Quality, and Solid Waste. (For a select group of products, BEES 2.0 also includes Ecological Toxicity, Human Toxicity, Ozone Depletion, and Smog. These “expanded impact” products are identified in Table 4.1.) You are presented with four sets of alternative weights. You may choose to define your own set of weights, or select a built-in weight set 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. If you select the user-defined weight set, you will be asked to enter weights for all impacts, as shown in Figure 4.3. These weights must sum to 100.



☐ No Weighting

Environmental vs. Economic Performance Weights

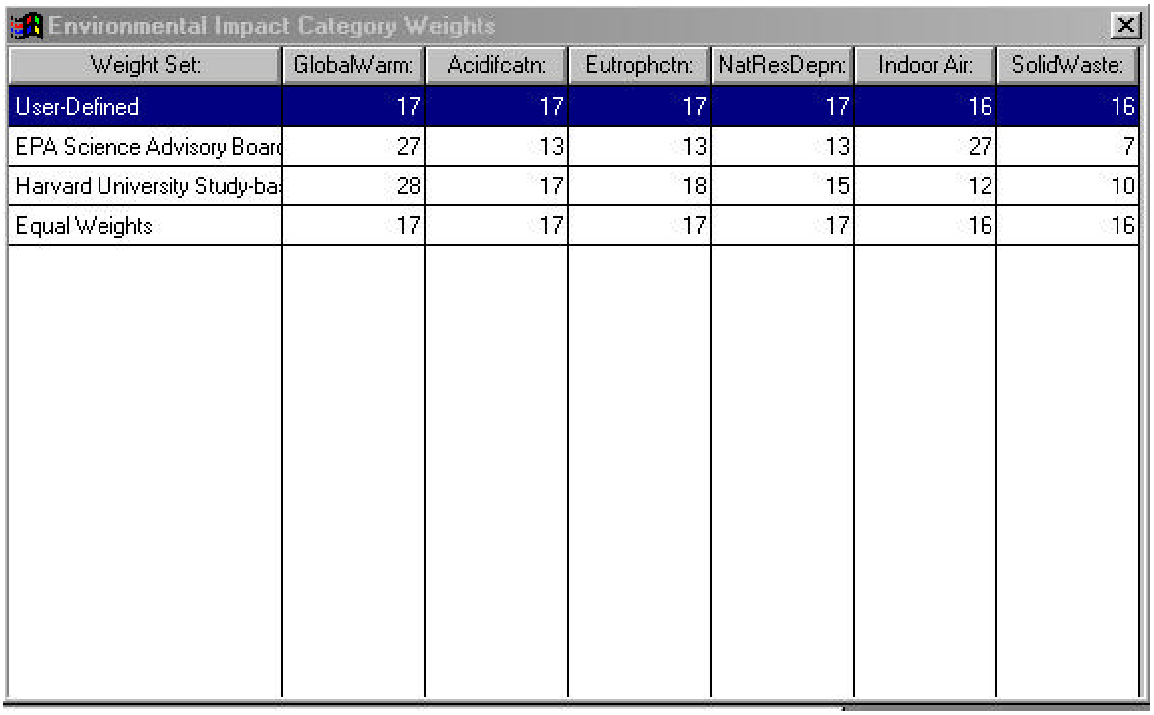
Environmental Performance (%): 50 vs. Economic Performance (%): 50

Environmental Impact Category Weights

● User-Defined
○ EPA Scientific Advisory Board
○ Harvard University
○ Equal Weights

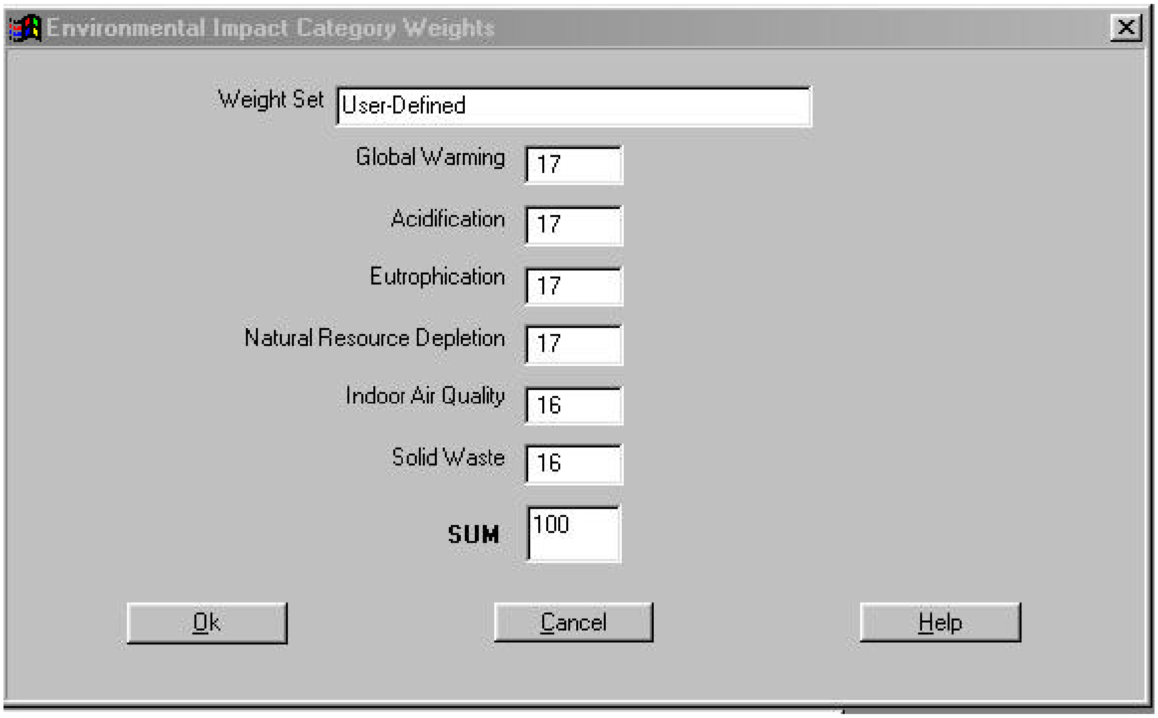
Discount Rate (%): (Excluding Inflation) 4.2

Figure 4.1 Setting Analysis Parameters



Weight Set:	GlobalWarm:	Acidifcatn:	Eutrophctn:	NatResDepn:	Indoor Air:	SolidWaste:
User-Defined	17	17	17	17	16	16
EPA Science Advisory Boarc	27	13	13	13	27	7
Harvard University Study-ba:	28	17	18	15	12	10
Equal Weights	17	17	17	17	16	16

Figure 4.2 Viewing Impact Category Weights

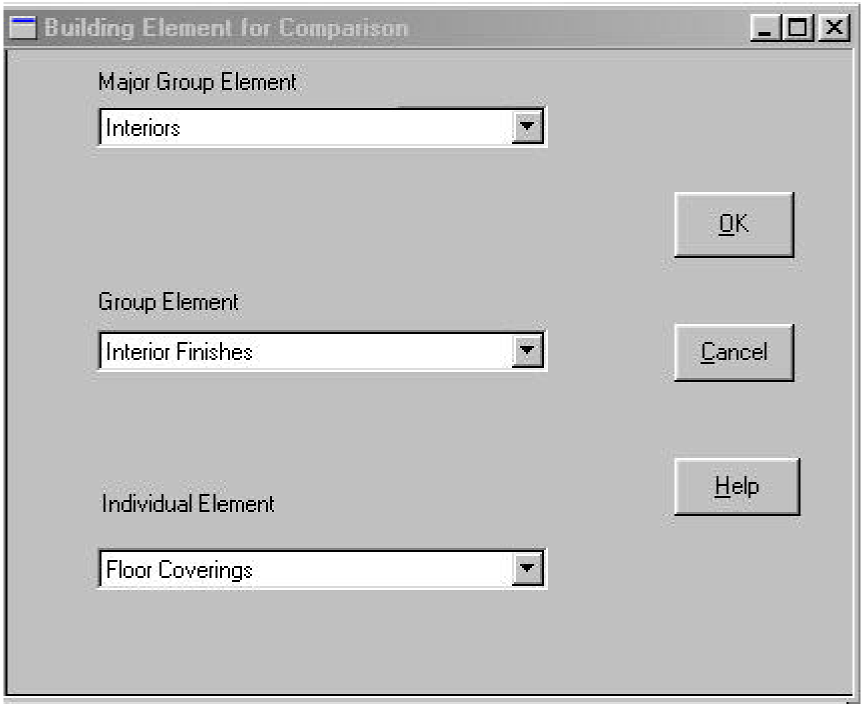


Weight Set: User-Defined
Global Warming: 17
Acidification: 17
Eutrophication: 17
Natural Resource Depletion: 17
Indoor Air Quality: 16
Solid Waste: 16
SUM: 100

Figure 4.3 Entering User-Defined 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 2000 rate mandated by the U.S. Office of Management and Budget for most Federal projects, 4.2 %, is provided as a default value.[102]

4.2 Defining Alternatives



Major Group Element: Interiors

Group Element: Interior Finishes

Individual Element: Floor Coverings

Figure 4.4 Selecting Building Element for BEES Analysis

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

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[102] 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, February 2000.

standard UNIFORMAT II classification system.[103] Click on the down arrows to display the complete lists of available choices at each level of the hierarchy. BEES 2.0 contains environmental and economic performance data for 65 products across 15 building elements: slabs on grade, basement walls, beams, columns, roof sheathing, exterior wall finishes, wall insulation, wall sheathing, framing, roof coverings, ceiling insulation, interior wall finishes, floor coverings, parking lot paving, and driveways. 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. Select an alternative with a mouse click. You must select at least two alternatives. After selecting each alternative, you will be presented with a window, such as in Figure 4.6, asking for the assumed distance for transporting the product from the manufacturing plant to your building site.[104]

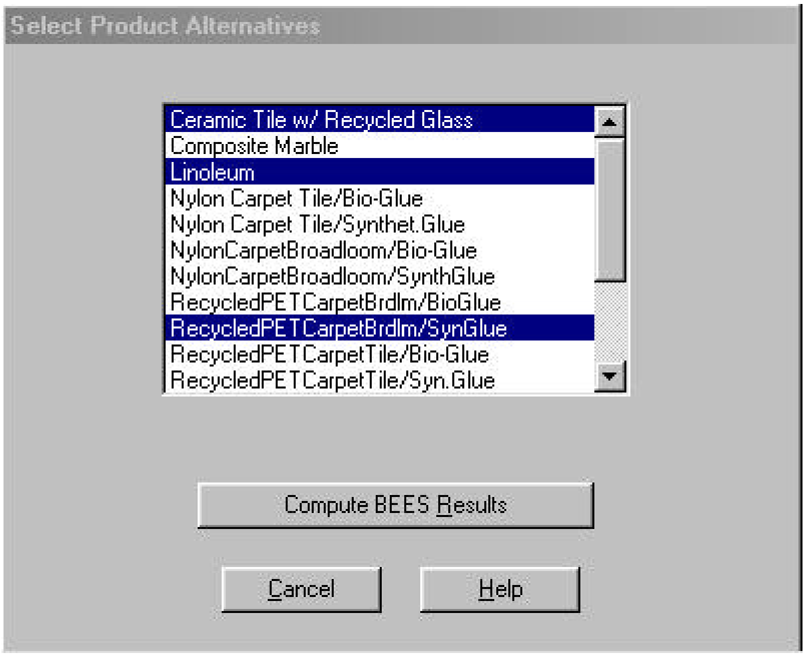

Figure 4.5 Selecting Building Product Alternatives

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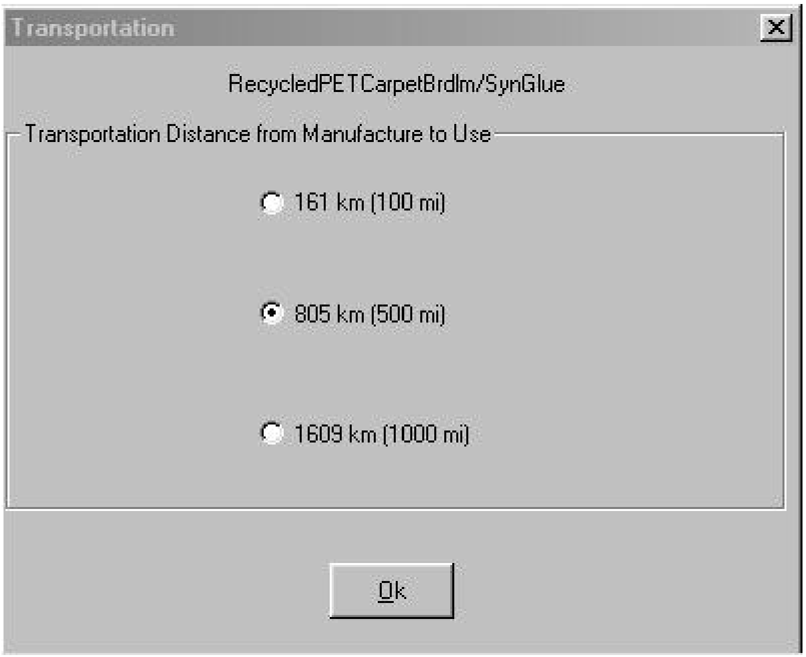
[103] American Society for Testing and Materials, *Standard Classification for Building Elements and Related Sitework--UNIFORMAT II,* ASTM Designation E 1557-96, West Conshohocken, PA, 1996.

[104] If you have chosen the wall insulation element, you will first be asked for parameter values so that heating and cooling energy use over the 50-year study period can be properly estimated. If you have chosen roof coverings and installation will be in a U.S. Sunbelt climate, you will be asked for parameter values that will permit accounting of 50-year heating and cooling energy use based on roof covering color. If you have chosen concrete beams or columns, you will be asked for assumed compressive strength.



Transportation

RecycledPETCarpetBrdlm/SynGlue

Transportation Distance from Manufacture to Use

○ 161 km (100 mi)

● 805 km (500 mi)

○ 1609 km (1000 mi)

Figure 4.6 Setting Transportation Parameters

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

4.3 Viewing Results

Once you have set your study parameters, defined your product alternatives, and computed BEES results, BEES displays the window for selecting BEES reports illustrated in Figure 4.7. By default, the three summary graphs shown in Figures 4.8, 4.9, and 4.10 are selected for display or printing. For all BEES graphs, the larger the value, the *worse* the performance. Also, all BEES graphs are stacked bar graphs, meaning the height of each bar represents a summary performance score consisting of contributing scores represented as its stacked bars.

1. The Overall Performance Results graph displays the weighted environmental and economic performance scores and their sum, the overall performance score. If you chose not to weight, this graph is not available.
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 environmental impact categories, it receives a score of 100, the worst possible score. If you chose not to weight, this graph is not available.
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 detailed BEES environmental and economic performance data, documented in section 3, may be browsed by selecting File/Open from the Main Menu.

From the window for selecting BEES reports, you may choose to display a summary table showing the derivation of summary scores, graphs depicting results by life-cycle stage and by contributing flow for each environmental impact category, graphs depicting embodied energy performance, and an *All Tables in One* option reporting detailed results in tabular form. Figures 4.11 through 4.15 illustrate each of these options[105].

To compare BEES results based on different parameter settings, either bring the summary table in focus and select Analysis/Set Parameters from the Main Menu, or press the *Change Parameters* button on the summary table. Change your parameters, and press Ok. You may now display reports based on your new parameters. You may find it convenient to view reports with different parameter settings side-by-side by selecting Window/Tile from the Main Menu. Note that parameter settings are displayed on the table corresponding to each graph.

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 vary 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. Table 4.1 also indicates the number of environmental impacts available for scoring for each product.[106]

The environmental performance data files are similarly structured, with 3 simulations in each. The first column in all these files, “Xport,” shows compressive strength (in MPa) for concrete products except concrete paving, or transportation distance from manufacture to use (in miles) for all other products. All files contain 3 sets of inventory data corresponding to the 3 simulations. For each simulation, the environmental performance data file lists a number of environmental flows. Flows marked “(r)” are raw materials inputs, “(a)” air emissions, “(ar)”

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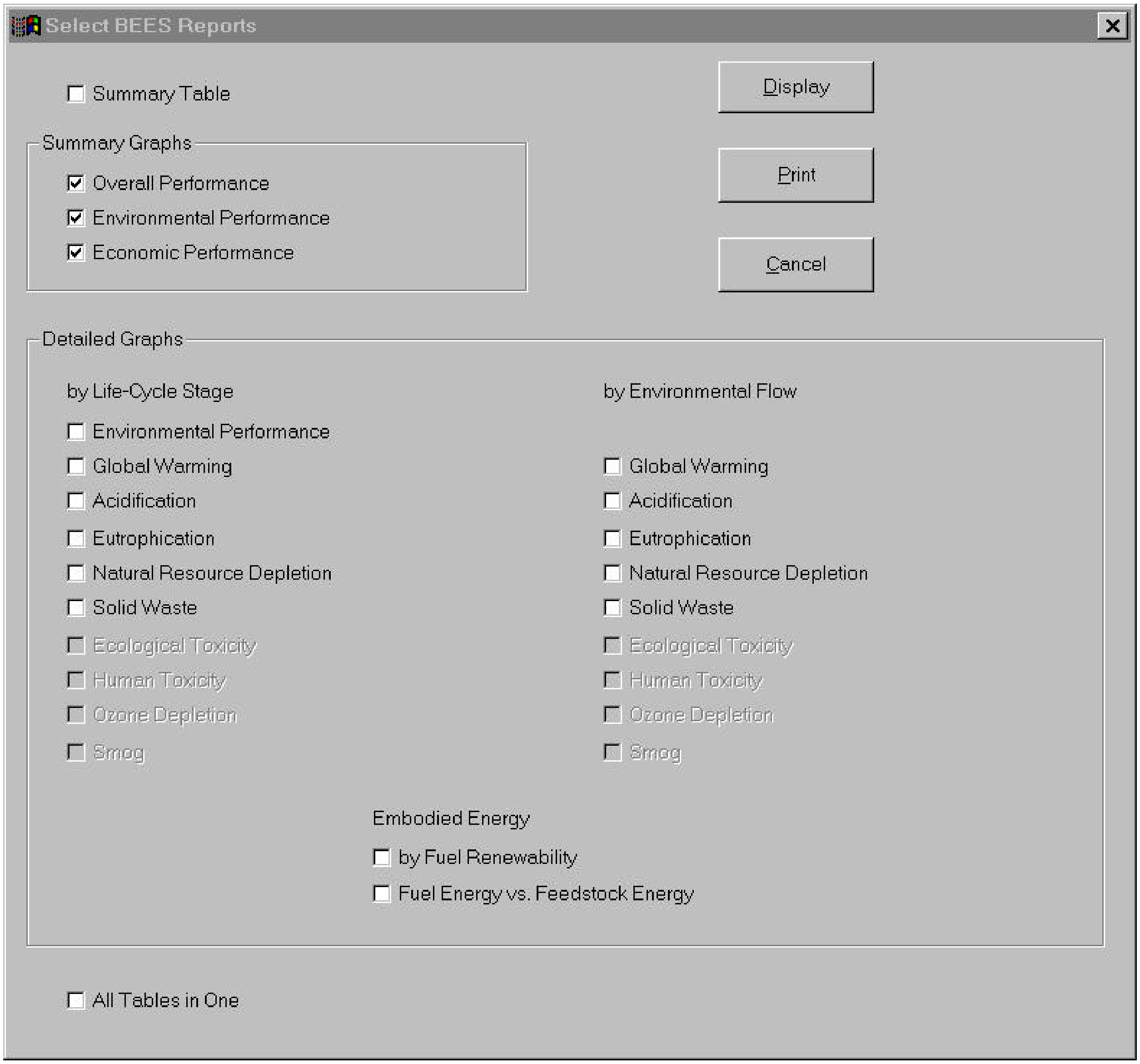
[105] Detailed results for the Indoor Air Quality impact are not reported because this impact is evaluated differently for each relevant building element. Refer to section 2.1.3 for detailed Indoor Air Quality results, and look for summary Indoor Air Quality scores in the BEES summary reports.

[106] Since floor coverings includes a mixture of six- and ten-impact products, if a six-impact product is selected for BEES analysis together with a ten-impact product, both will be scored based on six impacts. Thus, linoleum and vinyl composition tile may be scored based on ten impacts only by selecting these products alone.



☐ Summary Table

Summary Graphs
- ☑ Overall Performance
- ☑ Environmental Performance
- ☑ Economic Performance

Detailed Graphs

by Life-Cycle Stage	by Environmental Flow
☐ Environmental Performance	
☐ Global Warming	☐ Global Warming
☐ Acidification	☐ Acidification
☐ Eutrophication	☐ Eutrophication
☐ Natural Resource Depletion	☐ Natural Resource Depletion
☐ Solid Waste	☐ Solid Waste
☐ Ecological Toxicity	☐ Ecological Toxicity
☐ Human Toxicity	☐ Human Toxicity
☐ Ozone Depletion	☐ Ozone Depletion
☐ Smog	☐ Smog

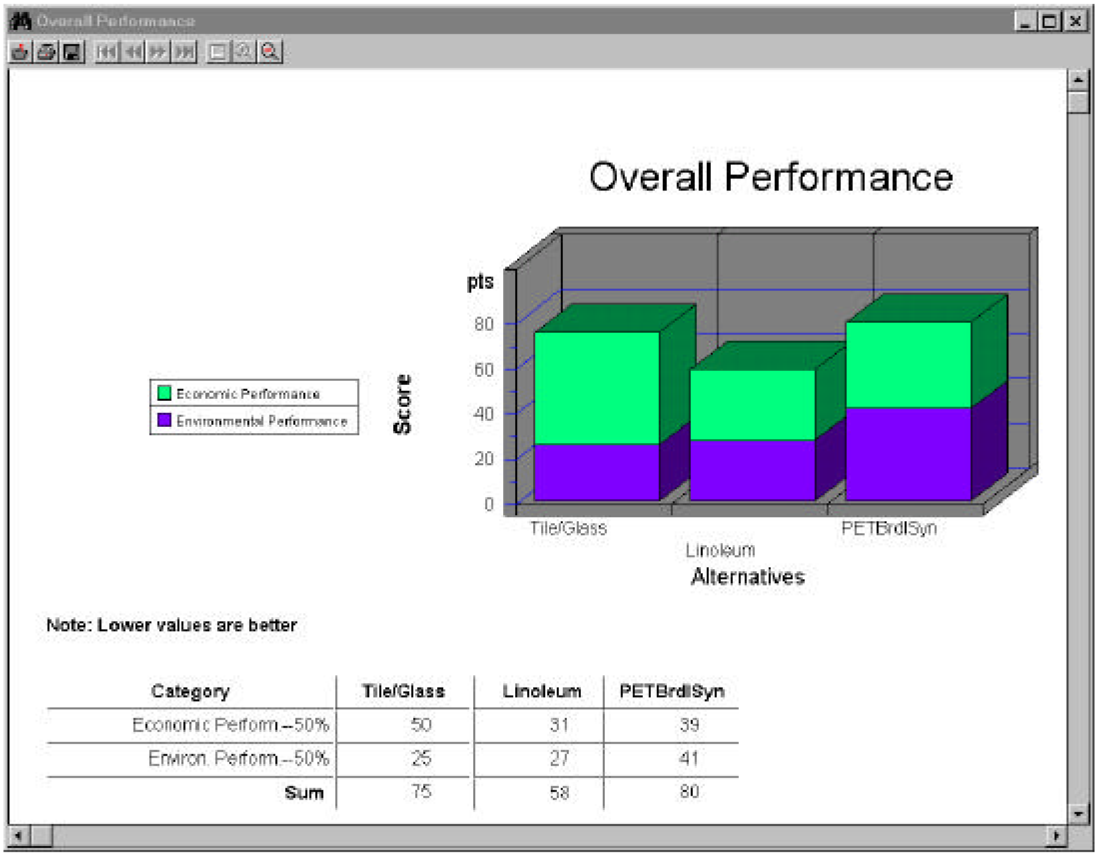
Embodied Energy
- ☐ by Fuel Renewability
- ☐ Fuel Energy vs. Feedstock Energy

☐ All Tables in One

Figure 4.7 Selecting BEES Reports

radioactive air emissions, “(w)” water effluents, “(wr)” radioactive water effluents, “(s)” releases to soil, and “E” energy usage. All quantities for concrete products except paving concrete are given per 0.76 m^3 (1 yd^3) of concrete over 50 years of use, and for all other building products, including concrete paving, per 0.09 m^2 (1 ft^2) of product over 50 years of use. The column labeled “Total” is the primary data column, giving total flow amounts. Next are columns giving flow amounts for each product component, followed by columns giving flow amounts 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.

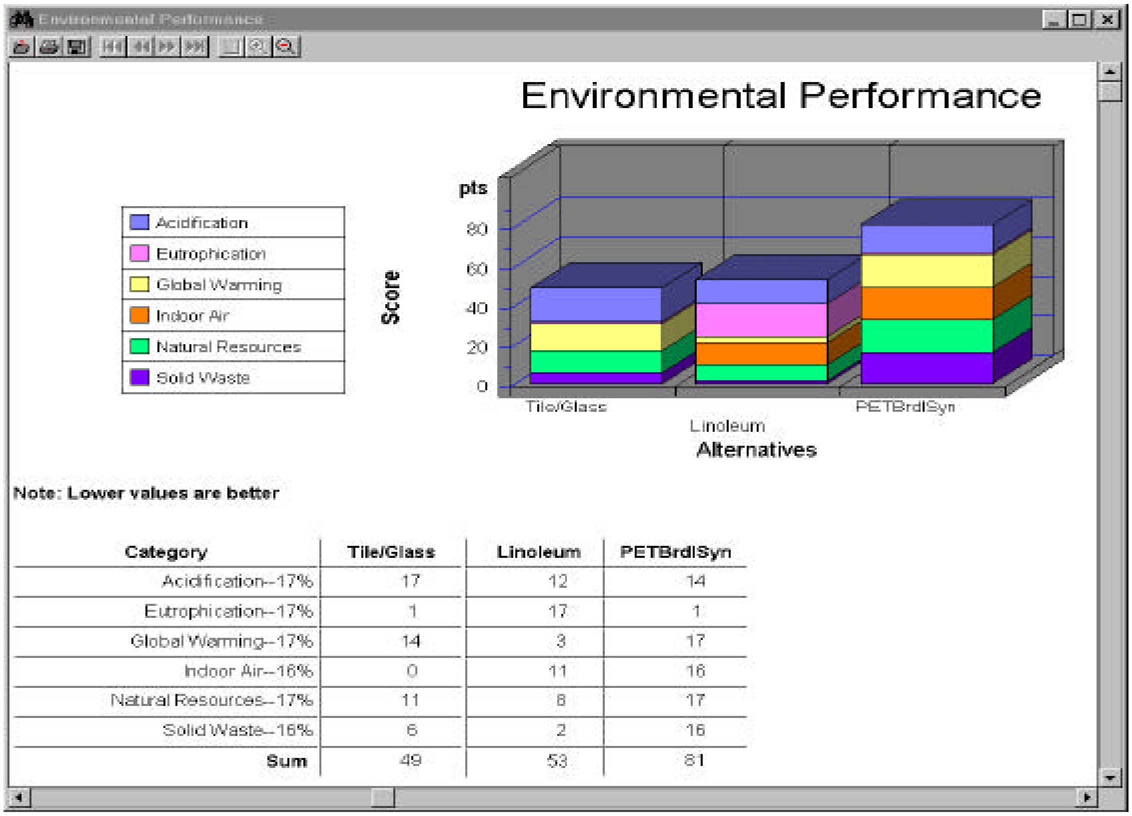
The economic performance data file LCCOSTS.DBF lists for each cost the year of occurrence (counting from year 0) and amount (in 2000 dollars) per 0.76 m^3 (1 yd^3) for concrete products



Note: Lower values are better

Category	Tile/Glass	Linoleum	PETBrdlSyn
Economic Perform.--50%	50	31	39
Environ. Perform.--50%	25	27	41
Sum	75	58	80

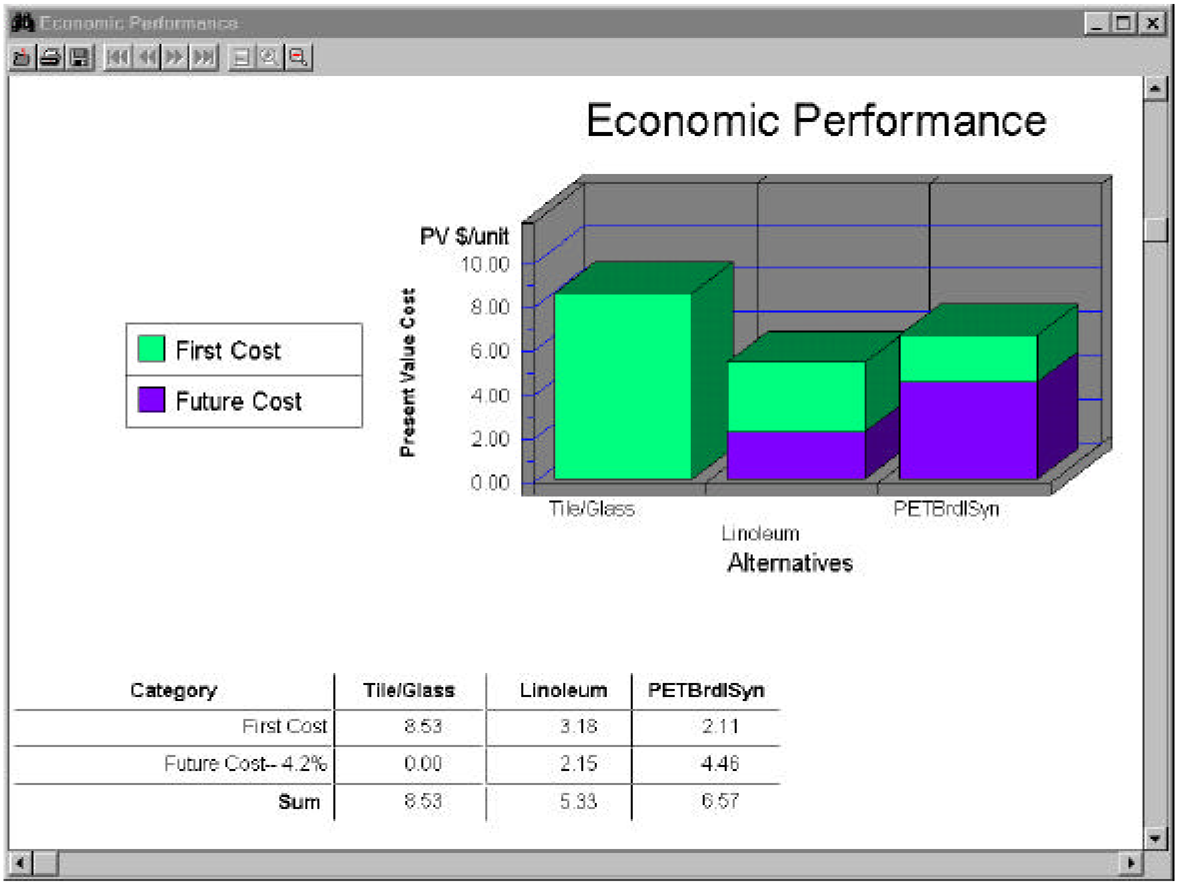
Figure 4.8 Viewing BEES Overall Performance Results



Note: Lower values are better

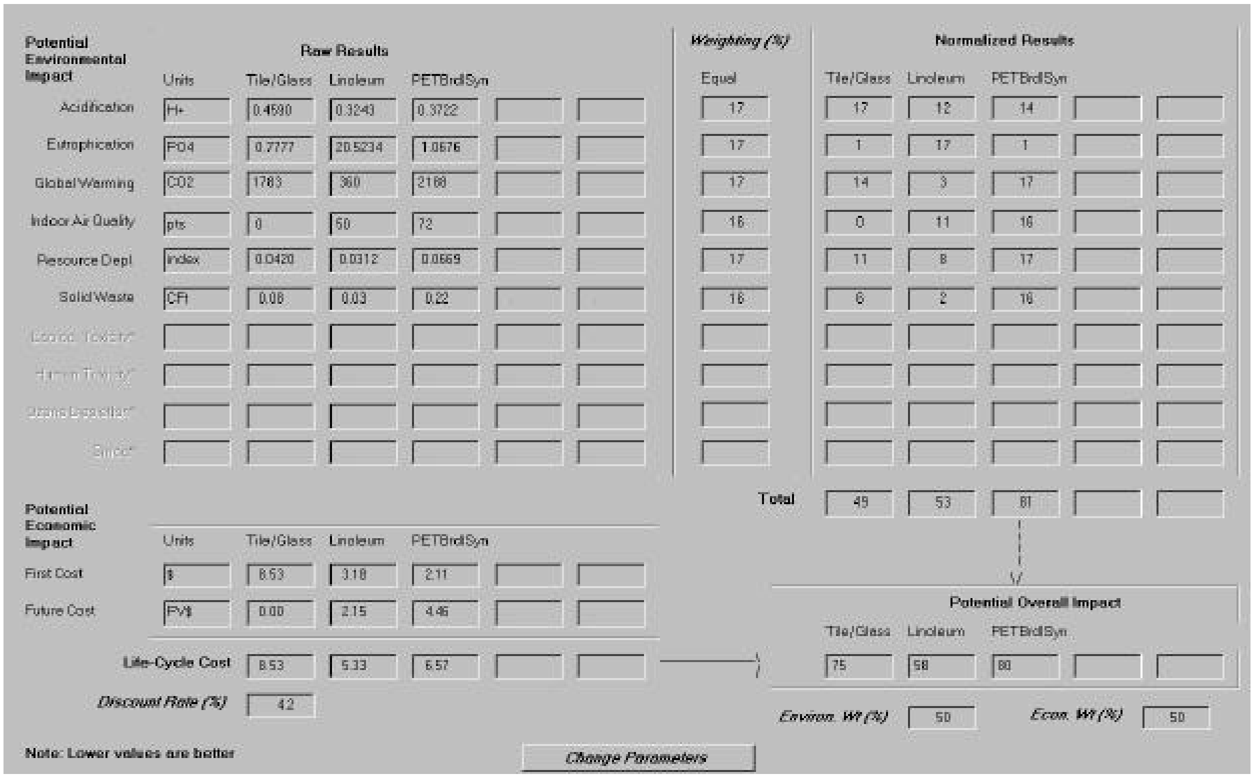
Category	Tile/Glass	Linoleum	PETBrdlSyn
Acidification--17%	17	12	14
Eutrophication--17%	1	17	1
Global Warming--17%	14	3	17
Indoor Air--16%	0	11	16
Natural Resources--17%	11	8	17
Solid Waste--16%	6	2	16
Sum	49	53	81

Figure 4.9 Viewing BEES Environmental Performance Results



Category	Tile/Glass	Linoleum	PETBrdlSyn
First Cost	8.53	3.18	2.11
Future Cost-- 4.2%	0.00	2.15	4.46
Sum	8.53	5.33	6.57

Figure 4.10 Viewing BEES Economic Performance Results



Potential Environmental Impact	Raw Results: Units	Raw Results: Tile/Glass	Raw Results: Linoleum	Raw Results: PETBrdlSyn	*Weighting (%)*: Equal	Normalized Results: Tile/Glass	Normalized Results: Linoleum	Normalized Results: PETBrdlSyn
Acidification	H+	0.4590	0.3243	0.3722	17	17	12	14
Eutrophication	PO4	0.7777	20.5234	1.0676	17	1	17	1
Global Warming	CO2	1783	360	2168	17	14	3	17
Indoor Air Quality	pts	0	50	72	16	0	11	16
Resource Depl	index	0.0420	0.0312	0.0669	17	11	8	17
Solid Waste	CFt	0.08	0.03	0.22	16	6	2	16
Total						49	53	81

Potential Economic Impact	Units	Tile/Glass	Linoleum	PETBrdlSyn
First Cost	$	8.53	3.18	2.11
Future Cost	PV$	0.00	2.15	4.46
Life-Cycle Cost		8.53	5.33	6.57

Discount Rate (%): 4.2

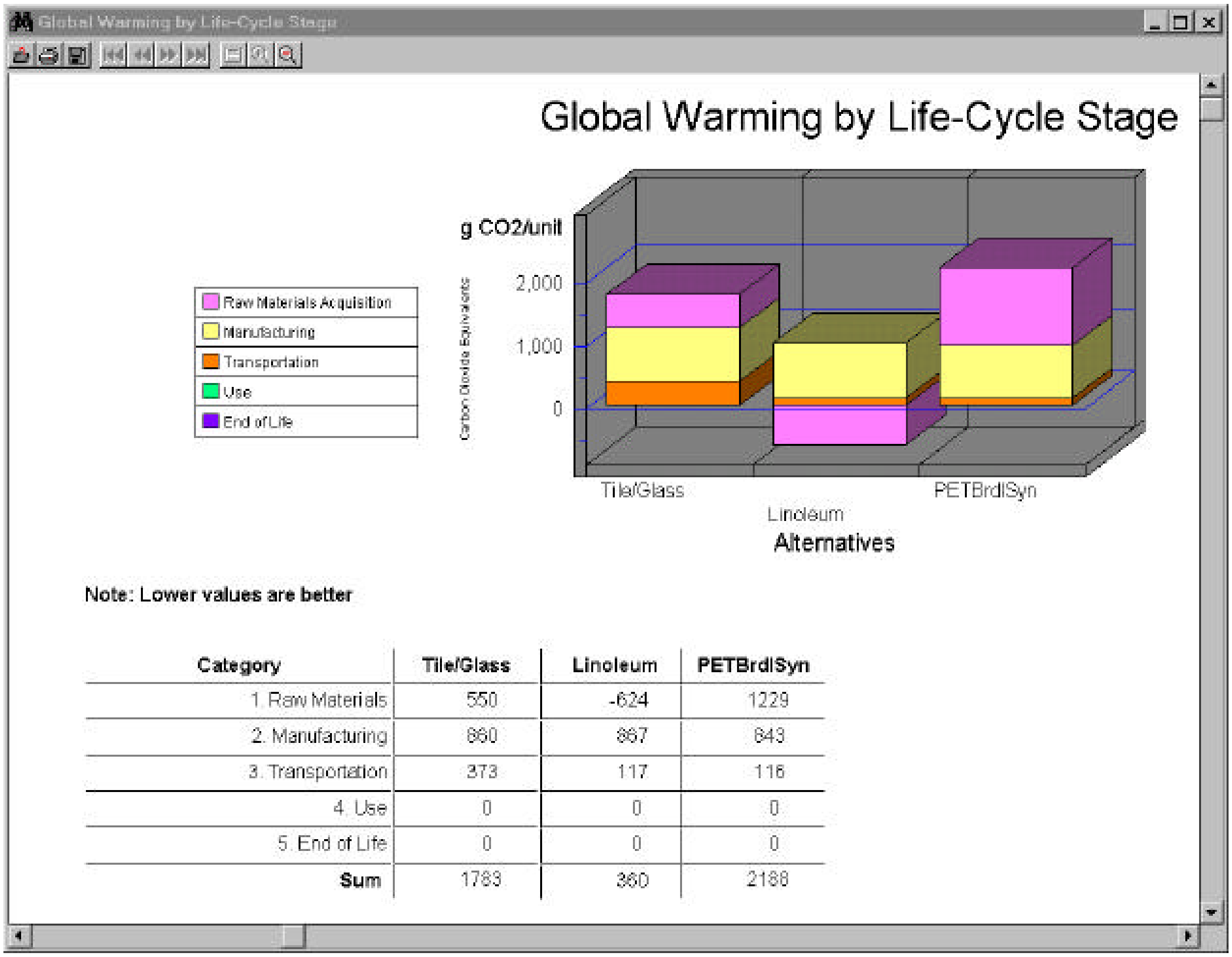
Potential Overall Impact		
Tile/Glass	Linoleum	PETBrdlSyn
75	58	80

Environ. Wt (%): 50

Econ. Wt (%): 50

Note: Lower values are better

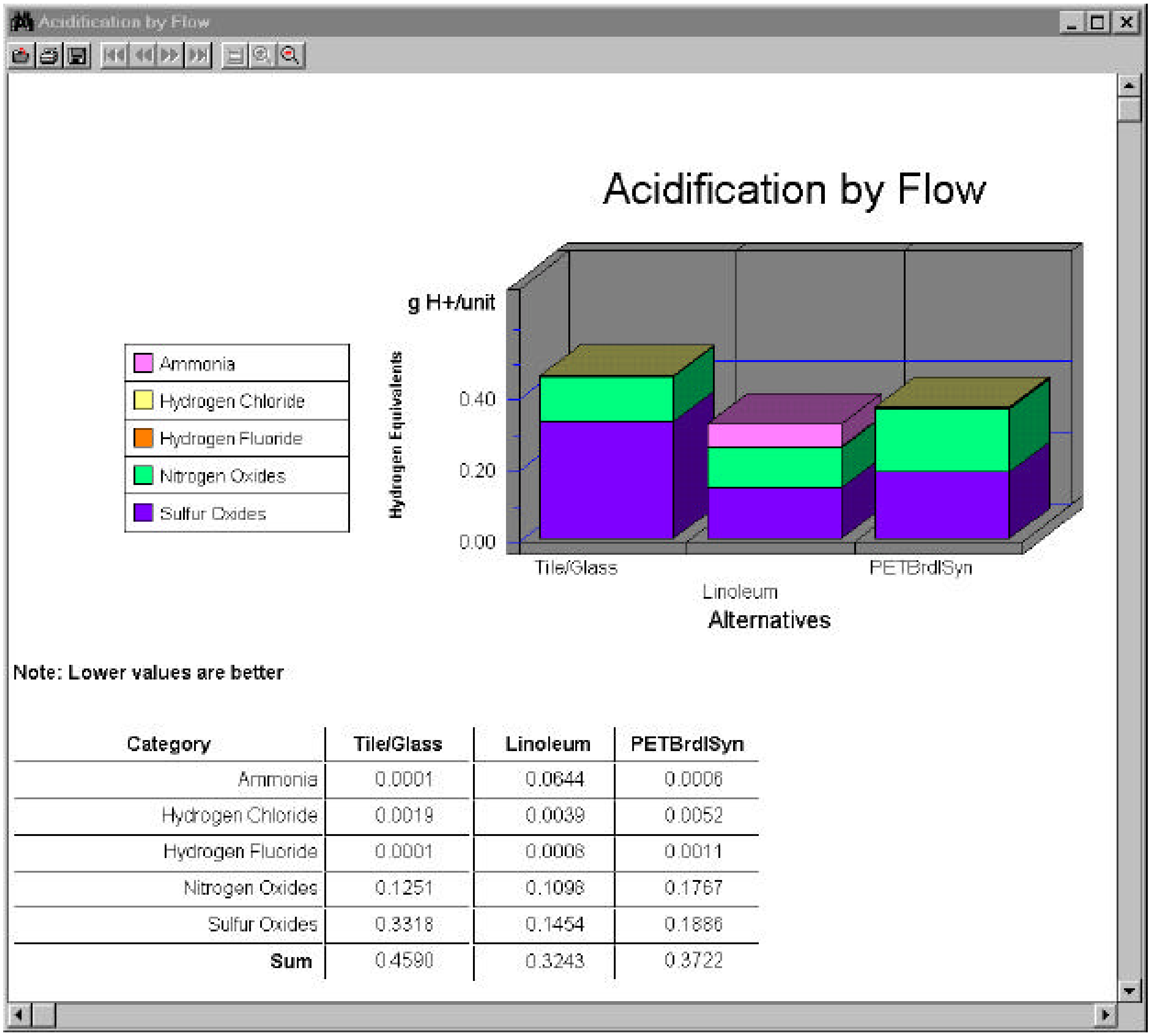
Figure 4.11 Viewing BEES Summary Table



Note: Lower values are better

Category	Tile/Glass	Linoleum	PETBrdlSyn
1. Raw Materials	550	-624	1229
2. Manufacturing	860	867	843
3. Transportation	373	117	116
4. Use	0	0	0
5. End of Life	0	0	0
Sum	1783	360	2188

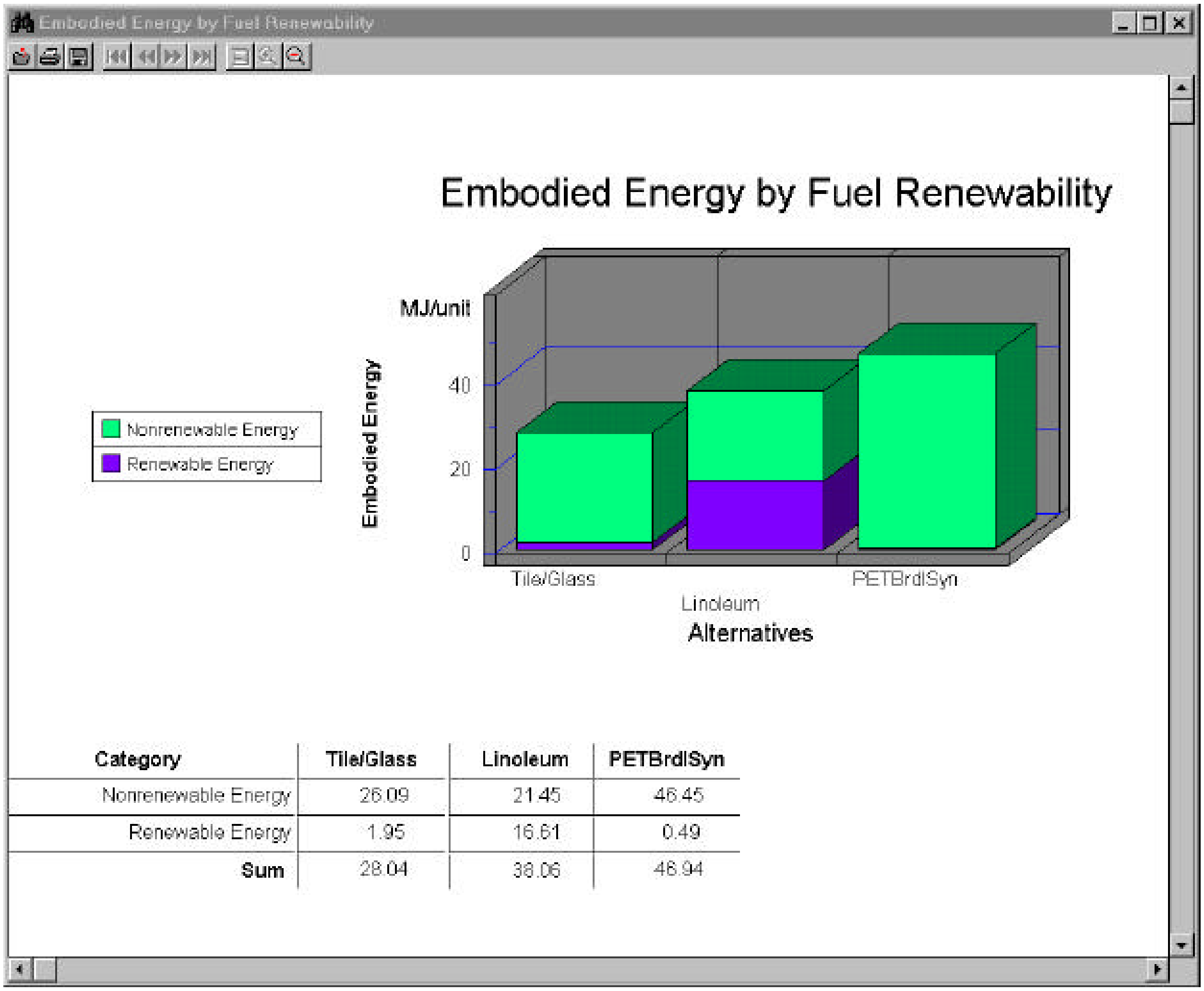
Figure 4.12 Viewing BEES Environmental Impact Category Performance Results by Life-Cycle Stage



Note: Lower values are better

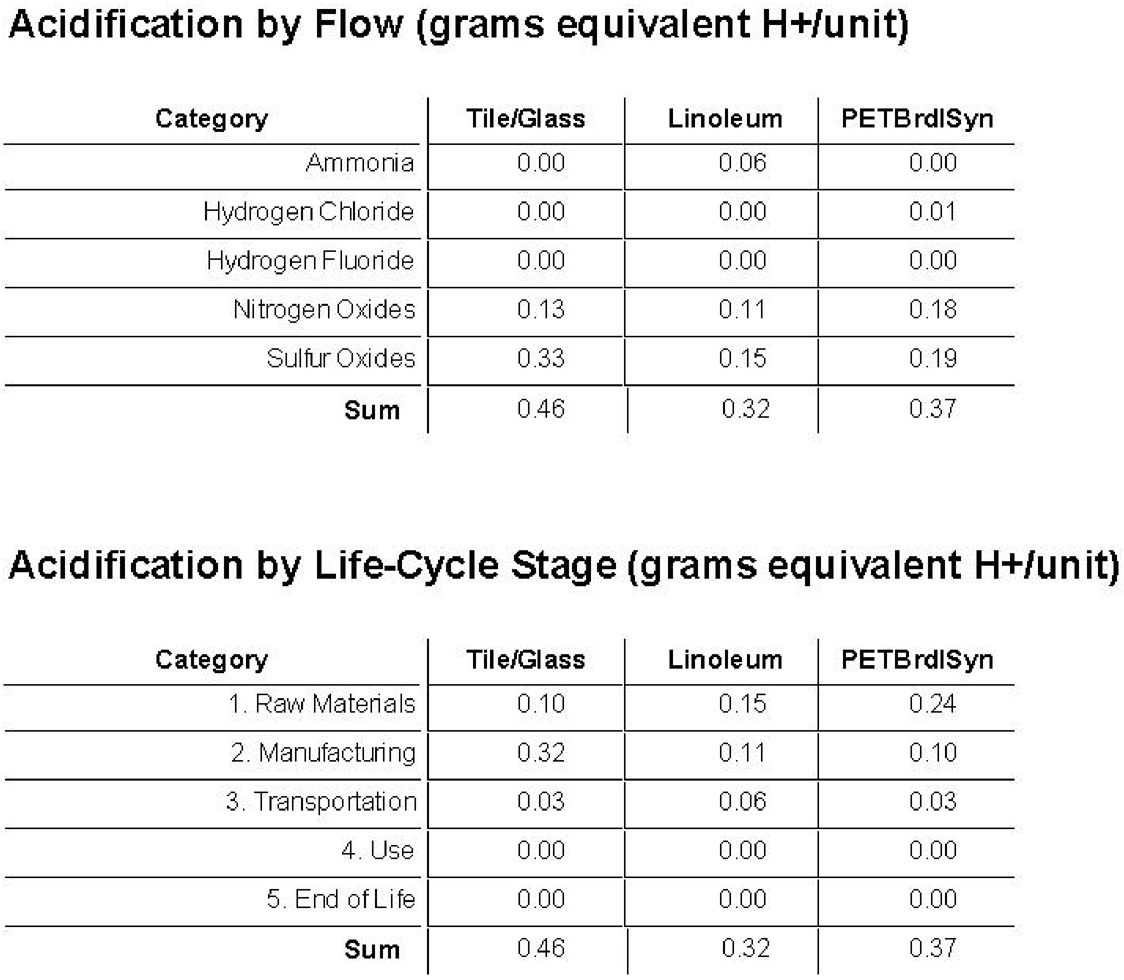
Category	**Tile/Glass**	**Linoleum**	**PETBrdlSyn**
Ammonia	0.0001	0.0644	0.0006
Hydrogen Chloride	0.0019	0.0039	0.0052
Hydrogen Fluoride	0.0001	0.0008	0.0011
Nitrogen Oxides	0.1251	0.1098	0.1767
Sulfur Oxides	0.3318	0.1454	0.1886
Sum	0.4590	0.3243	0.3722

Figure 4.13 Viewing BEES Environmental Impact Category Performance Results Contributing by Flow



Category	Tile/Glass	Linoleum	PETBrdlSyn
Nonrenewable Energy	26.09	21.45	46.45
Renewable Energy	1.95	16.61	0.49
Sum	28.04	38.06	46.94

Figure 4.14 Viewing BEES Embodied Energy Results



Acidification by Flow (grams equivalent H+/unit)

Category	Tile/Glass	Linoleum	PETBrdlSyn
Ammonia	0.00	0.06	0.00
Hydrogen Chloride	0.00	0.00	0.01
Hydrogen Fluoride	0.00	0.00	0.00
Nitrogen Oxides	0.13	0.11	0.18
Sulfur Oxides	0.33	0.15	0.19
Sum	0.46	0.32	0.37

Acidification by Life-Cycle Stage (grams equivalent H+/unit)

Category	Tile/Glass	Linoleum	PETBrdlSyn
1. Raw Materials	0.10	0.15	0.24
2. Manufacturing	0.32	0.11	0.10
3. Transportation	0.03	0.06	0.03
4. Use	0.00	0.00	0.00
5. End of Life	0.00	0.00	0.00
Sum	0.46	0.32	0.37

Figure 4.15 A Sampling of BEES "All Tables In One" Display

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

Individual Element	*BEES Product*	*Number Impacts*	*Environmental Data File Name*	*Economic Data Code*
Slab on Grade	100 % Cement Content Concrete	6	A1030A	A1030,A0
Slab on Grade	15 % Fly Ash Content Concrete	6	A1030B	A1030,B0
Slab on Grade	20 % Fly Ash Content Concrete	6	A1030C	A1030,C0
Slab on Grade	20 % Slag Content Concrete	6	A1030D	A1030,D0
Slab on Grade	35 % Slag Content Concrete	6	A1030E	A1030,E0
Slab on Grade	50 % Slag Content Concrete	6	A1030F	A1030,F0
Basement Walls	100 % Cement Content Concrete	6	A1030A	A2020,A0
Basement Walls	15 % Fly Ash Content Concrete	6	A1030B	A2020,B0
Basement Walls	20 % Fly Ash Content Concrete	6	A1030C	A2020,C0
Basement Walls	20 % Slag Content Concrete	6	A1030D	A2020,D0
Basement Walls	35 % Slag Content Concrete	6	A1030E	A2020,E0
Basement Walls	50 % Slag Content Concrete	6	A1030F	A2020,F0
Beams	100 % Cement Content Concrete	6	A1030A	B1011,A0
Beams	15 % Fly Ash Content Concrete	6	A1030B	B1011,B0
Beams	20 % Fly Ash Content Concrete	6	A1030C	B1011,C0
Beams	20 % Slag Content Concrete	6	A1030D	B1011,D0
Beams	35 % Slag Content Concrete	6	A1030E	B1011,E0
Beams	50 % Slag Content Concrete	6	A1030F	B1011,F0
Columns	100 % Cement Content Concrete	6	A1030A	B1012,A0
Columns	15 % Fly Ash Content Concrete	6	A1030B	B1012,B0
Columns	20 % Fly Ash Content Concrete	6	A1030C	B1012,C0
Columns	20 % Slag Content Concrete	6	A1030D	B1012,D0
Columns	35 % Slag Content Concrete	6	A1030E	B1012,E0
Columns	50 % Slag Content Concrete	6	A1030F	B1012,F0
Roof Sheathing	Oriented Strand Board	6	B1020A	B1020,A0
Roof Sheathing	Plywood	6	B1020B	B1020,B0
Exterior Wall Finishes	Brick & Mortar	6	B2011A	B2011,A0
Exterior Wall Finishes	Stucco	6	B2011B	B2011,B0
Exterior Wall Finishes	Aluminum Siding	6	B2011C	B2011,C0
Exterior Wall Finishes	Cedar Siding	6	B2011D	B2011,D0
Exterior Wall Finishes	Vinyl Siding	6	B2011E	B2011,E0
Wall Insulation	R-13 Blown Cellulose	6	B2012A	B2012,A0
Wall Insulation	R-11 Fiberglass Batt	6	B2012B	B2012,B0
Wall Insulating	R-15 Fiberglass Batt	6	B2012C	B2012,C0
Wall Insulation	R-12 Blown Mineral Wool	6	B2012D	B2012,D0
Wall Insulation	R-13 Fiberglass Batt	6	B2012E	B2012,E0
Framing	Steel	6	B2013A	B2013,A0
Framing	Wood	6	B2013B	B2013,B0
Wall Sheathing	Oriented Strand Board	6	B1020A	B2015,A0
Wall Sheathing	Plywood	6	B1020B	B2015,B0
Roof Coverings	Asphalt Shingle	6	B3011A	B3011,A0
Roof Coverings	Clay Tile	6	B3011B	B3011,B0
Roof Coverings	Fiber Cement Shingle	6	B3011C	B3011,C0
Ceiling Insulation	R-30 Blown Cellulose	6	B3012A	B3012,A0
Ceiling Insulation	R-30 Fiberglass Batt	6	B3012B	B3012,B0
Ceiling Insulation	R-30 Blown Mineral Wool	6	B3012C	B3012,C0
Ceiling Insulation	R-30 Blown Fiberglass	6	B3012D	B3012,D0
Interior Wall Finishes	Virgin Latex Paint	7	C3012A	C3012,A0

Interior Wall Finishes	Recycled Latex Paint	7	C3012B	C3012,B0
Floor Coverings	Ceramic Tile with Recycled Glass	6	C3020A	C3020,A0
Floor Coverings	Linoleum	10	C3020B	C3020,B0
Floor Coverings	Vinyl Composition Tile	10	C3020C	C3020,C0
Floor Coverings	Composite Marble Tile	6	C3020D	C3020,D0
Floor Coverings	Terrazzo	6	C3020E	C3020,E0
Floor Coverings	Nylon Carpet Tile w/Traditional Glue	6	C3020F	C3020,F0
Floor Coverings	Wool Carpet Tile w/Traditional Glue	6	C3020G	C3020,G0
Floor Coverings	Recycled Polyester Tile w/Traditional Glue	6	C3020H	C3020,H0
Floor Coverings	Nylon Carpet Tile w/Low-VOC Glue	6	C3020I	C3020,I0
Floor Coverings	Wool Carpet Tile w/Low-VOC Glue	6	C3020J	C3020,J0
Floor Coverings	Recycled Polyester Tile w/Low-VOC Glue	6	C3020K	C3020,K0
Floor Coverings	Nylon Broadloom Carpet w/Traditional Glue	6	C3020L	C3020,L0
Floor Coverings	Wool Broadloom Carpet w/Traditional Glue	6	C3020M	C3020,M0
Floor Coverings	Recycled Polyester Broadloom w/Traditional Glue	6	C3020N	C3020,N0
Floor Coverings	Nylon Broadloom Carpet w/Low-VOC Glue	6	C3020O	C3020,O0
Floor Coverings	Wool Broadloom Carpet w/Low-VOC Glue	6	C3020P	C3020,P0
Floor Coverings	Recycled Polyester Broadloom Carpet w/Low-VOC Glue	6	C3020Q	C3020,Q0
Parking Lot Paving	100 % Cement Content Concrete	10	G2022A	G2022,A0
Parking Lot Paving	15 % Fly Ash Content Concrete	10	G2022B	G2022,B0
Parking Lot Paving	20 % Fly Ash Content Concrete	10	G2022C	G2022,C0
Parking Lot Paving	Asphalt w/GSB88 Emulsified Sealer-Binder Maintenance	10	G2022D	G2022,D0
Parking Lot Paving	Asphalt w/Cement Maintenance	10	G2022E	G2022,E0
Driveways	100 % Cement Content Concrete	10	G2022A	G2031,A0
Driveways	15 % Fly Ash Content Concrete	10	G2022B	G2031,B0
Driveways	20 % Fly Ash Content Concrete	10	G2022C	G2031,C0
Driveways	Asphalt w/Sealer Maintenance	10	G2031D	G2031D

over 50 years of use (except concrete paving), and cost (in 2000 dollars) per 0.09 m^2 (1 ft^2) for all other products, including concrete paving, over 50 years of use.

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.

5. Future Directions

Development of the BEES tool does not end with the release of version 2.0. Plans to expand and refine BEES include releasing updates every 12 months to 18 months with model and software enhancements as well as expanded 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 1300 BEES 1.0 users:

Proposed Model Enhancements

- Combine building products to permit comparative analyses of entire building components, assemblies, and ultimately entire buildings
- Based on input from homebuilders, residential designers, and product suppliers, tailor the BEES tool to the residential sector (results of this effort may be disseminated as a separate software tool)
- Conduct and apply research leading to the refinement of indoor air performance measurement and to the inclusion of more environmental impacts for all BEES products, such as ecological toxicity, human toxicity, ozone depletion, smog, and land use.
- Update the BEES LCA methodology in line with future advances in the evolving LCA field, such as the anticipated development of national benchmarks for scoring environmental impacts
- 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

- Solicit cooperation from industry to include, manufacturer-specific building products in BEES version 3.0 (known as the "BEES Please" program)
- Add generic 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 locally scarce resources (e.g., water)
- Permit flexibility in study period length and in product specifications such as useful lives.
- Every five years, revisit products included in previous BEES releases for updates to their environmental and cost data
- In support of the U.S. 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 13101 (results of this effort may be disseminated as a separate software tool)

Proposed Software Enhancements

- Add feature permitting users to easily enter their own environmental and cost data for BEES analysis
- 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.

$$\text{EnvScore}_j = \sum_{k=1}^{p} \text{IAScore}_{jk},\ \text{where}$$

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:

$$\text{IAScore}_{jk} = \frac{\text{IA}_{jk} * \text{IVwt}_k}{\text{Max}\{\text{IA}_{1k}, \text{IA}_{2k} \ldots \text{IA}_{mk}\}} * 100,\ \text{where}$$

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:

$$\text{IA}_{jk} = \sum_{i=1}^{n} \text{I}_{ij} * \text{IAfactor}_i,\ \text{where}$$

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

$$\text{LCScore}_{sj} = \sum_{i=1}^{n} \text{IAScore}_{jk} * \text{IPercent}_{ij} * \text{LCPercent}_{sij},\ \text{where}$$

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

$$\text{IPercent}_{ij} = \frac{\text{I}_{ij} * \text{IAfactor}_i}{\sum_{i=1}^{n} \text{I}_{ij} * \text{IAfactor}_i}$$

$$\text{LCPercent}_{sij} = \frac{\text{I}_{sij}}{\sum_{s=1}^{r} \text{I}_{sij}},\ \text{where}$$

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:

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

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:

$$\mathrm{Score_j} = \left[EnvWt * EnvScore_j\right] + \left[EconWt * \left(\frac{LCC_j}{Max(LCC_1, LCC_2, ..., LCC_n)}\right) * 100\right], \text{ where}$$

$Score_j$ = 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);

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