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BEES® 3.0

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

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

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Technical Manual and User Guide

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Abstract

The BEES (**B**uilding for **E**nvironmental and **E**conomic **S**ustainability) version 3.0 software implements a rational, systematic technique for selecting environmentally-friendly, cost-effective 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 nearly 200 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 ASTM International 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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Getting Started

System Requirements
BEES 3.0 runs on Windows 95, 98, 2000, NT, and XP personal computers with a 486 or higher microprocessor, 32 Mb or more of RAM, and at least 110 Mb of available disk space. ***At least one printer must be installed.***

Uninstalling BEES 2.0
While uninstalling BEES 2.0 is not necessary to run BEES 3.0, you may choose to do so. *All* BEES 2.0 files are contained in the folder in which you installed BEES 2.0 (usually C:\BEES20b). Thus, the entire BEES 2.0 program may be uninstalled by simply deleting that folder. If you choose to leave BEES 2.0 on your system, *do not* install BEES 3.0 to its folder.

Installing BEES 3.0
From Download Site. Once you've completed the BEES registration form, click Submit, and then click bees30zip.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 3.0 installation process. During installation, you will need to choose a folder in which to install BEES 3.0; you must choose a folder different from the one that contains the setup file (SETUP.EXE). Once installation is complete, you are ready to run BEES 3.0 by selecting Start→Programs→BEES→BEES 3.0.

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 3.0 by selecting Start→Programs→BEES→BEES 3.0.

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.

Technical Support
For questions regarding the BEES model or software, contact blippiatt@nist.gov.

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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 not an 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) Healthy and Sustainable 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 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

[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 Keynote Address," *Engineering and Construction for Sustainable Development in the 21st Century,* Washington, DC, February 4-8, 1996, p 54)

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 $\$200 \times 10^9$ in products and services they purchase each year, including building products. BEES is being further developed as a tool to assist the Federal procurement community in carrying out the mandate of Executive Order 13101.

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 ASTM International 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 Organization for Standardization (ISO), *Environmental Management--Life-Cycle Assessment--Principles and Framework*, International Standard 14040, 1997; ISO, *Environmental Management--Life-Cycle Assessment—Goal and Scope Definition and Inventory Analysis*, International Standard 14041, 1998; ISO, *Environmental Management--Life-Cycle Assessment—Life Cycle Impact Assessment,* International Standard 14042, 2000; and International Organization for Standardization (ISO), *Environmental Management--Life-Cycle Interpretation—Life Cycle Impact Assessment,* International Standard 14043, 2000.

[4] ASTM International, *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] ASTM International, *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 accused of not being 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 environmental performance scores for building product alternatives sold in the United States. These will be combined with economic performance scores to help the building community select cost-effective, environmentally-friendly building products.

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[6] International Organization for Standardization (ISO), *Environmental Management--Life-Cycle Assessment--Principles and Framework,* International Standard 14040, 1997.

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 the U.S. EPA Office of Research and Development has deemed important in the subsequent impact assessment step.[8]

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.[9] For example, the functional unit for the BEES floor covering alternatives is *covering 0.09* m^2 *(1* ft^2*) of floor surface for 50 years*. For two building elements—roof coverings and wall insulation—it was necessary to further specify functional units to account for important factors affecting their influence on building heating and cooling loads (e.g., local climate, fuel type). Otherwise, all product alternatives are assumed to meet minimum technical performance requirements (e.g., acoustic and fire performance). 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 8 years, and data from the widely-used DEAM LCA database created in 1990.[10] Most of the DEAM data are updated annually. No data older than 1990 are used.
- Technology covered: For generic products, 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.

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[8] U.S. Environmental Protection Agency, *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI): User's Guide and System Documentation*, EPA/600/R-02/052, U.S. EPA Office of Research and Development, Cincinnati, OH, August 2002.

[9] The functional unit for concrete beams and columns is 0.76 cubic meters (1 cubic yard) of product service for 50 years, for chairs is office seating for 1 person for 50 years, for soil treatment is 1 kilogram of soil improver over 50 years, and for transformer oil is cooling for one 1000 kilovolt-ampere transformer for 30 years.

[10] PricewaterhouseCoopers (PwC), *DEAM: Data for Environmental Analysis and Management,* developed by Ecobilan (a member company of PwC), 2001.

2.1.2 Inventory Analysis

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

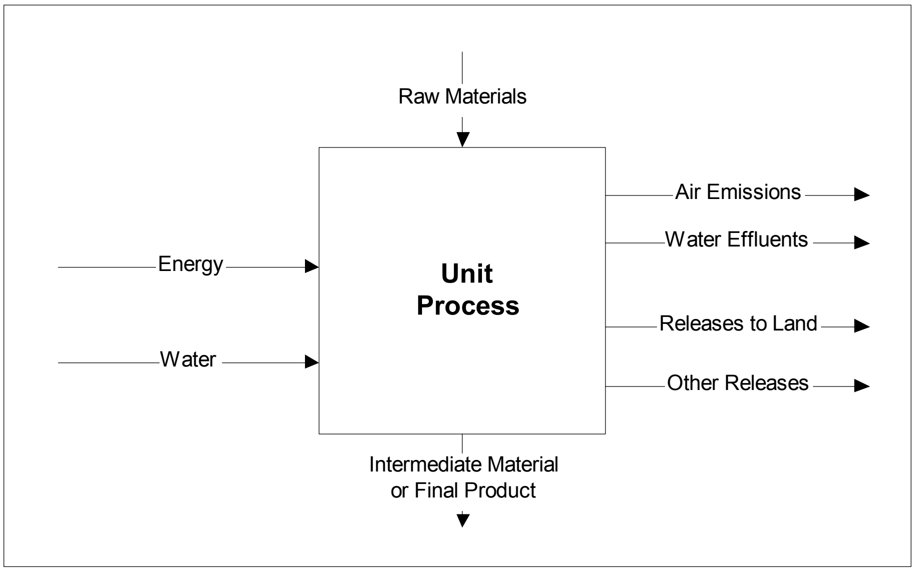

Figure 2.2 BEES Inventory Data Categories

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
- Descriptive: 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, generic product data are primarily collected using the industry-average approach. Manufacturer-specific product data are primarily collected using the unit process- and facility-specific approach, then aggregated to preserve manufacturer confidentiality. Data collection is done under contract with

[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 PricewaterhouseCoopers (PwC), using the PwC DEAM database covering more than 6 000 industrial processes gathered from actual site and literature searches from more than 15 countries. These data represent the closest approximations currently available of the burdens associated with the production, use, and disposal of BEES products. 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 descriptive literature and published reports. The descriptive 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 PwC gathered additional LCA data to fill data gaps for the BEES products. For generic products, assumptions regarding the associated unit processes were verified through experts in the appropriate industries to assure the data are correctly incorporated in BEES. For manufacturer-specific products, a U.S. Office of Management and Budget-approved *BEES Please* Questionnaire is completed by manufacturers to collect inventory data from their manufacturing plant(s); these data are validated by ESS and PwC, then associated upstream and downstream data added to yield cradle-to grave inventories. For more information about the *BEES Please* program, visit http://www.bfrl.nist.gov/oae/software/bees/please/bees_please.html.

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.

2.1.3.1 Impact Assessment Methods

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

[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.

being considered--air, water, or soil. However, the Critical Volume approach has been abandoned for the following reasons:

- Fate and exposure are not considered.
- The underlying assumption that the residual risk at threshold levels is the same for all substances does not hold.[13]
- 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.

Ecological Scarcity (Switzerland). A more general approach has been developed by the Swiss Federal Office of Environment, Forests, and Landscape and applied to Switzerland, Sweden, Belgium, The Netherlands, and Germany.[14] 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 measure of impact.

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

- It is valid only in a specific geographical area.
- Estimating target flows can be a difficult and time-consuming exercise.
- The underlying assumption that the residual risk at target levels is the same for all substances does not hold.[15]
- 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 Development System, the EPS System, was developed by the Swedish Environmental Research Institute.[16] 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.

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[13] M.A. Curran et al., *BEES 2.0, Building for Environmental and Economic Sustainability: Peer Review Report*, NISTIR 6865, Washington, DC, 2002.

[14] BUWAL, *Methode der ökologischen*, Knappheit - Ökofaktoren 1997, Schriftenreihe Umwelt Nr.297, ÖBU/BUWAL, Bern, Switzerland, 1998.

[15] M.A. Curran et al, 2002.

[16] B. Steen, *A Systematic Approach to Environmental Priority Strategies in Product Development (EPS). Version 2000*, CPM Report 1999:4 and 5, CPM, Chalmers University, Göteborg 1999.

- The cost of decreasing each inventory flow by one weight unit.

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

*Eco-Indicator 99***.** The Eco-indicator 99 method is a "damage-oriented" approach to life cycle impact assessment that has been developed in The Netherlands by Pré Consultants.[17] It is appealing for its emphasis on simplifying the subsequent life cycle assessment step, namely, weighting of the relative importance of environmental impacts. To this end, a very limited number of environmental damage categories, or "endpoints," are evaluated: Human Health, Ecosystem Quality, and Resources. Damage models are used to evaluate products in relation to these three impact categories. While the Eco-indicator 99 method offers promise for the future, it has been criticized to date due to the many assessment gaps in the underlying damage models. In addition, the approach has a European focus at present.

Environmental Problems. The Environmental Problems approach to impact assessment was developed within the Society for Environmental Toxicology and Chemistry (SETAC). It involves a two-step process:[18,19,20,21]

- 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 Environmental Problems approach does not offer the same degree of relevance for all environmental impacts. For global and regional effects (e.g., global warming and acidification) the method may result in an accurate description of the potential impact. For impacts dependent upon local conditions (e.g., smog, ecological toxicity, and human health) it may result in an oversimplification of the actual impacts because the indices are not tailored to localities. Another drawback of this method is the unclear environmental importance of the impacts, making the subsequent weighting step difficult.

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[17] M. Goedkoop and R. Spriensma, *The Eco-indicator'99: A damage oriented method for Life Cycle Impact Assessment*, VROM Zoetermeer, Nr. 1999/36A/B, 2nd edition, April 2000.

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

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

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

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

2.1.3.2 Assessing Impacts in BEES

The BEES model uses the Environmental Problems approach where possible because it enjoys some general consensus among LCA practitioners and scientists.[22] The U.S. EPA Office of Research and Development has recently completed development of TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts), a set of state-of-the-art, peer-reviewed U.S. life cycle impact assessment methods that has been adopted in BEES 3.0.[23] Ten of the 11 TRACI impacts follow the Environmental Problems approach: Global Warming Potential, Acidification Potential, Eutrophication Potential, Fossil Fuel Depletion, Habitat Alteration, Criteria Air Pollutants, Human Health, Smog, Ozone Depletion, and Ecological Toxicity. Water Intake, the eleventh impact, is assessed in TRACI using the Direct Use of Inventories Approach. BEES also assesses Indoor Air Quality, an impact not included in TRACI because it is unique to the building industry. Indoor Air Quality is assessed using the Direct Use of Inventories approach, for a total of 12 impacts for most BEES products.[24] Note that some flows characterized by TRACI did not have exact matches in the DEAM database used to develop life cycle inventories for BEES. Where discrepancies were found, a significance analysis was conducted to assess the relevance of the mismatched flows. Proxy flows or alternative characterization factors were developed for those mismatched flows found to be relevant, and validated with TRACI developers.

If the BEES user has important knowledge about other potential environmental impacts, it should be brought into the interpretation of the BEES results. The twelve 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.

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

[23] U.S. Environmental Protection Agency, *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI): User’s Guide and System Documentation*, EPA/600/R-02/052, U.S. EPA Office of Research and Development, Cincinnati, OH, August 2002. For a detailed discussion of the TRACI methods, see J.C.Bare *et al*, "TRACI: The Tool for the Reduction and Assessment of Chemical and other environmental Impacts," *Journal of Industrial Ecology*, Vol. 6, No. 3, 2002.

[24] There are a limited number of BEES products for which Smog, Ecological Toxicity, Human Toxicity, and Ozone Depletion are excluded from the evaluation due to resource contraints. Refer to table 4.1 for a listing of the number of impacts evaluated for each product.

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 characterize the increase in the greenhouse effect due to emissions generated by humankind. LCAs commonly use those GWPs representing a 100-year time horizon. GWPs permit computation of a single index, expressed in grams of carbon dioxide per functional unit of product, that measures the quantity of carbon dioxide with the same potential for global warming over a 100-year period:

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

m_i = mass (in grams) of inventory flow i, and

GWP_i = grams of carbon dioxide with the same heat trapping potential over 100 years as one gram of inventory flow i, as listed in Table 2.1.[25]

Table 2.1 BEES Global Warming Potential Characterization Factors

***Flow** (i)*	***GWP_i** (CO_2-equivalents)*
Carbon Dioxide (CO_2, fossil)	1
Carbon Tetrafluoride (CF_4)	5700
CFC 12 (CCl_2F_2)	10 600
Chloroform ($CHCl_3$, HC-20)	30
Halon 1301 (CF_3Br)	6900
HCFC 22 (CHF_2Cl)	1700
Methane (CH_4)	23
Methyl Bromide (CH_3Br)	5
Methyl Chloride (CH_3Cl)	16
Methylene Chloride (CH_2Cl_2, HC-130)	10
Nitrous Oxide (N_2O)	296
Trichloroethane (1,1,1-CH_3CCl_3)	140

*Acidification Potential***.** 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.

[25] U.S. Environmental Protection Agency, *TRACI*, 2002.

Characterization factors for potential acid deposition onto the soil and in water have been developed like those for the global warming potential, with hydrogen ions as the reference substance. These factors permit computation of a single index for potential acidification (in grams of hydrogen ions per functional unit of product), representing the quantity of hydrogen ion emissions with the same potential acidifying effect:

$$\text{acidification index} = \Sigma_i\, m_i * AP_i, \text{ where}$$

m_i = mass (in grams) of inventory flow i, and
AP_i = millimoles of hydrogen ions with the same potential acidifying effect as one gram of inventory flow i, as listed in Table 2.2.[26]

Table 2.2 BEES Acidification Potential Characterization Factors

***Flow** (i)*	***AP**$_i$* *(Hydrogen-Ion Equivalents)*
Ammonia (NH_3)	95.49
Hydrogen Chloride (HCl)	44.70
Hydrogen Cyanide (HCN)	60.40
Hydrogen Fluoride (HF)	81.26
Hydrogen Sulfide (H_2S)	95.90
Nitrogen Oxides (NO_x as NO_2)	40.04
Sulfur Oxides (SO_x as SO_2)	50.79
Sulfuric Acid (H_2SO_4)	33.30

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.

Characterization factors for potential eutrophication have been developed like those for the global warming potential, with nitrogen as the reference substance. These factors permit computation of a single index for potential eutrophication (in grams of nitrogen per functional unit of product), representing the quantity of nitrogen with the same potential nutrifying effect:

$$\text{eutrophication index} = \Sigma_i\, m_i \;x\; EP_i, \text{ where}$$

m_i = mass (in grams) of inventory flow i, and

[26] *ibid*.

EP_i = grams of nitrogen with the same potential nutrifying effect as one gram of inventory flow i, as listed in Table 2.3.[27]

Table 2.3 BEES Eutrophication Potential Characterization Factors

Flow *(i)*	***EP*** EP_i *(nitrogen-equivalents)*
Ammonia (NH_3)	0.12
Nitrogen Oxides (NO_x as NO_2)	0.04
Nitrous Oxide (N_2O)	0.09
Phosphorus to air (P)	1.12
Ammonia (NH_4^+, NH_3, as N)	0.99
BOD5 (Biochemical Oxygen Demand)	0.05
COD (Chemical Oxygen Demand)	0.05
Nitrate (NO_3^-)	0.24
Nitrite (NO_2^-)	0.32
Nitrogenous Matter (unspecified, as N)	0.99
Phosphates (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$, H_3PO_4, as P)	7.29
Phosphorus to water (P)	7.29

*Fossil Fuel Depletion***.** Some experts believe fossil fuel 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, fossil fuel depletion is at the heart of the sustainability debate.

Fossil fuel depletion is included in the TRACI set of impact assessment methods adopted by BEES 3.0. It is important to recognize that this impact addresses only the depletion aspect of fossil fuel 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.

To assess fossil fuel depletion, TRACI follows the approach developed for the EcoIndicator 99 method, which measures how the amount of energy required to extract a unit of energy for consumption changes over time. Characterization factors have been developed permitting computation of a single index for potential fossil fuel depletion--in surplus megajoules (MJ) per functional unit of product--and assess the surplus energy requirements from the consumption of fossil fuels:

$$\text{fossil fuel depletion index} = \Sigma_i\, c_i \times FP_i, \text{ where}$$

[27] *ibid*.

c_i = consumption (in kg) of fossil fuel i, and

FP_i = MJ input requirement increase per kilogram of consumption of fossil fuel i, as listed in Table 2.4.[28]

Table 2.4 BEES Fossil Fuel Depletion Potential Characterization Factors

Flow *(i)*	***FP_i*** *(surplus MJ/kg)*
Coal (in ground)	0.25
Natural Gas (in ground)	7.80
Oil (in ground)	6.12

While uranium is a major source of energy in the United States, it is not, at present, included in the TRACI assessment of the depletion of nonrenewable fuel resources. As impact assessment science continues to evolve over time, it is hoped that uranium will become part of that assessment. Future versions of BEES will incorporate improved impact assessment methods as they become available.

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 and 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, characterization factors would be available for indoor air pollutants as they are for other flows such as global warming gases. However, there is little scientific consensus about the relative contributions of pollutants to indoor air performance. In the absence of reliable characterization factors, a product's total volatile organic compound (VOC) emissions are often used as a measure of its indoor air performance. Note that a total VOC measure 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 is assessed for the following building elements currently covered in BEES: floor coverings, interior wall finishes, and chairs. Recognizing the inherent limitations in using total VOCs to assess indoor air quality performance, estimates of total VOC emissions are used as a proxy measure. The total VOC emissions over an initial number of hours (e.g., for floor coverings, combined product and adhesive emissions over the first 72 h) is multiplied by the number of times over the 50-year use period those "initial hours" will occur (to account for product replacements), to yield an estimate of total VOC emissions per functional unit of

[28] U.S. Environmental Protection Agency, *TRACI*, 2002.

product. The result is entered into the life cycle inventory for the product, and used directly to assess the indoor air quality impact. The rationale for this particular approach is that VOC emissions are at issue for a limited period of time after installation. The more installations required then, the greater the indoor air quality impact.

Indoor air quality is discussed in the context of sheathing and insulation products. Sheathing products are often made of wood, which is of concern for its 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 oriented strand board (OSB) and softwood plywood, both included as sheathing products in BEES. Most OSB is now made using a methylene diphenylisocyanate (MDI) binder, and is modeled as such in BEES. OSB using an MDI binder emits no formaldehyde other than the insignificant amount naturally occurring in the wood itself.[29] 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.[30] Thus, assuming formaldehyde emission is the only significant indoor air concern for wood products, neither of the two composite wood products as modeled in BEES are thought to significantly affect indoor air quality.

Indoor air quality is also an issue for 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 manufacturers' recommendations. Assuming proper installation, then, none of these products as modeled in BEES are thought to significantly affect indoor air quality.[31]

All other BEES building elements are primarily exterior elements, or interior elements made of inert materials, for which indoor air quality is not an issue.

Note that due to limitations in indoor air science, the BEES indoor air performance scores are based on heuristics. If the BEES user has better knowledge about indoor air performance, it should be brought into the interpretation of the results.

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

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

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

Habitat Alteration. The habitat alteration impact measures the potential for land use by humans to lead to damage of Threatened and Endangered (T&E) Species. In TRACI, the set of U.S. impact assessment methods adopted in BEES, the density of T&E Species is used as a proxy for the degree to which the use of land may lead to undesirable changes in habitats. Note that this approach does not consider the original condition of the land, the extent to which human activity changes the land, or the length of time required to restore the land to its original condition. As impact assessment science continues to evolve, it is hoped that these potentially important factors will become part of the habitat alteration assessment. Future versions of BEES will incorporate improved habitat alteration assessment methods as they become available.

Inventory data are not readily available for habitat alteration assessment across all life cycle stages; the use and end-of-life stages offer the only reliable inventory data for this impact to date. These two stages, though, may be the most important life cycle stages for habitat alteration assessment due to their contributions to landfills. Indeed, an informal evaluation of two interior wall products found that post-consumer landfill use accounted for more than 80 % of the total habitat alteration impact for both products. In BEES, habitat alteration is assessed at the use and end of life stages only, based on the landfilled waste (adjusted for current recycling practices) from product installation, replacement, and end of life. Future versions of BEES will incorporate more life cycle stages as consistent inventory data become available.

Characterization factors have been developed permitting computation of a single index for potential habitat alteration, expressed in T&E Species count per functional unit of product:

$$\text{habitat alteration index} = \Sigma_i \, a_i \times \text{TED, where}$$

a_i = surface area (in m^2 disrupted) of land use flow i, and
TED = U.S. T&E Species density (in T&E Species count per m^2), as listed in Table 2.5.[32]

Table 2.5 BEES Habitat Alteration Potential Characterization Factors

Flow (i)	***TED (T&E count/m²)***
Land Use (Installation Waste)	6.06E-10
Land Use (Replacement Waste)	6.06E-10
Land Use (End-of-Period Waste)	6.06E-10

[32]U.S. Environmental Protection Agency, *TRACI*, 2002.

Water Intake. Water resource depletion has not been routinely assessed in LCAs to date, but researchers are beginning to address this issue to account for areas where water is scarce, such as the Western United States. It is important to recognize that this impact addresses only the depletion aspect of water intake, not the fact that activities such as agricultural production and product manufacture may generate water pollution. Water pollution impacts, such as nitrogen runoff from agricultural production, are addressed in other impacts, such as eutrophication.

In TRACI, the set of U.S. impact assessment methods adopted in BEES, the Direct Use of Inventories approach is used to assess water resource depletion. Water intake from cradle to grave is recorded in the BEES life cycle inventory for each product (in liters per functional unit), and is used directly to assess this impact.

Criteria Air Pollutants. Criteria air pollutants are solid and liquid particles commonly found in the air. They arise from many activities including combustion, vehicle operation, power generation, materials handling, and crushing and grinding operations. They include coarse particles known to aggravate respiratory conditions such as asthma, and fine particles that can lead to more serious respiratory symptoms and disease.[33]

Disability-adjusted life years, or DALYs, have been developed to measure health losses from air pollution. They account for years of life lost and years lived with disability, adjusted for the severity of the associated unfavorable health conditions. TRACI characterization factors permit computation of a single index for criteria air pollutants, with disability-adjusted life years (DALYs) as the common metric:

$$\text{criteria air pollutants index} = \Sigma_i\, m_i \times CP_i, \text{ where}$$

m_i = mass (in grams) of inventory flow i, and

CP_i = microDALYs per gram of inventory flow i, as listed in Table 2.6.[34]

Table 2.6 BEES Criteria Air Pollutant Characterization Factors

***Flow** (i)*	***CP_i** (microDALYs/g)*
Nitrogen Oxides (NO_x as NO_2)	0.002
Particulates (>PM10)	0.046
Particulates (<=PM 10)	0.083
Particulates (unspecified)	0.046
Sulfur Oxides (SO_x as SO_2)	0.014

Human Health.

There are many potential human health 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 widely varying

[33] i*bid.*
[34] *ibid*.

tolerances to different substances. BEES adopts and extends the TRACI approach to evaluating human health impacts. Note that this approach does not include occupational health effects.

TRACI has developed Toxicity Equivalency Potentials (TEPs), which are characterization factors measuring the relative health concern associated with various chemicals from the perspective of a generic individual in the United States. For cancer effects, the TRACI system's TEPs are expressed in terms of benzene equivalents, while for noncancer health effects, they are denominated in toluene equivalents. In order to synthesize all environmental impacts in the next LCA step (interpretation), however, BEES requires a combined measure of cancer and noncancer health effects because default impact importance weights are available only at the combined level. The BEES 2.0 Peer Review Team suggested that to address this need, threshold levels for toluene and benzene be obtained from the developers of the TRACI TEPs and be given equal importance in combining cancer and noncancer health effects.[35] Threshold levels were thus obtained and used to develop a ratio converting benzene equivalents to toluene equivalents (21 100 kg/kg).[36]

The "extended" TRACI characterization factors permit computation of a single index for potential human health effects (in grams of toluene per functional unit of product), representing the quantity of toluene with the same potential human health effects:

$$\text{human health index} = \Sigma_i\ m_i \times HP_i, \text{ where}$$

m_i = mass (in grams) of inventory flow i, and
HP_i = grams of toluene with the same potential human health effects as one gram of inventory flow i.

There are more than 200 flows included in the BEES human health impact assessment. A sampling of the most important of these flows and their characterization factors are reported in Table 2.7, sorted in descending order of toluene equivalents.[37] Flows to air are preceded with the designation "(a)" and flows to water with the designation "(w)." To browse the entire list of human health flows and factors, open the file EQUIV12.DBF under the File/Open menu item in the BEES software.

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[35] M.A. Curran *et al., BEES 2.0, Building for Environmental and Economic Sustainability: Peer Review Report*, 2002.

[36] Personal correspondence with Edgar Hertwich, International Institute for Applied Systems Analysis, Laxenburg, Austria, 6/20/2002.

[37] U.S. Environmental Protection Agency, *TRACI*, 2002. As discussed, TRACI benzene equivalents have been converted to toluene equivalents.

Table 2.7 Sampling of BEES Human Health Characterization Factors

***Flow** (i)*	***HP_i** (toluene-equivalents)*
Cancer--(a) Dioxins (unspecified)	38 292 661 685 580
Noncancer--(a) Dioxins (unspecified)	2 286 396 218 965
Cancer--(a) Diethanol Amine ($C_4H_{11}O_2N$)	2 532 000 000
Cancer--(a) Arsenic (As)	69 948 708
Cancer--(a) BenzoCancer--(a)pyrene ($C_{20}H_{12}$)	34 210 977
Noncancer--(a) Mercury (Hg)	19 255 160
Noncancer--(w) Mercury (Hg^+, Hg^{++})	18 917 511
Cancer--(a) Carbon Tetrachloride (CCl_4)	17 344 285
Cancer--(w) Arsenic (As^{3+}, As^{5+})	17 210 446
Cancer--(w) Carbon Tetrachloride (CCl_4)	16 483 833
Cancer--(a) Benzo(k)fluoranthene	12 333 565
Cancer--(w) Hexachloroethane (C_2Cl_6)	8 415 642
Cancer--(w) Phenol (C_6H_5OH)	8 018 000
Noncancer--(a) Cadmium (Cd)	4 950 421
Cancer--(a) Trichloropropane (1,2,3-$C_2H_5Cl_3$)	3 587 000
Cancer--(a) Chromium (Cr III, Cr VI)	3 530 974
Cancer--(a) Dimethyl Sulfate ($C_2H_6O_4S$)	2 976 375
Cancer--(a) Cadmium (Cd)	1 759 294
Cancer--(a) Indeno (1,2,3,c,d) Pyrene	1 730 811
Noncancer--(a) Lead (Pb)	1 501 293
Cancer--(a) Dibenzo(a,h)anthracene	1 419 586
Cancer--(a) Benzo(b)fluoranthene	1 356 632
Cancer--(a) Benzo(bjk)fluoranthene	1 356 632
Cancer--(a) Lead (Pb)	748 316
Cancer--(a) Ethylene Oxide (C_2H_4O)	650 701

*Smog Formation Potential***.** 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). Smog leads to harmful impacts on human health and vegetation. In BEES, the smog impact does not account for indoor VOCs that make their way outdoors. Rather, indoor VOCs are evaluated under the BEES Indoor Air Quality impact.

Characterization factors for potential smog formation have been developed for the TRACI set of U.S. impact assessment methods, with nitrogen oxides as the reference substance. These factors permit computation of a single index for potential smog formation (in grams of nitrogen oxides per functional unit of product), representing the quantity of nitrogen oxides with the same potential for smog formation:

$$\text{smog index} = \Sigma_i\ m_i \times SP_i, \text{ where}$$

m_i = mass (in grams) of inventory flow i, and
SP_i = grams of nitrogen oxides with the same potential for smog formation as one gram of inventory flow i.

There are more than 100 flows included in the BEES smog assessment. A sampling of the most important of these flows and their characterization factors are reported in Table 2.8, sorted in descending order of nitrogen oxides equivalents.[38] To browse the entire list of smog flows and factors, open the file EQUIV12.DBF under the File/Open menu item in the BEES software.

Table 2.8 Sampling of BEES Smog Characterization Factors

***Flow** (i)*	***SP_i*** *(nitrogen oxides-equivalents)*
Furan (C_4H_4O)	3.54
Butadiene (1,3-$CH_2CHCHCH_2$)	3.23
Propylene ($CH_3CH_2CH_3$)	3.07
Xylene (m-$C_6H_4(CH_3)_2$)	2.73
Butene (1-$CH_3CH_2CHCH_2$)	2.66
Crotonaldehyde (C_4H_6O)	2.49
Formaldehyde (CH_2O)	2.25
Propionaldehyde (CH_3CH_2CHO)	2.05
Acrolein (CH_2CHCHO)	1.99
Xylene (o-$C_6H_4(CH_3)_2$)	1.93
Xylene ($C_6H_4(CH_3)_2$)	1.92
Trimethyl Benzene (1,2,4-$C_6H_3(CH_3)_3$)	1.85
Acetaldehyde (CH_3CHO)	1.79
Aldehyde (unspecified)	1.79
Butyraldehyde ($CH_3CH_2CH_2CHO$)	1.74
Isobutyraldehyde ($(CH_3)_2CHCHO$)	1.74
Ethylene Glycol ($HOCH_2CH_2OH$)	1.40
Acenaphthene ($C_{12}H_{10}$)	1.30
Acenaphthylene ($C_{12}H_8$)	1.30
Hexanal ($C_6H_{12}O$)	1.25
Nitrogen Oxides (NOx as NO_2)	1.24
Glycol Ether (unspecified)	1.11
Methyl Naphthalene (2-$C_{11}H_{10}$)	1.10
Xylene (p-$C_6H_4(CH_3)_2$)	1.09
Toluene ($C_6H_5CH_3$)	1.03

Ozone Depletion Potential. 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

[38] *Ibid.*

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.

Characterization factors for potential ozone depletion are included in the TRACI set of U.S. impact assessment methods, with CFC-11 as the reference substance. These factors permit computation of a single index for potential ozone depletion (in grams of CFC-11 per functional unit of product), representing the quantity of CFC-11 with the same potential for ozone depletion:

$$\text{ozone depletion index} = \Sigma_i \, m_i \times OP_i, \text{ where}$$

m_i = mass (in g) of inventory flow i, and

OP_i = grams of CFC-11 with the same ozone depletion potential as one gram of inventory flow i, as listed in Table 2.9.[39]

Table 2.9 BEES Ozone Depletion Potential Characterization Factors

***Flow** (i)*	***OP$_i$*** *(CFC-11 equivalents)*
Carbon Tetrachloride (CC_{l4})	1.10
CFC 12 (CCl_2F_2)	1.00
Halon 1301 (CF_3Br)	10.00
HCFC 22 (CHF_2Cl)	0.06
Methyl Bromide (CH_3Br)	0.60
Trichloroethane (1,1,1-CH_3CCl_3)	0.10

*Ecological Toxicity***.** The ecological toxicity impact measures the potential of a chemical released into the environment to harm terrestrial and aquatic ecosystems. An assessment method for this impact was developed for the TRACI set of U.S. impact assessment methods and adopted in BEES. The method involves measuring pollutant concentrations from industrial sources as well as the potential of these pollutants to harm ecosystems.

TRACI characterization factors for potential ecological toxicity use 2,4-dichlorophenoxy-acetic acid (2,4-D) as the reference substance. These factors permit computation of a single index for potential ecological toxicity (in grams of 2,4-D per functional unit of product), representing the quantity of 2,4-D with the same potential for ecological toxicity:

$$\text{ecological toxicity index} = \Sigma_i \, m_i \times EP_i, \text{ where}$$

m_i = mass (in grams) of inventory flow i, and

[39] *ibid*.

EP_i = grams of 2,4-D with the same ecological toxicity potential as one gram of inventory flow i.

There are more than 150 flows included in the BEES ecological toxicity assessment. A sampling of the most important of these flows and their characterization factors are reported in Table 2.10, sorted in descending order of 2,4-D equivalents.[40] Flows to air are preceded with the designation "(a)" and flows to water with the designation "(w)." To browse the entire list of ecological toxicity flows and factors, open the file EQUIV12.DBF under the File/Open menu item in the BEES software.

Table 2.10 Sampling of BEES Ecological Toxicity Potential Characterization Factors

Flow *(i)*	***EP_i*** *(2,4-D equivalents)*
(a) Dioxins (unspecified)	2 486 822.73
(a) Mercury (Hg)	118 758.09
(a) Benzo(g,h,i)perylene ($C_{22}H_{12}$)	4948.81
(a) Cadmium (Cd)	689.74
(a) Benzo(a)anthracene	412.83
(a) Chromium (Cr VI)	203.67
(w) Naphthalene ($C_{10}H_8$)	179.80
(a) Vanadium (V)	130.37
(a) Benzo(a)pyrene ($C_{20}H_{12}$)	109.99
(a) Beryllium (Be)	106.56
(a) Arsenic (As)	101.32
(a) Copper (Cu)	89.46
(w) Vanadium (V^{3+}, V^{5+})	81.82
(a) Nickel (Ni)	64.34
(w) Mercury (Hg^{+}, Hg^{++})	58.82
(a) Cobalt (Co)	49.45
(a) Selenium (Se)	35.07
(a) Fluoranthene	29.47
(w) Copper (Cu^{+}, Cu^{++})	26.93
(a) Chromium (Cr III, Cr VI)	24.54
(w) Cadmium (Cd^{++})	22.79
(w) Formaldehyde (CH_2O)	22.62
(a) Zinc (Zn)	18.89
(w) Beryllium (Be)	16.55
(a) Lead (Pb)	12.32

2.1.3.3 Normalizing Impacts in BEES

Once impacts have been assessed, the resulting impact category performance measures are expressed in noncommensurate units. Global warming is expressed in carbon dioxide equivalents, acidification in hydrogen ion equivalents, eutrophication in nitrogen equivalents,

[40] *Ibid.*

and so on. In order to assist in the next LCA step, interpretation, performance measures are often placed on the same scale through normalization.

The U.S. EPA Office of Research and Development has recently developed normalization data corresponding to its TRACI set of impact assessment methods.[41] These data are used in BEES to place its impact assessment results on the same scale. The data, reported in table 2.11, estimate for each impact its performance at the U.S. level. Specifically, inventory flows contributing to each impact have been quantified and characterized in terms of U.S. flows per year per capita.[42] Summing all characterized flows for each impact then yields, in effect, impact category performance measures for the United States. As such, they represent a new "U.S. impact yardstick" against which to evaluate the *significance* of product-specific impacts. Normalization is accomplished by dividing BEES product-specific impacts by the fixed U.S.-scale impacts, yielding an impact category performance measure that has been placed in the context of all U.S. activity contributing to that impact. By placing each product-specific impact measure in the context of its associated U.S. impact measure, the measures are all reduced to the same scale, allowing comparison across impacts.

Table 2.11 BEES Normalization Values

Impact	***Normalization Value***
Global Warming	25 582 640.09 g CO_2 equivalents/year/capita
Acidification	7 800 200 000.00 millimoles H+ equivalents/year/capita
Eutrophication	19 214.20 g N equivalents/year/capita
Fossil Fuel Depletion	35 309.00 MJ surplus energy/year/capita
Indoor Air Quality	35 108.09 g TVOCs/year/capita
Habitat Alteration	0.00335 T&E count/acre/capita[a]
Water Intake	529 957.75 liters of water/year/capita
Criteria Air Pollutants	19 200.00 microDALYs/year/capita
Smog	151 500.03 g NO_X equivalents/year/capita
Ecological Toxicity	81 646.72 g 2,4-D equivalents/year/capita
Ozone Depletion	340.19 g CFC-11 equivalents/year/capita
Human Health	158 768 677.00 g C_7H_7 equivalents/year/capita

[a] One acre is equivalent to 0.40 hectares.

Normalized BEES impact scores now have powerful implications. For the first time, the significance of impact scores is evaluated, meaning that scores no longer need be compared to one another without reference to their importance in a larger context. As a result, for example, an

[41] J.C. Bare *et al*, *U.S. Normalization Database and Methodology for Use within Life Cycle Impact Assessment*, submitted to the Journal of Industrial Ecology. Note that while a normalization value is not reported for the Indoor Air Quality impact, a figure for U.S. VOC emissions/year/capita is reported. To approximate the Indoor Air Quality normalization value, 30 % of this reported value is taken, based on a U.S. EPA Fact Sheet citing that 30 % of annual U.S. VOC emissions flow from consumer products such as surface coatings, personal care products, and household cleaning products (U.S. Environmental Protection Agency, *Fact Sheet: Final Air Regulations for Consumer Products*, 1998).

[42] Habitat alteration flows have been quantified and characterized in terms of U.S. flows per 0.40 hectares (per acre) per capita.

impact to which a product contributes little will not appear important when, by comparison, competing products contribute even less to that impact.

Second, while *selecting* among building products continues to make sense only with reference to the same building element, like floor covering, normalized impact scores can now be compared across building elements if they are first scaled to reflect the product quantities to be used in the building under analysis over the same time period. Take the example of global warming scores for roof coverings and chairs. If these scores are each first multiplied by the quantity of their functional units to be used in a particular building (roof area to be covered and seating requirements, respectively), they may then be compared. Comparing across elements can provide insights into which building elements lead to the larger environmental impacts, and thus warrant the most attention.

2.1.4 Interpretation

At the LCA interpretation step, the normalized impact assessment results are evaluated. Few products are likely to dominate competing products in all BEES impact categories. Rather, one product may out-perform the competition relative to fossil fuel depletion and habitat alteration, 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 scores for all impact categories may be synthesized. Note that in BEES, synthesis of impact scores is optional.

Impact scores may be synthesized by weighting each impact category by its relative importance to overall environmental performance, then computing the weighted average impact score. 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 diverse aspects of the environment.

Refer to Appendix A for the BEES environmental performance computational algorithms.

2.1.4.1 EPA Science Advisory Board study

In 1990 and again in 2000, EPA's Science Advisory Board (SAB) developed lists of the relative importance of various environmental impacts to help EPA best allocate its resources.[43] The following criteria were used to develop the lists:

- The spatial scale of the impact
- The severity of the hazard
- The degree of exposure

[43] United States Environmental Protection Agency, Science Advisory Board, *Toward Integrated Environmental Decision-Making*, EPA-SAB-EC-00-011, Washington, D.C., August 2000 and United States Environmental Protection Agency, Science Advisory Board, *Reducing Risk: Setting Priorities and Strategies for Environmental Protection,* SAB-EC-90-021, Washington, D.C., September 1990, pp 13-14.

- The penalty for being wrong

Ten of the twelve BEES impact categories were included in the SAB lists of relative importance:

- Highest-Risk Problems: global warming, habitat alteration
- High-Risk Problems: indoor air quality, ecological toxicity, human health
- Medium-Risk Problems: ozone depletion, smog, acidification, eutrophication, criteria air pollutants

The SAB did not explicitly consider fossil fuel depletion or water intake as impacts. For this exercise, fossil fuel depletion and water intake are assumed to be relatively medium-risk and low-risk problems, respectively, based on other relative importance lists.[44]

Verbal importance rankings, such as "highest risk," may be translated into numerical importance weights by following guidance provided by a Multiattribute Decision Analysis method known as the Analytic Hierarchy Process (AHP).[45] 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 verbal importance rankings, and the resulting SAB importance weights computed for the BEES impacts, respectively. Note that the pairwise comparison values were assigned through an iterative process based on NIST's background and experience in applying the AHP technique.

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[44] 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.

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

Table 2.12 Pairwise Comparison Values for Deriving Impact Category Importance Weights

Verbal Importance Comparison	*Pairwise Comparison Value*
Highest vs. Low	6
Highest vs. Medium	3
Highest vs. High	1.5
High vs. Low	4
High vs. Medium	2
Medium vs. Low	2

Table 2.13 Relative Importance Weights based on Science Advisory Board Study

	Relative Importance Weight (%)	
Impact Category	*8 Impacts*[a]	*12 Impacts*
Global Warming	24	16
Acidification	8	5
Eutrophication	8	5
Fossil Fuel Depletion	8	5
Indoor Air Quality	16	11
Habitat Alteration	24	16
Water Intake	4	3
Criteria Air Pollutants	8	6
Smog		6
Ecological Toxicity		11
Ozone Depletion		5
Human Health		11

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

2.1.4.2 Harvard University Study

In 1992, an extensive study was conducted at Harvard University to establish the relative importance of environmental impacts.[46] 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.

Eleven of the 12 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 fossil fuel depletion as an impact. For this exercise, fossil fuel depletion is assumed to rank in the medium range for both current and future consequences, based on other relative importance lists.[47]

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[46] 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.

[47] See, for example, Hal Levin, "Best Sustainable Indoor Air Quality Practices in Commercial Buildings," p 148.

Verbal importance rankings from the Harvard study are translated into numerical, relative importance weights using the same, AHP-based numerical comparison scale and pairwise 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.[48]

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	Medium-Low
Eutrophication	Medium	Medium-High
Fossil Fuel Depletion	Medium	Medium
Indoor Air Quality	Medium	Medium-Low
Habitat Alteration	Low	Medium-Low
Water Intake	Med	Medium-High
Criteria Air Pollutants	High	Medium
Smog	High	Medium-Low
Ecological Toxicity	Medium-Low	Medium-Low
Ozone Depletion	Low	High
Human Health	Medium-Low	Medium-Low

Table 2.15 lists the resulting importance weights for the twelve 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.

[48] 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.

Table 2.15 Relative Importance Weights based on Harvard University study

	Relative Importance Weight Set[a]					
	Current (%)		*Future (%)*		*Combined (%)*	
Impact Category	***8[b]***	***12***	***8[b]***	***12***	***8[b]***	***12***
Global Warming	6	4	22	15	17	11
Acidification	22	15	8	6	13	9
Eutrophication	11	8	16	10	14	9
Fossil Fuel Depletion	11	8	11	7	11	7
Indoor Air Quality	11	8	8	6	9	7
Habitat Alteration	6	4	8	6	7	6
Water Intake	11	8	16	10	14	9
Criteria Air Pollutants	22	15	11	7	15	10
Smog		14		6		9
Ecological Toxicity		6		6		6
Ozone Depletion		4		15		11
Human Health		6		6		6

[a]So that each weight set would appropriately sum to 100, some individual weights have been rounded up or down.
[b]This set of reduced impacts is assessed for a limited number of BEES products, as identified in table 4.1.

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.[49]

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

[49]ASTM International, *Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems,* ASTM Designation E 917-99, West Conshohocken, PA, 1999.

period length is often set at the useful life of the longest-lived product alternative. However, when 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 accounts for the fact that different products have different useful lives by 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 inventory flows are prorated to year 50 for products with lives longer than the 50-year study period.

The LCC method sums over the study period all relevant costs associated with a product. Alternative products for the same function, say floor covering, can then be compared on the basis of their LCCs to determine which is the least cost means of fulfilling 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.[50]

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[50] For example, a product with a 40 year life that costs $111/m^2$ ($10/ft^2$) to install would have a residual value of $7.50 in year 50, considering replacement in year 40.

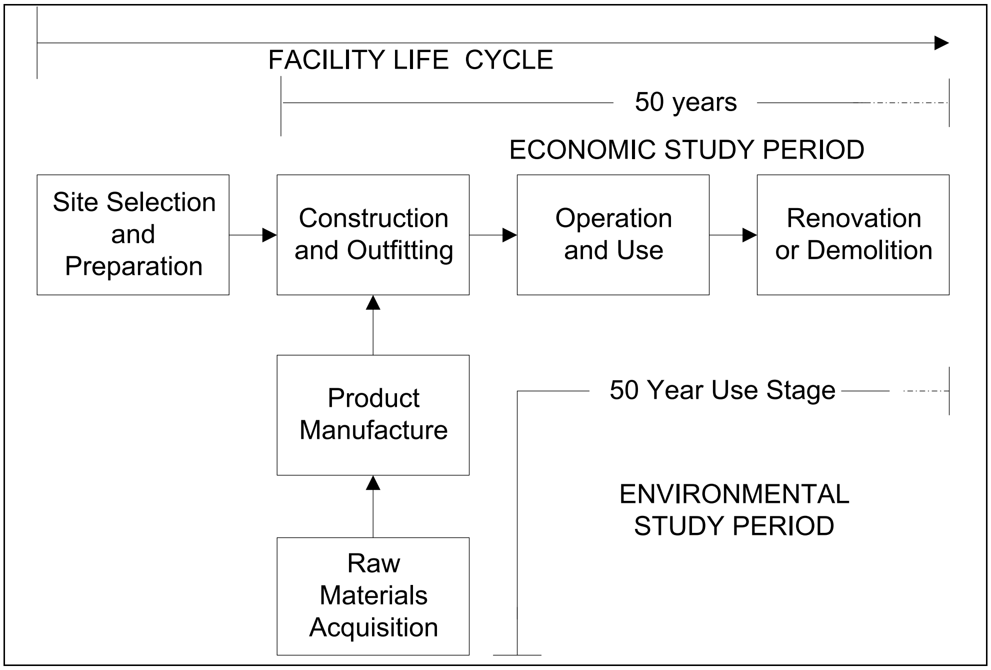

Figure 2.3 BEES Study Periods For Measuring Building Product Environmental And Economic Performance

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., 2002) costs. Real discount rates reflect that 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 2002 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 same LCC results. The BEES model computes LCCs using constant 2002 dollars and a real discount rate.[51] As a default, the BEES tool offers a real rate of 3.9 %, the 2002 rate mandated by the U.S. Office of Management and Budget for most Federal projects.[52]

[51]Any year 2000 costs were converted to year 2002 dollars using a 0.994 inflation factor developed from producer price indices for new construction reported in U.S. Department of Labor, *Producer Price Indices: New Construction*, Series PCUBNEW#, Bureau of Labor Statistics, www.bls.gov, July 8, 2002.

[52] U.S. 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, Washington, DC, 2002.

2.3 Overall Performance

The BEES overall performance measure synthesizes the environmental and economic results into a single score, as illustrated in Figure 2.4. Yet the environmental and economic performance scores are denominated in different units. How can these diverse measures of performance be combined into a meaningful measure of overall 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 environmental and economic performance results. The BEES system follows the ASTM standard for conducting MADA evaluations of building-related investments.[53]

Before combining the environmental and economic performance scores, each is placed on a common scale by dividing by the sum of corresponding scores across all alternatives under analysis. In effect, then, each performance score is rescaled in terms of its share of all scores, and is placed on the same, relative scale from 0 to 100. Then the two scores are combined into an overall score by weighting environmental and economic performance by their relative importance and taking a weighted average. The BEES user specifies the relative importance weights used to combine environmental and economic performance scores and should 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. 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 and manufacturer-specific product alternatives. The BEES results do not apply to products sold in other countries where manufacturing and agricultural practices, fuel mixes, environmental regulations, transportation distances, and labor and material markets may differ.[54] Furthermore, all products in a 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. The BEES results for the generic product group do not necessarily represent the performance of an individual product.

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[53] ASTM International, *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.

[54] BEES *does* apply to products manufactured in other countries and sold in the United States. These results, however, do not apply to those same products as sold in other countries because transport to the United States is built into their BEES life cycle inventory data.

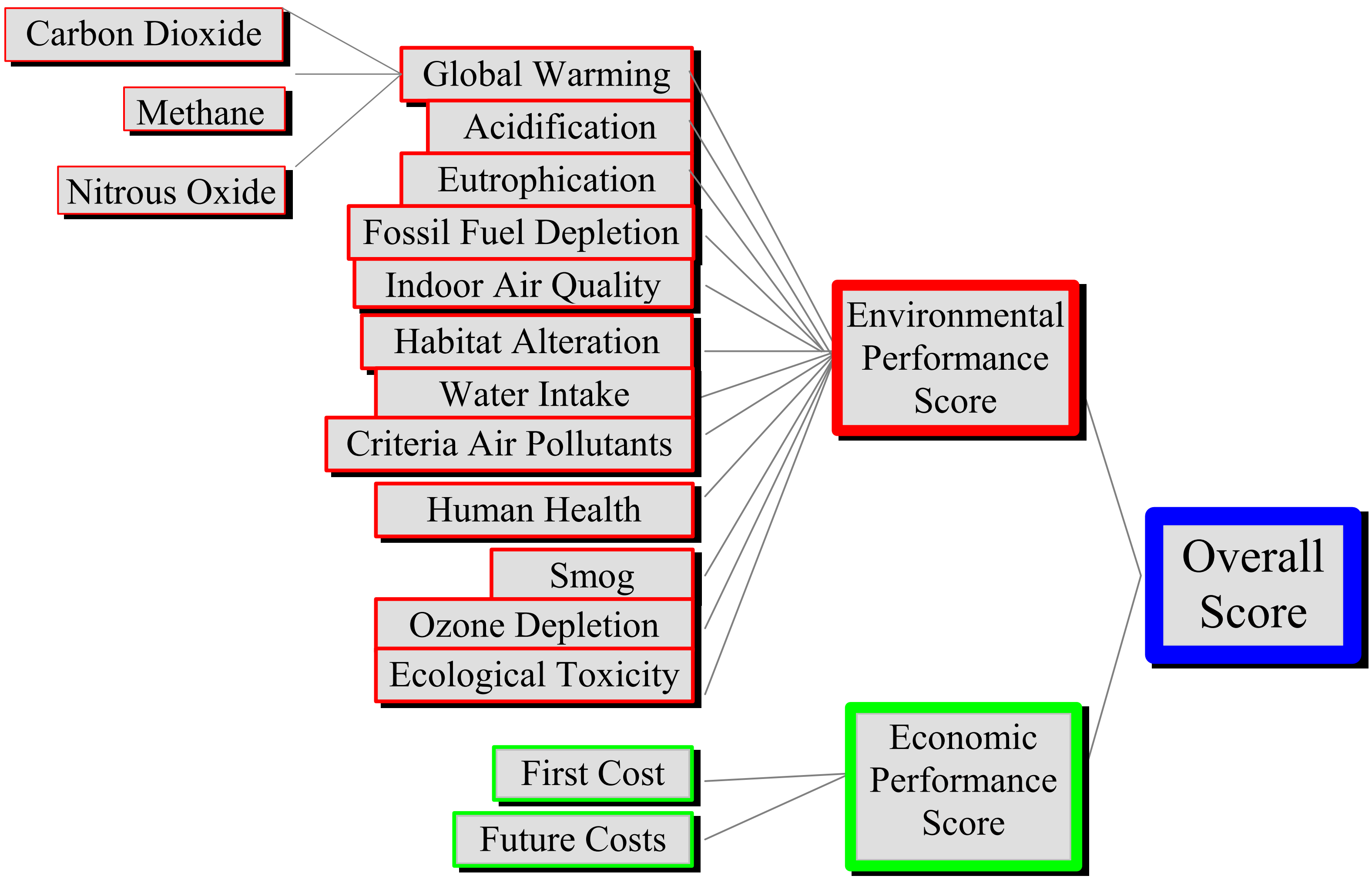

Figure 2.4 Deriving the BEES Overall Performance Score

The BEES LCAs use 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. If the BEES user has important knowledge about these issues, it should be brought into the interpretation of the BEES results.

Life cycle impact assessment is a rapidly evolving science. Assessment methods unheard of several years ago have since been developed and are now being used routinely in LCAs. While BEES 3.0 incorporates state-of-the-art impact assessment methods, the science will continue to evolve and methods in use today—particularly those for fossil fuel depletion, habitat alteration, and indoor air quality—are likely to change and improve over time. Future versions of BEES will incorporate these improved methods as they become available.

During the interpretation step of the BEES LCAs, 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 LCAs do not incorporate uncertainty analysis as required by ISO 14043.[55] At present, incorporating uncertainty analysis is problematic due to a lack of underlying uncertainty data. The BEES 2.0 Peer Review Team discussed this issue and advised NIST not to incorporate uncertainty analysis into BEES in the short run.[56] In the long run, however, one aspect of uncertainty may be addressed: the representativeness of generic products. That is, once BEES is extensively populated with manufacturer-specific data, the variation in manufacturer-specific products around their generic representations will become available.

The BEES overall performance scores do not represent *absolute* performance. Rather, they represent proportional differences in performance, or *relative* performance, among competing alternatives. Consequently, the overall 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 overall scores across building elements. For example, if exterior wall finish Product A has an overall performance score of 30, and roof covering Product D has an overall performance score of 20, Product D does not necessarily perform better than Product A (keeping in mind that lower performance scores are better). This limitation does *not* apply to comparing environmental performance scores across building elements, as discussed in section 2.1.3.2.

There are inherent limits to comparing product alternatives without reference to the whole building design context. Such comparisons may overlook important environmental and cost interactions among building elements. For example, the useful life of one building element (e.g.,

[55] International Organization for Standardization (ISO), *Environmental Management--Life-Cycle Interpretation—Life Cycle Impact Assessment,* International Standard 14043, 2000.

[56] Curran, M.A. et al., *BEES 2.0, Building for Environmental and Economic Sustainability: Peer Review Report*, NISTIR 6865, National Institute of Standards and Technology, Washington, DC, 2002.

floor coverings), which influences both its environmental and economic performance scores, may depend on the selection of related building elements (e.g., subflooring). There is no substitute for good building design.

Environmental and economic performance are but two attributes of building product performance. The BEES model assumes that competing product alternatives all meet minimum technical performance requirements.[57] However, there may be significant differences in technical performance, such as acoustic or fire performance, which may outweigh environmental and economic considerations.

[57] BEES environmental and economic performance results for wall insulation and roof coverings *do* consider one important technical performance difference. For these building elements, BEES accounts for differential heating and cooling energy consumption.

3. BEES Product Data

The BEES model uses the ASTM standard classification system, UNIFORMAT II,[58] 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 Concrete Slabs, Walls, Beams, and Columns (BEES Codes A1030, A2020, B1011, B1012) and Cement Kiln Dust (G1030)

3.1.1 Generic Portland Cement Products (A1030: A-I, O; A2020: A-I; B1011: A-R; B1012: A-R; G1030B)

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 lb/in^2 to 20 000 lb/in^2), concrete for residential slabs and basement walls often has a compressive strength of 21 MPa (3 000 lb/in^2) or less, and concrete for structural applications such as beams and columns often has compressive strengths of 28 MPa or 34 MPa (4 000 lb/in^2 or 5 000 lb/in^2). Thus, concrete mixes modeled in the BEES software are limited to compressive strengths of 21 MPa, 28 MPa, and 34 MPa (3 000 lb/in^2, 4 000 lb/in^2, and 5 000 lb/in^2).

To reduce cost, heat generation, and the environmental burden of concrete, ground granulated blast furnace slag (referred to as GGBFS or “slag”), fly ash, or limestone 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, and limestone is an abundant natural resource. When used in concrete, slag, fly ash, and limestone are cementitious materials that can act in a similar manner as cement by facilitating

[58] 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.

compressive strength development.

BEES performance data apply to four concrete building elements: 21 MPa (3 000 lb/in^2) Slabs on Grade and Basement Walls; and 28 MPa or 34 MPa (4 000 lb/in^2 or 5 000 lb/in^2) Beams and Columns. For each building element, concrete alternatives with 100 % cement (no fly ash, slag, or limestone); 15 % and 20 % fly ash content; 20 %, 35 %, and 50 % slag content; and 5 %, 10 %, and 20 % limestone content, all by mass fraction of cement, may be compared. A 35 % fly ash content concrete is also included for the slab on grade building element only. In addition, BEES includes a portland cement product used to enhance or stabilize soil. The detailed environmental performance data for all these products may be viewed by opening their corresponding files, as identified in Table 4.1, under the File/Open menu item in the BEES software.

BEES manufacturing 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.[59] The LCA dataset was completed by BEES contractors Environmental Strategies and Solutions (ESS) and PricewaterhouseCoopers (PwC) by adding environmental flows for raw material acquisition, transportation from the ready-mix plant to the building site, installation (including formwork and reinforcing steel), use, and end of life.

Figures 3.1 and 3.2 show the elements of concrete production with and without blended cements (i.e., cements with fly ash, slag, or limestone).

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 and slag are equal replacements for cement. The same is true for a 5 % limestone blended cement, but at the 10 % and 20 % blend levels, Table 3.1 shows that more blended cement is needed in the concrete to achieve equivalent strength as mixes with no limestone replacements. Quantities of constituent materials used in an actual project may vary.

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

[59] Construction Technology Laboratories, Inc, *Completed BEES Site Questionnaire for Portland Cement,* CTL Project No. 312006, June 2002; Construction Technology Laboratories, Inc, *Theoretical Concrete Mix Designs for Cement with Limestone as a Partial Replacement for Portland Cement,* CTL Project 312006, June 2002; 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.

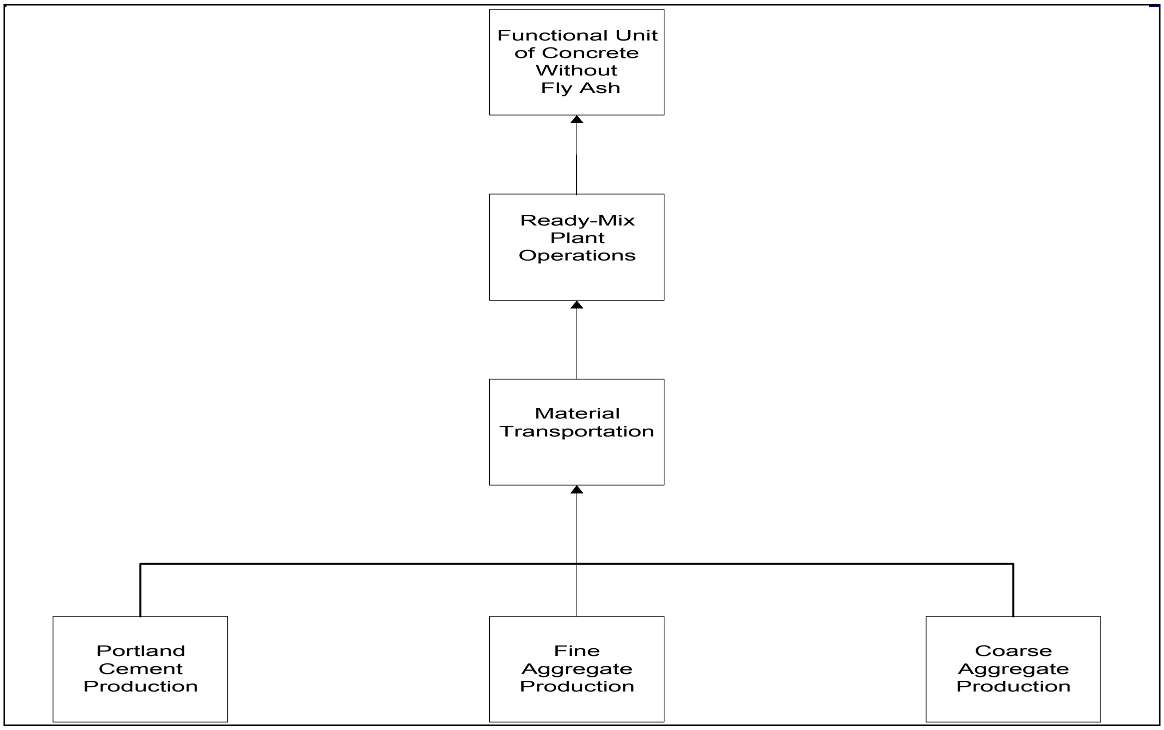

Figure 3.1 Concrete Without Blended Cements Flow Chart

these oxides, the mixture of the major raw materials and minor ingredients (as required) varies among cement plants. BEES data for cement manufacture is based on the average raw material mix and oxide content for all U.S. cement plants for an ASTM C150 Type I/II cement, the most commonly used cement in North America. The average raw materials for U.S. cement include limestone, cement rock/marl, shale, clay, bottom ash, fly ash, foundry sand, sand, and iron/iron ore.

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

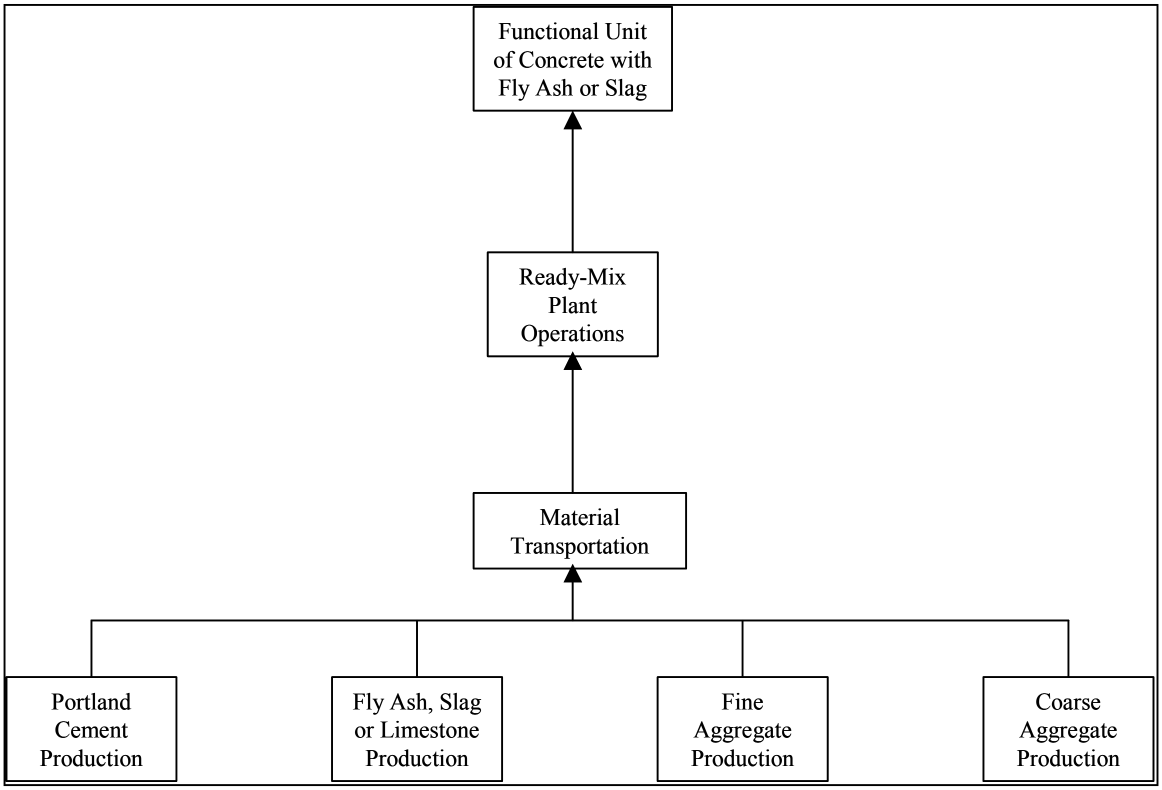

Figure 3.2 Concrete with Blended Cements Flow Chart

Table 3.1 Concrete Constituent Quantities by Cement Blend and Compressive Strength of Concrete

Concrete Constituent	***Constituent Density in kg/m³ (lb/ yd³)*** 21 MPa (3 000 lb/in²)	28 MPa (4 000 lb/in²)	34 MPa (5 000 lb/in²)
Cement and Fly Ash, Slag, or 5 % Limestone	223 (376)	279 (470)	335 (564)
Coarse Aggregate	1 127 (1 900)	1 187 (2 000)	1 187 (2 000)
Fine Aggregate	831 (1 400)	771 (1 300)	712 (1 200)
Water	141 (237)	141 (237)	141 (237)
Cement and 10 % Limestone	236 (397)	294 (496)	353 (595)
Coarse Aggregate	1 127 (1 900)	1 187 (2 000)	1 187 (2 000)
Fine Aggregate	831 (1 400)	771 (1 300)	712 (1 200)
Water	148 (250)	147 (248)	148 (250)
Cement and 20 % Limestone	265 (447)	331 (558)	397 (670)
Coarse Aggregate	1 127 (1 900)	1 127 (1 900)	1 187 (2 000)
Fine Aggregate	831 (1 400)	771 (1 300)	653 (1 100)
Water	167 (281)	166 (279)	167 (281)

"free" input material.[60] However, transport of the fly ash to the ready mix plant is included.

Slag. Slag is a waste material that 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. 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.

Limestone. Limestone is an abundant resource that may be used as a partial replacement for portland cement. While not common practice in the United States, limestone is used as a partial replacement for portland cement in some European countries. The concrete mix designs used in BEES are estimates based on available literature and have not been tested in the laboratory. Mixes at the higher limestone replacement levels are based on limited data.

Energy Requirements: *Portland Cement.* Portland cement is manufactured using one of four processes: wet process, dry process, preheater, or precalciner. The wet process is the oldest and uses the most energy due to the energy required to evaporate the water. New cement manufacturing plants are being constructed, and older plants converted, to use the more energy efficient preheater or precalciner processes. As of 1999, the mix of production processes was 21 % wet, 18 % dry, 20 % preheater, and 41 % 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).

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

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

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

Table 3.2 Energy Requirements for Portland Cement Manufacturing

	*Cement Manufacturing Process**				
Fuel Use	***Wet*** *(%)*	***Long Dry*** *(%)*	***Preheater*** *(%)*	***Precalciner*** *(%)*	***Weighted Average*** *(%)*
Coal	50	55	71	63	59
Petroleum Coke	16	27	9	10	15
Natural Gas	4	5	5	10	7
Liquid Fuels**	1	1	1	1	1
Wastes	21	3	2	4	8
Electricity	8	9	12	12	10
All Fuels:	100	100	100	100	100
Total Energy in kJ/kg of cement (Btu/lb)	6 570 (2 820)	6 060 (2 610)	4 900 (2 100)	4 520 (1 940)	5 320 (2 280)

* Cement constitutes 10 % to 15 % by mass fraction of the total mass of concrete.
** Liquid fuels include gasoline, middle distillated, residual oil, and light petroleum gas

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).

Limestone. Energy burdens for limestone production are included.

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 0.10 MJ/kg (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 different combinations of compressive strength and blended cements as shown in the concrete environmental performance data files.

Installation and Use. Installing each of the BEES concrete applications requires different quantities of plywood forms and steel reinforcement as shown in Table 3.3. The quantities used are drawn from the R.S. Means publication, *1997 Building Construction Cost Data* (p. 488).

Table 3.3 Concrete Form and Reinforcing Requirements

Building Element	***Compressive Strength MPa (lb/in^2)***	***Plywood Forms (SFCA/functional unit)***	***Steel Reinforcing (lb/ft^2 for slabs, lb/yd^3 for rest)***	***Comment***
Slabs	21 (3 000)	1.03	3.88	For 7.62 m (25 ft) span
Basement Walls	21 (3 000)	0	44	For 0.20 m (8 in) thick, 2.44 m (8 ft) high walls. Plywood wall forms are reused over 75 times and steel wall forms over 300 times; hence those elements are not taken into account.
Columns	28 (4 000)	65	290	For 0.51 m x 0.51 m (20 in x 20 in) columns with a 7.62 m (25 ft) span. The steel value is twice the amount for beams. The steel amounts are between 90 kg/m^3 and 645 kg/m^3 (150 lb/yd^3 and 1 080 lb/yd^3). Values for forms and reinforcement provided for 28 MPa (4 000 lb/in^2) columns are used for 34 MPa (5 000 lb/in^2) columns.
	34 (5 000)	65	290	
Beams	28 (4 000)	54	145	For 7.62 m (25 ft) span beams. Values for forms and reinforcement provided for 21 MPa (3 000 lb/in^2) beams are used For 28 Mpa (4 000 lb/in^2) and 34 MPa (5 000 lb/in^2) beams.
	34 (5 000)	54	145	

Notes: 1. Plywood is reused 4 times, each time with a 10 % loss. Plywood forms are12.7 mm (0.5 in) thick and their surface density is 5.88 kg/m^2 (1.17 lb/ft^2). Plywood production impacts are the same as those reported for the BEES Plywood Wall Sheathing product.
2. SFCA=0.09 m^2 (1 ft^2) contact area.
3. Steel reinforcing is made from 100 % recycled steel.

Beams, columns, basement walls, and slabs are all assumed to have 75-year lifetimes. Portland cement is assumed to be used once for soil treatment over a 50-year period.

Cost. The detailed life-cycle cost data for these 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 products' BEES codes as listed in Table 4.1. 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. Cost data have been adjusted to year 2002 dollars.

3.1.2 Lafarge North America Products (A1030: J, L-N, P; A2020: J, L-P; B1011: J, L-P, B1012: S, U-X, AA-DD; G1030A; G2022G)

Lafarge North America, part of the Lafarge Group, is a large, diversified supplier of cement, aggregates and concrete, and other materials for residential, commercial, institutional, and public works construction in the United States and Canada. Five Lafarge products are included in BEES; their environmental performance data may be browsed in the BEES software by opening their corresponding environmental data files as given in table 4.1:

- *Silica Fume Cement (SFC).* A mixture of portland cement (90 %) and silica fume (10 %)
- *NewCem Slag Cement*. Ground granulated blast furnace slag used as a partial replacement for portland cement
- *BlockSet*. A blend of cement kiln dust, fly ash, and cement used to make concrete blocks for basement walls
- *Cement Kiln Dust (CKD) Soil Enhancer*. A coproduct of cement production used as a soil enhancer
- *Portland Type I Cement*.

BEES data for Silica Fume Cement, BlockSet, and CKD Soil Enhancer products come from the Lafarge plant in Paulding, Ohio, with an annual production of 436 810 metric tons (481 500 short tons) of SFC, Type I, and masonry cement. The Lafarge South Chicago location manufactures a total of 816 466 metric tons (900 000 short tons) of slag products. While most data reflect 2001 production results, some emissions date from 1996. Data for the Portland Type I Cement product come from the Lafarge plant in Alpena, Michigan, with an annual production of 2 059 310 metric tons (2 270 000 short tons). The Portland Cement manufactured in Alpena is shipped by lake vessels to terminals around the Great Lakes. Data predominantly reflect 2001 production results, with some raw material consumption data dating to 1999. These cementitious products are incorporated in different concrete products in BEES as shown in Table 3.4.

Table 3.4 Lafarge North America Concrete Products

BEES Building Element	***Lafarge Product***	***Specifications***
Concrete for Slabs, Basement Walls, Beams and Columns	Silica Fume Cement	1 kg of SFC is equivalent to 1 kg of generic portland cement. Fully 100 % of the portland cement is replaced by SFC.
Concrete for Slabs, Basement Walls, Beams and Columns	Slag Cement	1 kg of slag cement is equivalent to 1 kg of generic portland cement. The following substitution ratios of slag cement for portland cement are used: 20 %, 35 %, 50 %.
Concrete for Slabs, Basement Walls, Beams and Columns	Alpena Portland Type I	1 kg of Alpena portland Type I cement is equivalent to 1 kg of generic portland cement
Concrete for Basement Walls	BlockSet	1 kg of BlockSet is equivalent to 1 kg of generic portland cement. Forty percent (40 %) of the portland cement is replaced by BlockSet.
Soil Treatment	Cement Kiln Dust	1 kg of CKD replaces 1 kg of portland cement
Parking Lot Paving	Alpena Portland Type I	1 kg Alpena portland Type I cement is equivalent to 1 kg of generic portland cement used in the concrete layer of paving.

Raw Materials. The five Lafarge products are comprised of the raw materials given in Table 3.5.

Table 3.5 Lafarge Product Constituents

Constituent	***Silica Fume Cement***	***Slag Cement***	***BlockSet***	***Cement Kiln Dust***	***Alpena Portland Type I***
Limestone	72 %	--	76 %	76 %	91 %
Clay	16 %	--	16 %	16 %	--
Silica Fume	5 %	--	--	--	--
Sand	3 %	--	3 %	3 %	3 %
Gypsum	3 %	--	3 %	3 %	--
Slag	--	100 %	--	--	--
Fly Ash	<0.01 %	--	<0.01 %	<0.01 %	5 %
Iron source	1 %	--	1 %	1 %	1 %

Energy consumption and air emissions data for clay and limestone production were provided by Construction Technology Laboratories, Inc. These data take into account fuel combustion, quarry operations, and haul roads (1.61 km, or 1 mile, to the Paulding cement plant and 3.22 km, or 2 miles, to the Alpena site).

Silica fume is a by-product of the metallurgical processes used in the production of silicon metals. It is called "fume" because it is an extremely fine smoke-like particulate material. Because it is both pozzolanic and extremely fine (about 100 times finer than cement particles), silica fume may be used to considerable advantage as a supplementary cementitious material in portland cement concrete. Silica fume has been used in the North American cement and concrete industry for over 20 years and can be used in concretes to withstand aggressive exposure conditions. Silica fume is transported to the Paulding plant by truck 241 km (150 mi).

Sand production takes into account energy combustion, waste production, and air emissions from fuel combustion and quarry operations. Sand is transported to the Paulding and Alpena plants by truck (80 km, or 50 mi, and 16 km, or 10 mi, respectively).

Gypsum production takes into account electricity and diesel fuel consumption used in surface mining and processing, as well as air emissions and waste production. Gypsum is transported to the Paulding plant by truck (97 km, or 60 mi)

Slag is a waste material from the blast furnace during the production of pig iron. Blast furnaces, which produce iron from iron ore in the presence of limestone or dolomite fluxes, produce a molten slag. This slag is tapped off the furnace separately from the iron. Slag is transported to the South Chicago location by truck (32 km, or 20 mi).

The iron source for the Paulding site is mill scale, a by-product from hot rolling steel. It is transported to the Paulding plant by truck (32 km, or 20 mi).

Fly ash production takes into account transportation from the production site (322 km, or 200 mi, by rail). Fly ash is the fine ash resulting from burning coal in electric utility plants.

Manufacturing. The Paulding site uses electricity, petroleum coke, diesel oil and fuel-quality waste (primarily solvents) as energy sources to produce silica fume cement, BlockSet, and cement dust. Fuel-quality waste is the largest source of energy for the plant. Material and energy consumption are allocated on a mass basis to the different coproducts of the plant (SFC, class I masonry cements, BlockSet and CKD), except for silica fume, which is entirely allocated to the SFC product.

To prepare for use in concrete, slag is quenched with water and ground. Since the water evaporates, there is no effluent run off. Water, electricity, and natural gas consumption are taken into account.

The Alpena site uses electricity, coke, coal, diesel oil, fuel oil, and gasoline as energy sources to produce portland Type I cement. Coke and coal are the largest energy sources for the site. Material and energy consumption are allocated on a mass basis to the different coproducts of the plant (Type I/II cement, Type III cement, mortar cement and CKD).

Use. Beams, columns, basement walls, and slabs are all assumed to have 75-year lifetimes. Cement kiln dust is assumed to be used once for soil treatment over a 50-year period. Concrete parking lot paving is assumed to last 30 years.

Transportation. Transportation of finished products to the building site is evaluated based on the same parameters given for the generic counterparts to Lafarge products. All products are shipped by diesel truck. Emissions from transportation allocated to each product depend on the overall weight of the product.

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Cost. The detailed life-cycle cost data for Lafarge products may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under the Lafarge BEES codes as listed in Table 4.1. First cost data include purchase and installation costs. Purchase costs were provided by Lafarge and installation costs were collected from the R.S. Means publication, *2000 Building Construction Cost Data.* 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. Cost data have been adjusted to year 2002 dollars.

3.1.3 ISG Resources Concrete Products (A1030K, A2020K, B1011T, B1011Y, B1012T, B1012Y, B2011:G-I, G2022F)

Headquartered in Salt Lake City, Utah, ISG Resources supplies materials to products as diverse as ready-mix concrete, precast concrete, roofing, carpeting, mortar, and stucco. Five ISG products are included in BEES; their environmental performance data may be browsed in the BEES software by opening their corresponding environmental data files as given in table 4.1:

- *Masonry Cement Type N.* Meets ASTM C-91 Type N standard for masonry cement.
- *Masonry Cement Type S.* Meets ASTM C-91 Type S standard for masonry cement.
- *Mason's Portland*. Meets ASTM C-595 Type IP standard for blended hydraulic cement. Used as a replacement for ASTM C-150 Type 1 portland cement.
- *Scratch & Brown Stucco Cement.* Meets ASTM C-1328 Type S standard for plastic (Stucco) cement. Used as a replacement for job-site-mixed stuccos (usually portland and lime or portland and masonry cement) under ASTM C-926.
- *One-Coat Stucco*. Produced and sold under ICBO Evaluation Report No. 4776 and NES Evaluation Report 459. At this time there are no ASTM standards for this class of products.

These five products are sold under the following brand names:

- Best
- Hill Country
- Magna Wall

BEES data for these products are based on 2001 data from the manufacturer's San Antonio, Texas plant, with an annual production of 14 000 tons. These cementitious products are incorporated in different concrete products in BEES as shown in Table 3.6.

Table 3.6 ISG Resources Concrete Products

BEES Building Element	***ISG Resources Product***	***Specifications***
Concrete for Slabs, Basement Walls, Beams and Columns	Mason's Portland (Type IP)	1 kg of Mason's Portland is equivalent to 1 kg of generic Portland Cement. Fully 100 % of the Portland Cement is replaced by Mason's Portland Cement.
Exterior Wall Finishes 3-coat Stucco	Masonry Cement Type S or Scratch & Brown Stucco Cement	1 kg of Masonry Cement Type S produced by ISG Resources or 1 kg of Scratch & Brown Stucco Cement produced by ISG Resources replaces 1 kg of traditional Masonry Cement Type S used in generic stucco. Fully 100 % of the traditional cement is replaced by ISG's Masonry Cement.
	Scratch & Brown Stucco Cement Type S	1 kg of Scratch & Brown Stucco Cement Type S produced by ISG Resources replaces 1 kg of traditional Masonry Cement Type S used in generic stucco. Fully 100 % of the traditional cement is replaced by ISG's Scratch and Brown Stucco Cement.
1-coat Stucco	One-Coat Stucco	1 kg of One-Coat Stucco produced by ISG Resources replaces 2 kg of traditional Masonry Cement. Fully 100 % of the traditional cement is replaced by ISG's One-Coat Stucco. The metallic lath weighs either 0.95 kg/m^2 (1.75 lbs/yd^2) or 1.36 kg/m^2 (2.50 lbs/yd^2). The lighter-weight lath is used in 60 % of the applications.
Brick and Mortar	Masonry Cement Type N	1 kg of Masonry Cement type N produced by ISG Resources replaces 1 kg of traditional Masonry Cement Type N used in the mortar. Fully 100 % of the traditional cement is replaced by ISG's Masonry Cement.
	Masonry Cement Type S	1 kg of Masonry Cement Type S produced by ISG Resources replaces 1 kg of traditional Masonry Cement Type S used in the mortar. Fully 100 % of the traditional cement is replaced by ISG's Masonry Cement.

Raw Materials. The five ISG Resources products are comprised of the raw materials given in Table 3.7.

Table 3.7 ISG Resources Product Constituents

Constituent	***Masonry Cement type N***	***Masonry Cement type S***	***Mason's Portland***	***Scratch & Brown Stucco Cement***	***One-Coat Stucco***
Fly Ash (class F)	Yes	Yes	Yes	Yes	Yes
Portland Cement (gray, type I)	Yes	Yes	Yes	Yes	Yes
Hydrated Lime (type S)	Yes	Yes	No	Yes	Yes
Polypropylene Fibers	No	No	No	No	Yes

The BEES generic portland cement data are used for the portland cement constituent. Portland cement is transported by truck over 48 km (30 mi).

Fly Ash production takes into account transportation from the production site (660 km, or 410 mi, by truck). Fly ash comes from coal-fired, electricity-generating power plants. These power plants grind coal to a powder fineness before it is burned. Fly ash – the mineral residue produced by burning coal – is captured from the power plant's exhaust gases and collected for use. Fly ash particles are nearly spherical in shape, allowing them to flow and blend freely in mixtures, one of the properties making fly ash a desirable admixture for concrete.

Hydrated Lime Production takes into account limestone extraction, crushing and calcination, and quick lime hydration. Half the yield from limestone crushing (by mass) consists of small pieces that are sold for other purposes. An allocation rule for limestone crushing was therefore required, and assigned half the crushing electricity consumption to hydrated lime production. Hydrated lime is transported by truck over 51 km (32 mi).

Manufacturing. Raw materials are brought to the plant in 18-wheel tankers and blown into silos. Material drops from the silos to a weigh-batcher, a blender, and a bagger. Only one product is produced at a time for at least a full day before changing products. Since all gray (fly ash containing) products are related, changing products consists of tapping the system down and bagging the last of the product in the system. Allocation of the resources is based on the number of bags of each product produced. Energy consumed on site is mostly electricity (87 %) and diesel fuel oil. The site produces solid waste (1 % to 2 % of production) and emits particulates.

Transportation. Transportation of finished products to the building site is evaluated based on the same parameters given for the generic counterparts to ISG Resources products. All products are shipped by diesel truck. Emissions from transportation allocated to each product depend on the overall weight of the product.

Use. Beams, columns, basement walls, and slabs are all assumed to have 75-year lifetimes, and exterior wall finishes 100-year lifetimes. Concrete parking lot paving is assumed to last 30 years.

Cost. The detailed life-cycle cost data for ISG Resources products may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under the ISG Resources BEES codes as listed in Table 4.1. First cost data include purchase and installation costs. Purchase costs were provided by ISG Resources and installation costs were collected from the R.S. Means publication, *2000 Building Construction Cost Data.* 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. Cost data have been adjusted to year 2002 dollars.

3.2 Roof and Wall Sheathing Alternatives (B1020, B2015)

3.2.1 Generic 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.[61] The average energy use reported is 0.22 MJ/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 DEAM 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

[61] 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; 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.

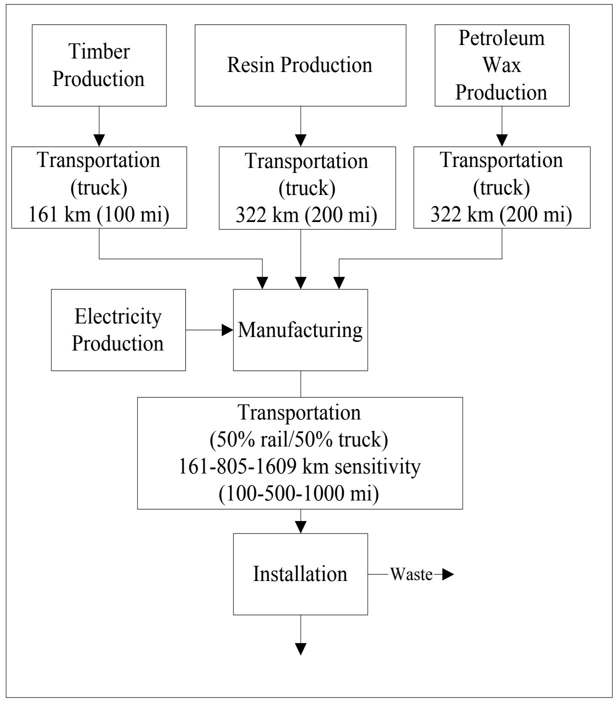

Figure 3.3 Oriented Strand Board Flow Chart

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

Manufacturing. The components and energy requirements for OSB manufacturing are based on a study performed by the United States Department of Agriculture (USDA).[62] Table 3.8 shows the constituents of OSB production.

Table 3.8 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

[62]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).

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 Btu/lb) of OSB produced.

The emissions from the OSB manufacturing process are based on a Forintek Canada Corporation Study, as reported in Table 3.9.[63] 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 3.9 Oriented Strand Board Manufacturing Emissions

Emission	***Value (per oven dry tonne of OSB)***
Carbon Dioxide	488 kg (1 076 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 PricewaterhouseCoopers database.

The wax used in the production of OSB is assumed to be petroleum wax. Production of the petroleum wax is based on the PricewaterhouseCoopers 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 PricewaterhouseCoopers database.

Installation and Use. Installation waste with a mass fraction of 0.015 is assumed. The product is assumed to have a useful life of 50 years.

[63] 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.

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
- 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. Cost data have been adjusted to year 2002 dollars.

3.2.2 Generic 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.[64] The average energy use reported was 0.22 MJ/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 DEAM 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).

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[64] 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; 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.

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 PricewaterhouseCoopers database.

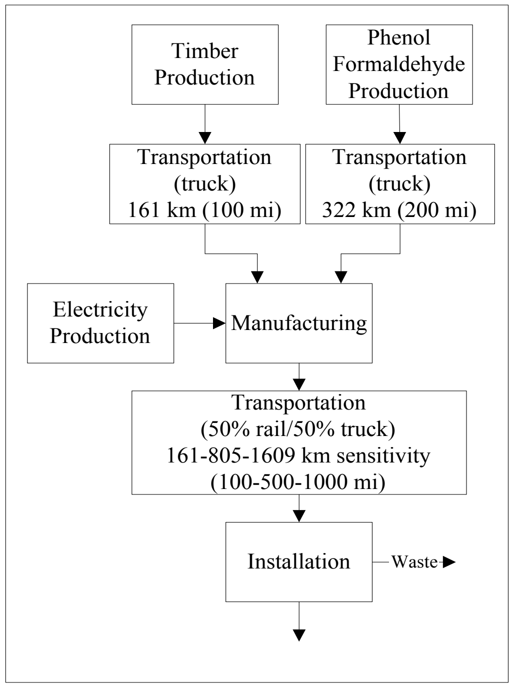

Figure 3.4 Plywood Sheathing Flow Chart

Manufacturing. The components and energy requirements for plywood manufacturing are based on a Forintek Canada Corporation study[65]. Table 3.10 shows the constituents of plywood production.

Table 3.10 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).

[65] 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.

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/t (151 Btu/lb) of oven dry plywood produced. Electricity production emissions are based on a standard U.S. electricity grid. The emissions from the plywood manufacturing process are based on the Forintek Canada Corporation study, as reported in Table 3.11.

Table 3.11 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 PricewaterhouseCoopers 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 PricewaterhouseCoopers database.

Installation and Use. Installation waste with a mass fraction of 0.015 is assumed. The product is assumed to have a useful life of 50 years.

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. Cost data have been adjusted to year 2002 dollars.

3.3 Exterior Wall Finish Alternatives (B2011)

3.3.1 Generic 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.

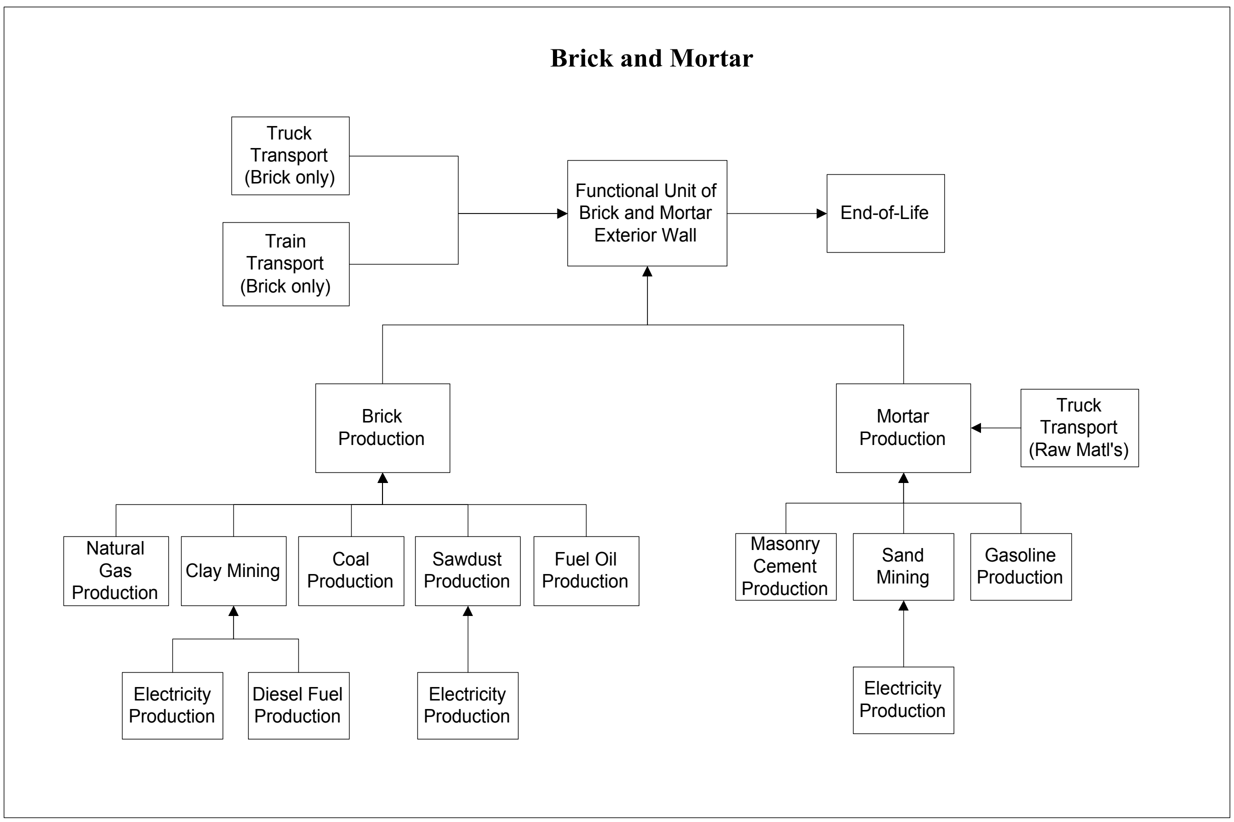

Figure 3.5 Brick and Mortar Flow Chart

Raw Materials. Production of the raw materials for brick and mortar are based on the DEAM database. Type N mortar consists of 1 part (volume fraction) masonry cement, 3 parts sand,[66] and 6.3 L (1.67 gal) of water. Masonry cement is modeled based on the assumptions outlined below for stucco exterior walls.

Energy Required. The energy requirements for brick production are listed in Table 3.12. These figures include the drying and firing production steps only, based on an industry report stating that these are the most important steps in terms of energy use. The production of the different types of fuel is based on the DEAM database.

Table 3.12 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 mortar flow rate of 0.25 m^3/h (9 ft^3/h), running for 5 min.

Emissions. Emissions are based on AP-42[67] 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 2 002 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 (75 %) of the bricks are assumed to be recycled after the 100-year use.

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

[67] 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.

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 *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. Cost data have been adjusted to year 2002 dollars.

3.3.2 Generic 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 3.13.

Table 3.13 Masonry Cement Constituents

Masonry Cement Constituent	*Mass Fraction (%)*
Portland Cement Clinker	50
Limestone	47.5
Gypsum	2.4

Production of these raw materials is based on the DEAM database.

Stucco consists of the raw materials listed in Table 3.14.[68]

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 PricewaterhouseCoopers database.

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

Energy Requirements. The energy requirements for masonry cement production are shown in Table 3.15.

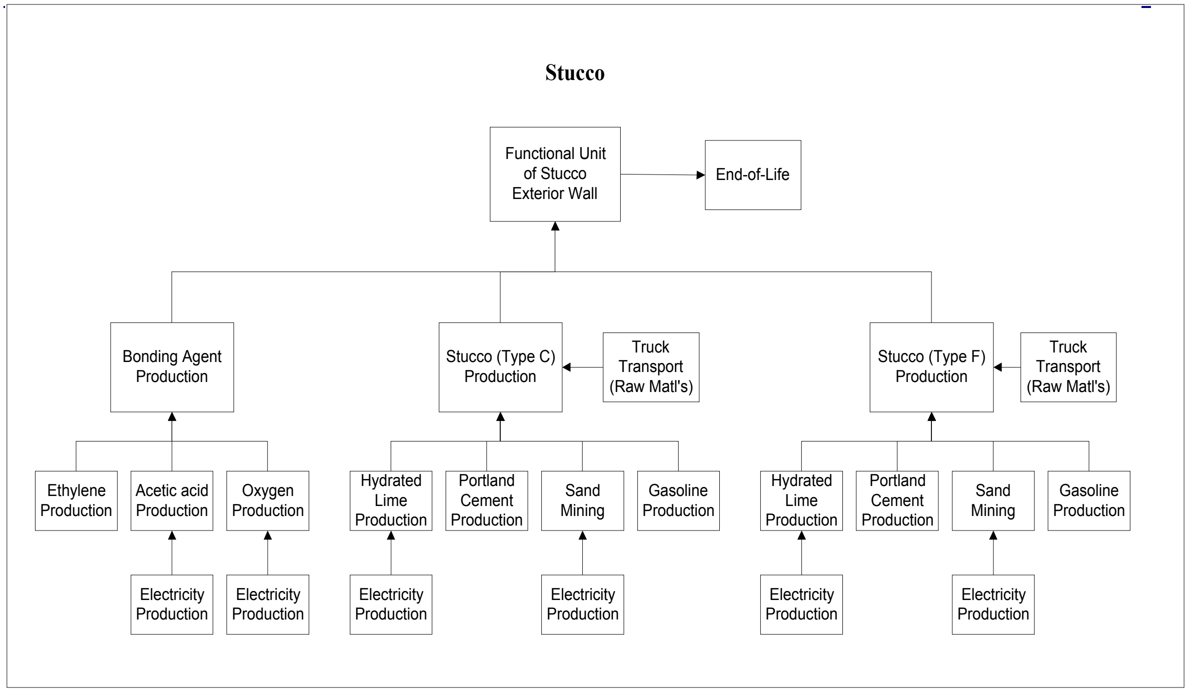

Figure 3.6 Stucco (Type C) Flow Chart

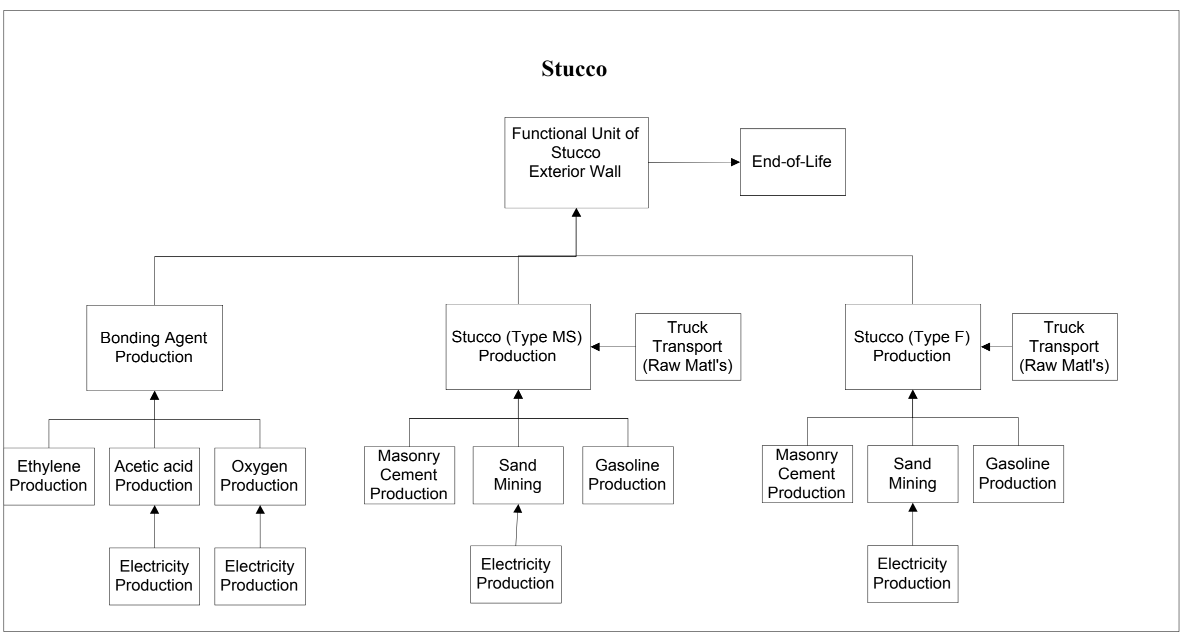

Figure 3.7 Stucco (Type MS) Flow Chart

Table 3.14 Stucco Constituents

Type of Stucco	*Cementitious Materials (volume fraction)* Portland Cement	Masonry Cement	Lime	*Sand (volume fraction of cementitious material)*
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 3.15 Energy Requirements for Masonry Cement Manufacturing

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

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

Stucco is assumed to be mixed in a 5.9 kW (8 hp), gasoline powered mixer with a stucco flow rate of 0.25 m^3/h (9 ft^3/h), running for 5 min.

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 3.16. A lath made of 100 % recycled steel is assumed to be used when applying stucco. The product is assumed to have a useful life of 100 years.

Table 3.16 Density of Stucco by Type

Type of Stucco	Density kg/m^3 (lb/ft^3)
Base Coat C	1 830 (114.18)
Finish Coat F	1 971 (122.97)
Base Coat MS	1 907 (118.98)
Finish Coat FMS	2 175 (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 *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. Cost data have been adjusted to year 2002 dollars.

3.3.3 Generic Aluminum Siding (B2011C)

Aluminum siding is a commonly-used exterior wall cladding. It 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. These manufacturing steps, however, are not assigned to aluminum siding in BEES for two reasons: (1) aluminum is one of the few commodities for which a mature recycling market exists, and (2) aluminum can be recycled into the same products over and over again without loss of technical performance. In other words, aluminum for siding is assumed to be produced through a closed loop recycling system. 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.

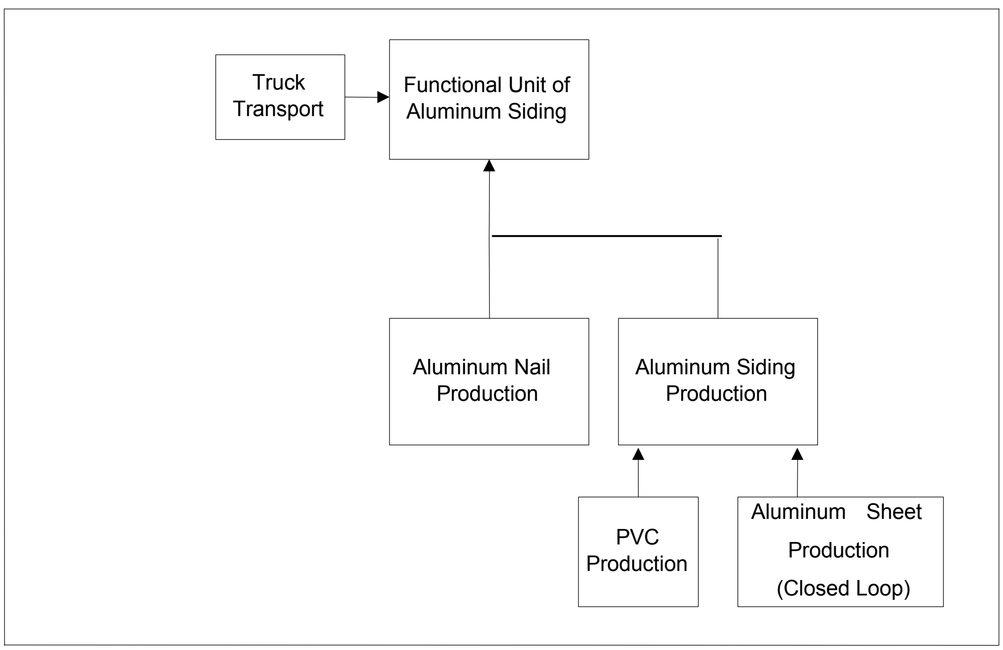

Figure 3.8 Aluminum Siding Flow Chart

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 3.17 presents the major constituents of aluminum siding. Production requirements for these constituents are based on the DEAM database.

Table 3.17 Aluminum Siding Constituents

Constituent	***Mass Fraction (%)***
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 DEAM database.

Use. Installation waste with a mass fraction of 0.05 is assumed. The product is assumed to have a useful life of 80 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 *B2011*, 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. Cost data have been adjusted to year 2002 dollars.

3.3.4 Generic 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 10 years. The flow diagram in Figure 3.9 shows the major elements of cedar siding production.

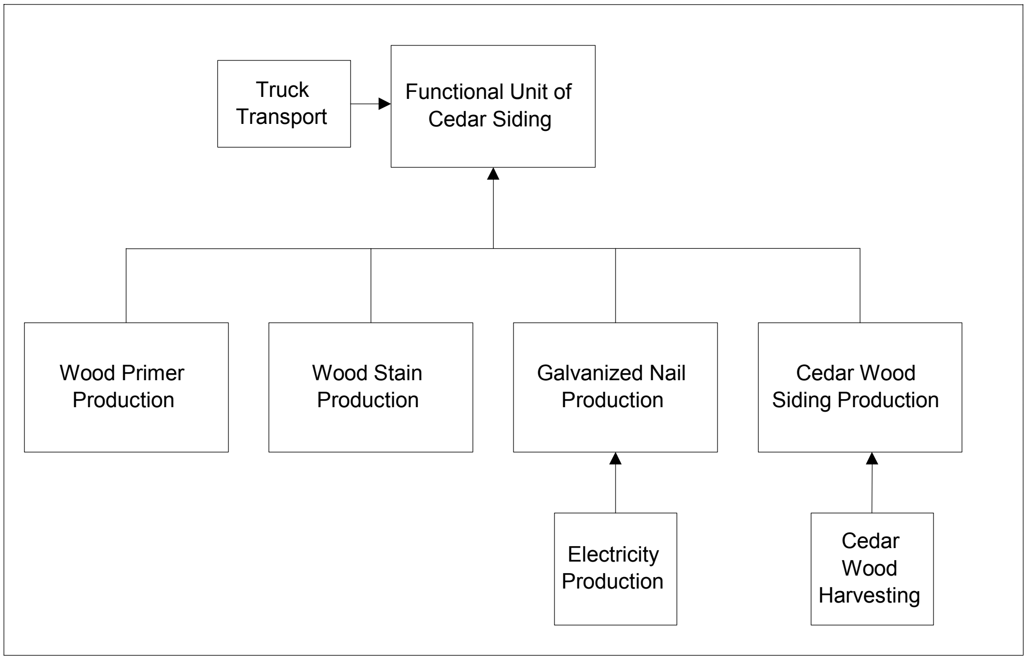

Figure 3.9 Cedar Siding Flow Chart

Raw Materials. Production data for cedar wood is derived from the DEAM database. These data account for the absorption of carbon dioxide by trees.

Energy Requirements. The energy requirements for cedar siding manufacture are approximately 5.6 MJ/kg (2 413 Btu/lb) of cedar siding produced.[69] Table 3.18 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 PricewaterhouseCoopers database.

Table 3.18 Energy Requirements for Cedar Siding Manufacture

Fuel Use[70]	***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 3.19.

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

Table 3.19 Hogfuel Emissions[71]

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 PricewaterhouseCoopers 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. The product is assumed to have a useful life of 40 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 *B2011*, 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. Cost data have been adjusted to year 2002 dollars.

3.3.5 Generic Vinyl Siding (B2011E)

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

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

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.

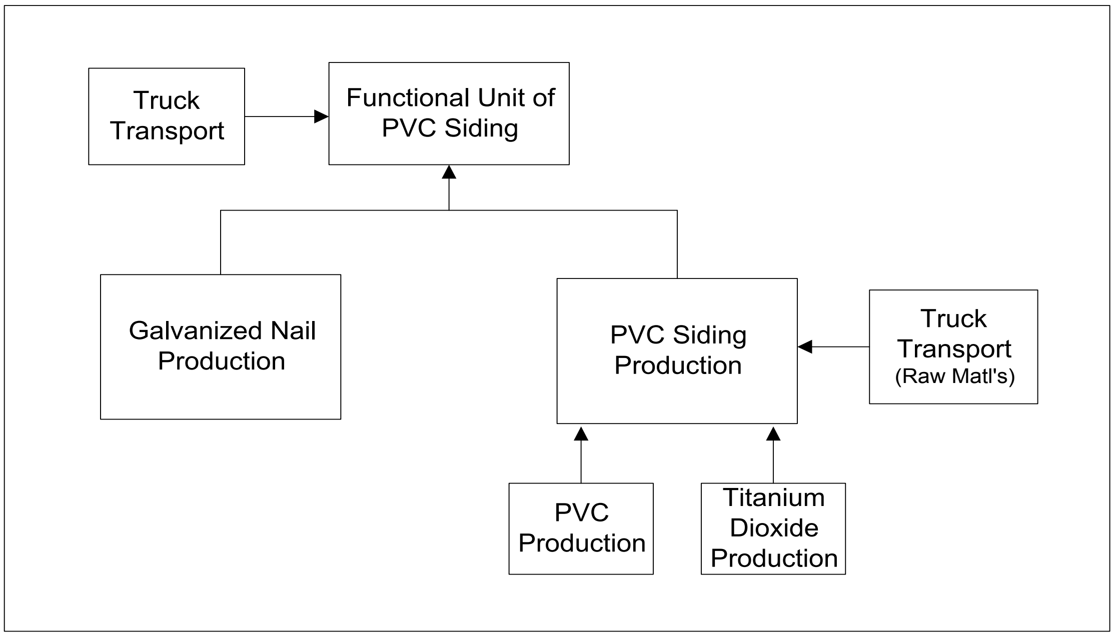

Figure 3.10 Vinyl Siding Flow Chart

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 3.20 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 PricewaterhouseCoopers database.

Table 3.20 Vinyl Siding Constituents

Constituent	*Mass Fraction (%)*
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 PricewaterhouseCoopers database.

Use. At installation, 5 % of the product is lost to waste. The product is assumed to have a useful life of 40 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 *B2011*, 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. Cost data have been adjusted to year 2002 dollars.

3.3.6 Trespa Meteon (B2011F)

For documentation on this product, see section 3.8.1.

3.4 Wall and Ceiling Insulation Alternatives (B2012, B3012)

3.4.1 Generic 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 3.21, 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 PricewaterhouseCoopers database.

Manufacturing. The constituents for cellulose insulation manufacture are based on information from CIMA, as shown in Table 3.22.

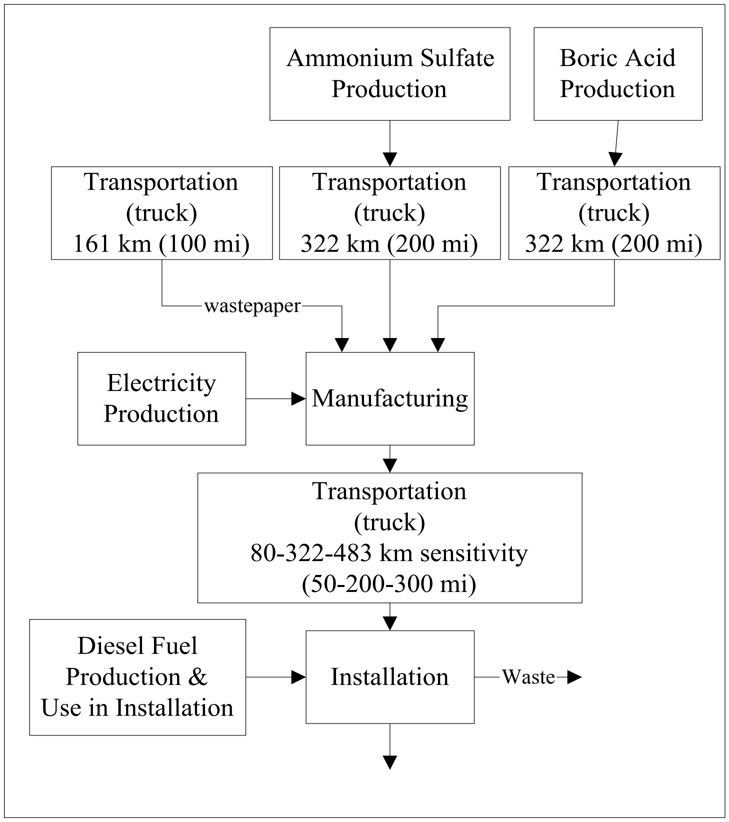

Figure 3.11 Blown Cellulose Insulation Flow Chart

Table 3.21 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 3.22 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/kg (150 Btu/lb) of cellulose insulation produced. Electricity production emissions are based on the PricewaterhouseCoopers 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 PricewaterhouseCoopers 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 PricewaterhouseCoopers 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 PricewaterhouseCoopers 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 1 134 kg/h (2 500 lb/h) 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.[72] BEES environmental performance results account for the energy-related inventory flows resulting from these energy requirements. To account for the 50-year energy

[72] 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.

requirements in BEES economic performance results, 1997 fuel prices by State[73] and U.S. Department of Energy fuel price projections over the next 30 years[74] are used to compute the present value cost of operational energy per functional unit for each alternative R-value.

The product is assumed to have a useful life of 50 years.

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.* Cost data have been adjusted to year 2002 dollars.

3.4.2 Generic 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 3.23. 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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[73] 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.

[74] 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.

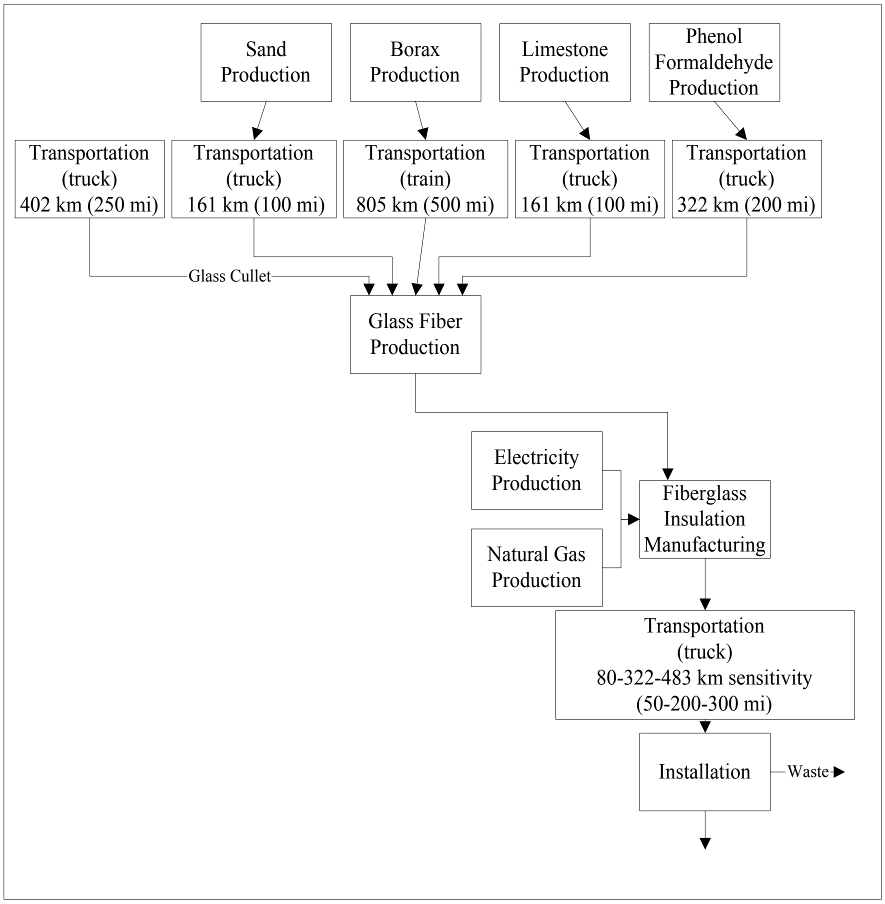

Figure 3.12 Fiberglass Batt Insulation Flow Chart

- 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 3.23 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 3.24. Production requirements for these materials are based on the DEAM database.

Table 3.24 Fiberglass Batt Constituents

Constituent	***Mass Fraction (%)***
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 3.25.

Table 3.25 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 (2580 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.[75] 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[76] and U.S. Department of Energy fuel price projections over the next 30 years[77] are used to compute the present value cost of operational energy per functional unit for each R-value.

[75] 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.

[76] 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.

[77] 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.

When installing fiberglass batt insulation, approximately 2 % of the product is lost to waste. The product is assumed to have a useful life of 50 years. 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.* Cost data have been adjusted to year 2002 dollars.

3.4.3 Generic 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 3.26. 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.

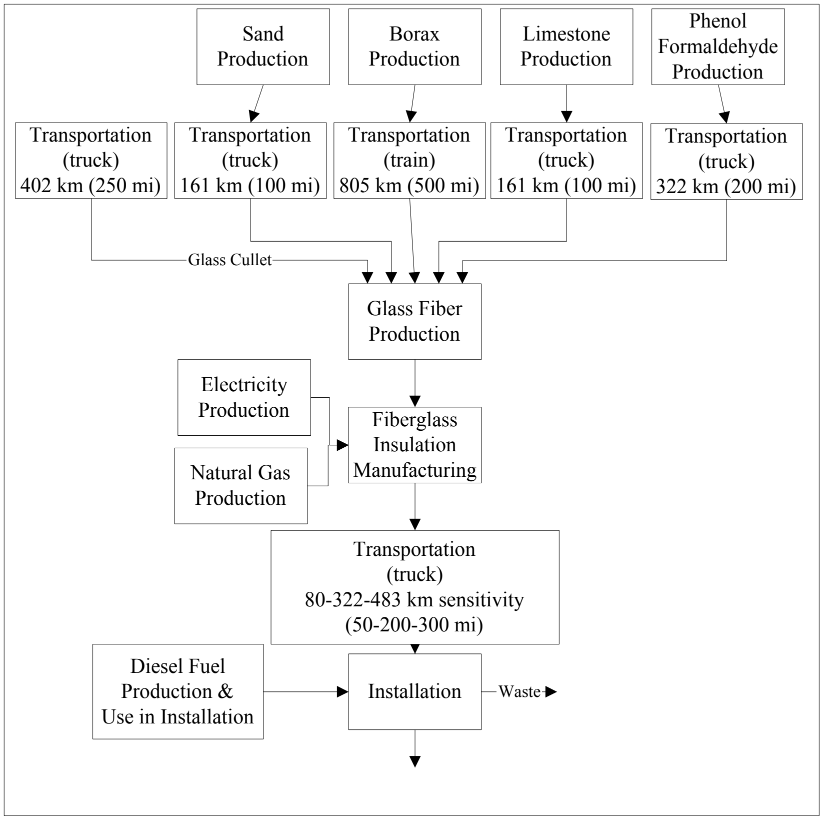

Figure 3.13 Blown Fiberglass Insulation Flow Chart

Table 3.26 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 3.27.

Table 3.27 Blown Fiberglass Constituents

Constituent	*Mass Fraction (%)*
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 DEAM database.

Fiberglass production involves the energy requirements as listed in Table 3.28.

Table 3.28 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. The product is assumed to have a useful life of 50 years. 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 1 134 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.* Cost data have been adjusted to year 2002 dollars.

3.4.4 Generic 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.

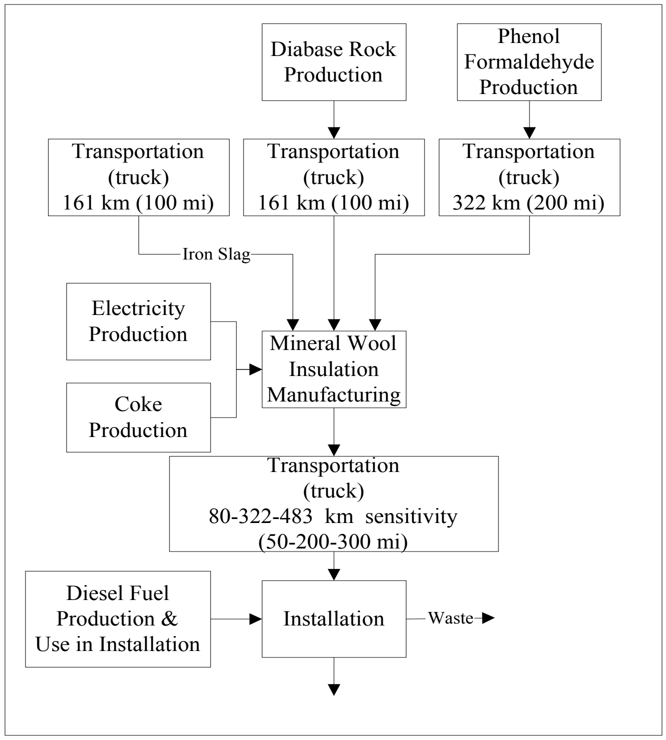

Figure 3.14 Blown Mineral Wool Insulation Flow Chart

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 3.29. Production requirements for the mineral wool constituents are based on the DEAM database.

Table 3.29 Blown Mineral Wool Constituents

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

Mineral wool production involves the energy requirements listed in Table 3.30.

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

Table 3.30 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.[78] 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[79] and U.S. Department of Energy fuel price projections over the next 30 years[80] 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 1 134 kg/h (2 500 lb/h) with a 19 kW (25 hp) diesel engine. During installation, 5 % of the product is lost to waste. The product is assumed to have a useful life of 50 years.

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,

[78] 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.

[79] 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.

[80] 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.* Cost data have been adjusted to year 2002 dollars.

3.5 Framing Alternatives (B2013)

3.5.1 Generic 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

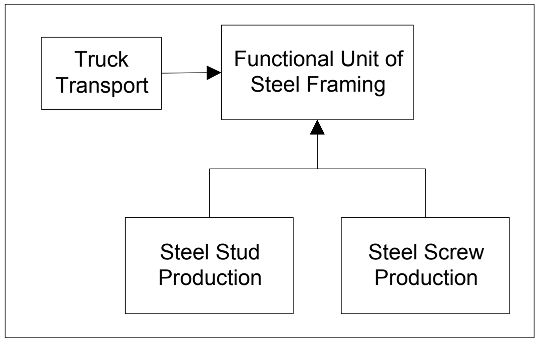

Figure 3.15 Steel Framing Flow Chart

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[81].

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 DEAM database.

Emissions. Emissions for steel stud and self-tapping screw production are based on the DEAM 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 PricewaterhouseCoopers 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. The product is assumed to have 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 *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

[81] 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. Cost data have been adjusted to year 2002 dollars.

3.5.2 Generic Wood Framing (B2013B, B2013C)

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., 2x4). 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. Treated lumber is used for framing in places with serious termite problems such as Hawaii and the Virgin Islands. Both treated and untreated wood framing are included in BEES.

The functional unit of comparison for BEES framing alternatives is 0.09 m^2 (1 ft^2) of load bearing wall framing for 50 years. Both untreated and preservative-treated pine wood studs, 5.08 cm x 10.16 cm (2 in x 4 in), with a moisture content of 19 %, are studied. For the treated alternative, 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 these products may be viewed by opening the following files under the File/Open menu item in the BEES software:

- B2013B.DBF—Preservative-Treated Wood Framing
- B2013C.DBF—Untreated Wood Framing

Raw Materials. For BEES, data were collected for the harvested trees used to produce the lumber necessary for framing load-bearing walls. These data account for the absorption of carbon dioxide by trees. Production of the other raw materials--steel for nails and chromated copper arsenate for the preservative-treated product--is based on data from the DEAM database.

Energy Requirements. The energy requirements for lumber manufacture are shown in Table

3.31. These requirements are based on Canadian growing conditions, recovery factors, and proportions of old growth, second growth, and tree plantations. The energy is assumed to come primarily from burning wood waste. Other fuel sources, including natural gas and petroleum, are also used.

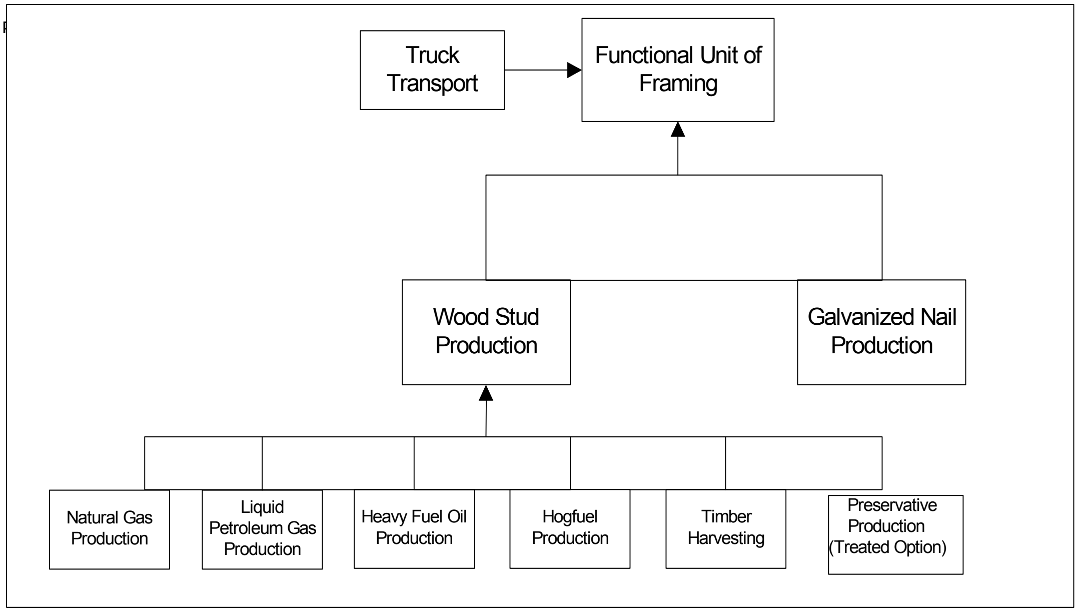

Figure 3.16 Wood Framing Flow Chart

Table 3.31 Energy Requirements for Lumber Manufacture[82]

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

[a]Excluding electricity.
[b]Total fossil fuel value is a gross figure including production of both lumber and its coproducts.

Emissions. The emissions from the lumber manufacturing process are shown in Table 3.32.

Transportation. Since sawmills are often located close to tree harvesting areas, the transportation of round wood to the sawmill is not taken into account. However, truck transportation of 322 km (200 mi) is assumed for transport of the preservative for the preservative- treated option. The tailpipe emissions from the truck engine and the emissions that

[82] 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.

Table 3.32 Hogfuel Emissions[83]

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)

result from the production of the fuel used in the truck are taken into account based on the PricewaterhouseCoopers 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 19 % moisture content (seasoned wood) is assumed to be 449 kg/m^3 (28 lb/ft^3). For the preservative-treated option, 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. The product is assumed to have a useful life of 75 years.

Cost. The detailed life-cycle cost data for these products may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under BEES code *B2013*, product code *B0* for preservative-treated wood framing; and under BEES code *B2013*, product code *C0* for untreated wood framing. 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. Cost data have been adjusted to year 2002 dollars.

3.6 Roof Covering Alternatives (B3011)

3.6.1 Generic 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

[83] Forintek Canada Corporation, *op cit*, Appendix A.

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 DEAM database.

Type-15 felt consists of asphalt and organic felt as listed in Table 3.34. 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 DEAM database.

Energy Requirements. The energy requirement for asphalt shingle production is assumed to be

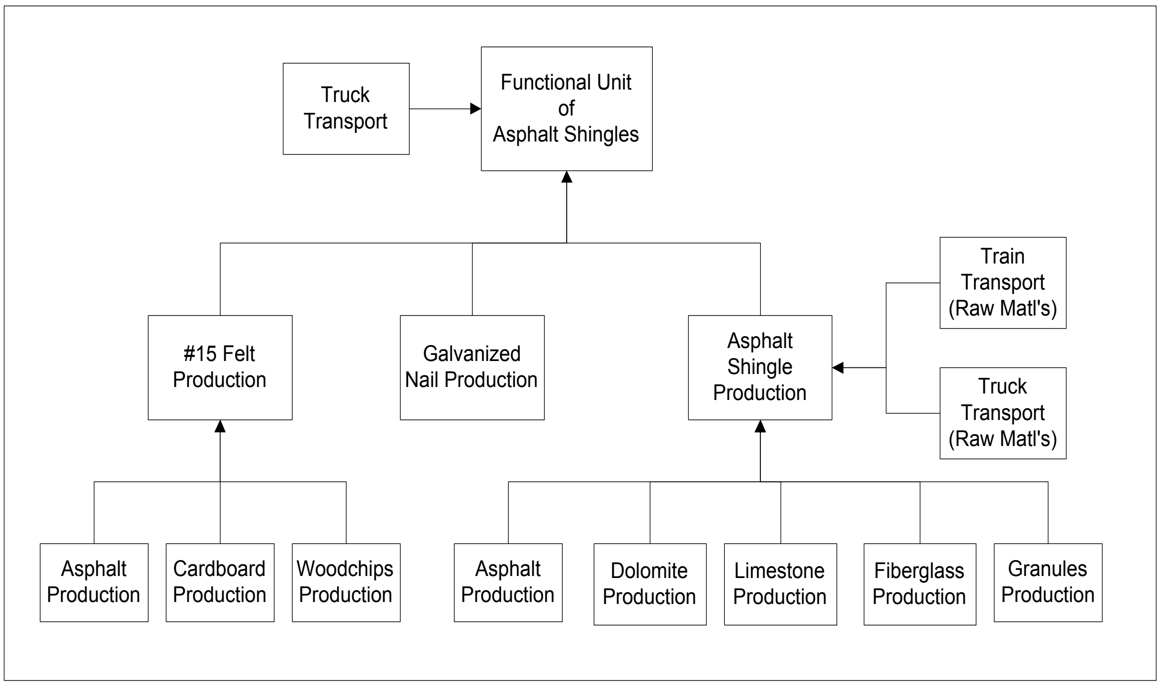

Figure 3.17 Asphalt Shingles Flow Chart

33 MJ/m^2 of natural gas (2843 Btu/ft^2) of shingles.

Raw Materials. Asphalt shingles are composed of the materials listed in Table 3.33.

Table 3.33 Asphalt Shingle Constituents

Asphalt Shingle Constituents	*Physical Weight*
Asphalt	1.9 kg/m^2 (40 lb/square[a])
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)

[a]One square is equivalent to 9.29 m^2 (100 ft^2)

Table 3.34 Type 15 Roofing Felt Constituents

Type 15 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 %.[84] 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,[85] 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

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

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

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.[86] 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 per m^2 (440 nails per 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.

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. Cost data have been adjusted to year 2002 dollars.

3.6.2 Generic 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, Type-30 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 DEAM database.

Type-30 felt consists of asphalt and organic felt as listed in Table 3.35. 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 DEAM database.

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[86] 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 Building," *ASHRAE Transactions*, SF-98-6-2, Vol. 104, 1998, p. 1.

Table 3.35 Type-30 Roofing Felt Constituents

Felt Constituents	*Mass per Applied Area*
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)

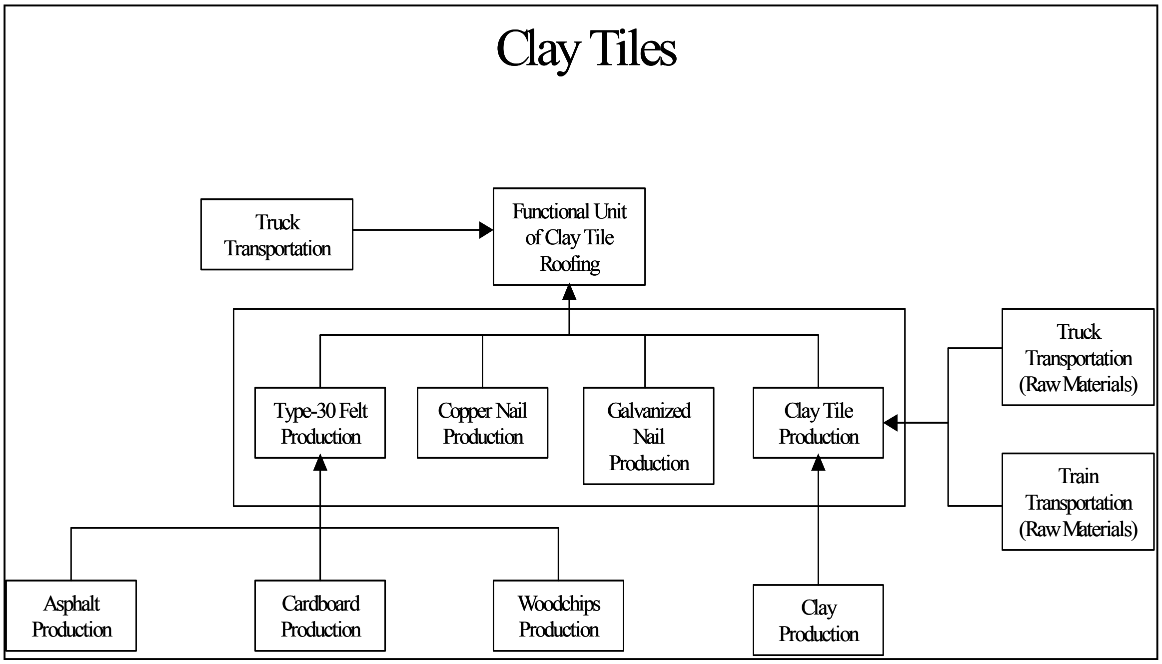

Figure 3.18 Clay Tile Flow Chart

Energy Requirements. The energy required to fire clay tile is 6.3 MJ/kg (2708 Btu/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 %.[87] 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, [88] 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.[89] 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 Type-30 roofing felt, 13 galvanized nails per m^2 (120/square) for underlayment, and 37 copper nails per 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. Cost data have been adjusted to year 2002 dollars.

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

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

[89] 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 Building,” *ASHRAE Transactions*, SF-98-6-2, Vol. 104, 1998, p. 1.

3.6.3 Generic 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 3.36. The filler is sand, and the organic fiber is wood chips. The mass of fiber cement shingles per applied area 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.

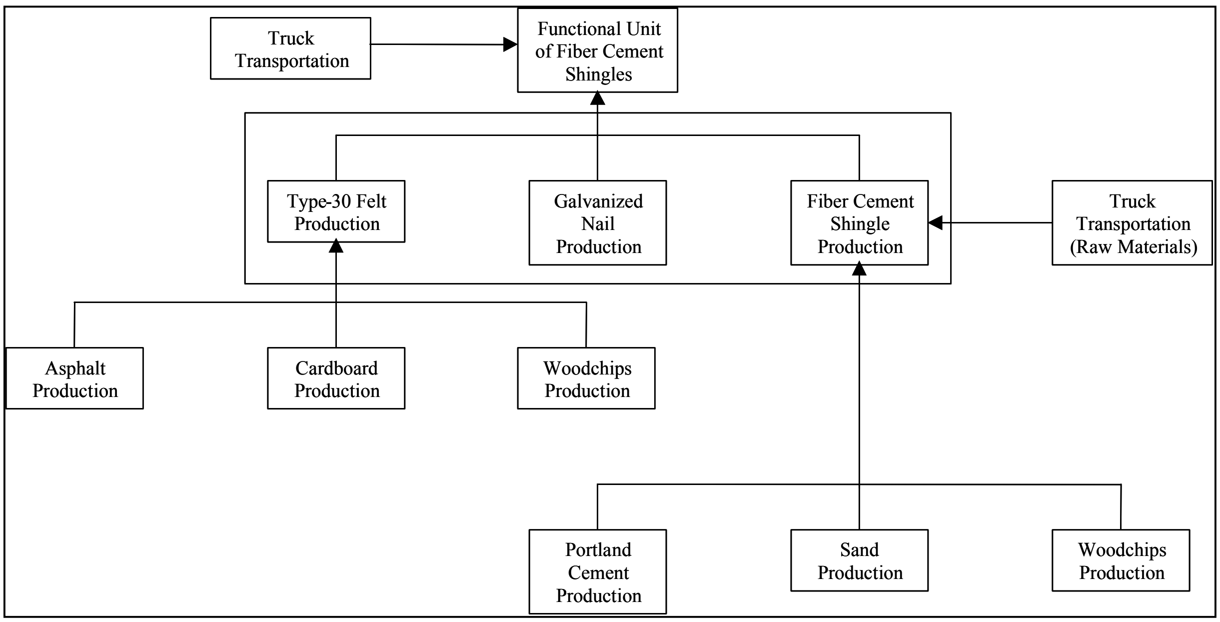

Figure 3.19 Fiber Cement Shingles Flow Chart

Table 3.36 Fiber Cement Shingle Constituents

Fiber Cement Shingle Constituents	***Mass Fraction (%)***
Portland Cement	90
Filler	5
Organic Fiber	5

Portland cement production requirements are identical to those noted above for a stucco exterior wall finish. Type-30 roofing felt is modeled as noted above for clay tile roofing.

Production requirements for the raw materials is based on the DEAM 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 %.[90] 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, [91] 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.[92] 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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[90] Memorandum from Sarah Bretz/Lawrence Berkeley National Laboratory to Barbara Lippiatt/National Institute of Standards and Technology, 12/18/98.

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

[92] 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 Building," *ASHRAE Transactions*, SF-98-6-2, Vol. 104, 1998, p. 1.

Fiber cement shingle roofing requires one layer of Type-30 felt underlayment, 13 nails per m^2 (120 nails per square) for the underlayment, and 32 nails per 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. Cost data have been adjusted to year 2002 dollars.

3.7 Partitions (C1011)

3.7.1 Generic Drywall (C1011A)

Gypsum board, or drywall, consists of a core of gypsum surrounded by kraft paper facings. Several types of drywall are produced, each with a modification to the gypsum core or facings. These include moisture-resistant drywall (green board), Type-X drywall with glass fibers and improved fire resistance, and foil-backed drywall.

Gypsum board is installed using joint tape and compound, and is typically applied to wood framing with nails, screws, or adhesives. It can also be applied to metal framing with screws. Joints between gypsum boards are covered with paper or glass-fiber joint tape embedded in joint compound. Joint compound is usually a vinyl-based, ready-to-use product that contains limestone or gypsum to provide body. Clay, mica, talc, or perlite is often used as a filler. Ethylene glycol is used as an extender, and antibacterial and antifungal agents are also applied. Other types of joint compounds which set when mixed with chemical hardeners are also used on a more limited basis.

For the BEES system, 13 mm (½ in) gypsum wallboard, joint tape, joint compound, and wallboard nails are studied. Gypsum wallboard is assumed to be nailed to wood studs, 41 cm (16 in) on center. Joints are assumed to be treated with 52 mm-thick (2-1/16 in-thick) paper joint tape and ready mix, all-purpose joint compound.

Wallboard is produced using partially dehydrated or calcinated gypsum, also called "stucco." Stucco is fed into a mixer where it is combined with water and other ingredients to make a slurry or paste. The slurry is spread on a moving stream of paper and then covered with top paper, or "gray back," to form wallboard. It is cut into specific lengths and then sent to kilns to dry. After drying, the wallboard is sent to bundling areas where it is trimmed to exact lengths. The wallboard is then moved to warehouses for shipment to the building site. Figure 3.20 shows the major elements of gypsum wallboard production. The detailed environmental performance data for this product may be viewed by opening the file C1011A.DBF under the File/Open menu item in the BEES software.

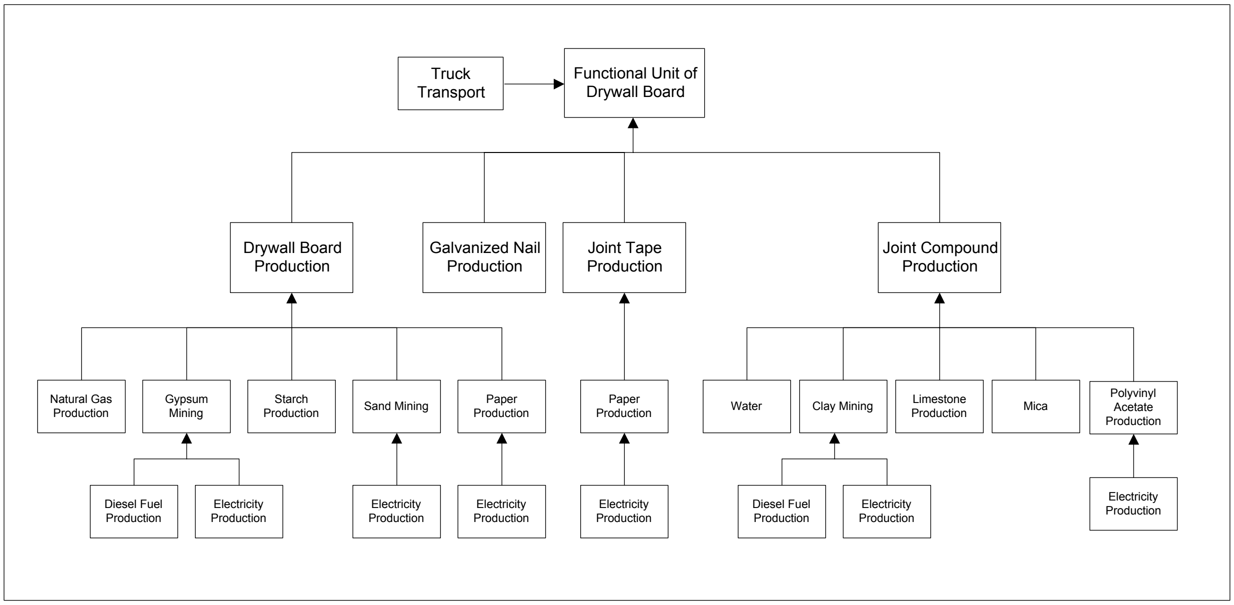

Figure 3.20 Gypsum Board Flow Chart

Raw Materials. The production of raw materials for drywall is based on the DEAM database. Table 3.37 lists the constituents of drywall and their proportions by weight.

Table 3.37 Gypsum Board Constituents

Constituent	*Physical Weight (%)*
Gypsum	85 %
Paper	10 %
Sand	3 %
Starch	2 %

Energy Requirements. Energy requirements data are from primary sources (gypsum manufacturing plants) and the DEAM database, and are given in Table 3.38.

Table 3.38 Energy Requirements for Gypsum Board Manufacturing

Fuel Use	*Manufacturing Energy*
Natural Gas	19.02 MJ/kg (8 196 Btu/lb)

The production of the natural gas used in gypsum processing is based on the DEAM database.

Emissions. Emissions are based on AP-42 emissions factors for gypsum processing.

Transportation. Transport of raw materials to the manufacturing site is not accounted for. However, transportation by truck to the building site is modeled as a variable in the BEES system. Both emissions associated with the combustion of fuel in the truck engine and emissions associated with production of the fuel are included.

Use. The product is assumed to have a useful life of 50 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 C1011, 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. Cost data have been adjusted to year 2002 dollars.

3.7.2 Trespa Virtuon and Athlon (C1011B, C1011C)

For documentation on these products, see section 3.8.1.

3.8 Fabricated Toilet Partitions, Lockers, Ceiling Finishes, Fixed Casework, Table Tops/Counter Tops/Shelving (C1031, C1032, C3030, E2010, E2021)

3.8.1 Trespa Composite Panels

Based in The Netherlands, Trespa is the world's largest manufacturer of solid composite panels. Trespa entered the U.S. market in 1991, and now produces millions of square feet of sheet material annually. Trespa products offer an alternative to thin laminate and epoxy-resin products. Each of Trespa's four composite panel lines has been designed for a particular use:

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1. Athlon, a panel developed for durable interior fittings;
2. Meteon, a panel developed for exterior applications such as cladding or soffits;
3. TopLab Plus, a panel designed for lab work surface areas; and
4. Virtuon, an interior panel system that is impact, moisture and stain resistant.

The detailed environmental performance data for these products may be viewed by opening the following files under the File/Open menu item in the BEES software:

- C3030B.DBF—Athlon
- B2011F.DBF—Meteon
- E2021A.DBF—TopLab Plus
- C3030A.DBF—Virtuon

Raw Materials. All Trespa panels are made in the same way – with an interior core material and a layer of decorative facing on both sides. The core and facing materials come from different sources for different applications, so the overall mix of raw material inputs is different for each product as shown in Table 3.39.

Table 3.39 Trespa Composite Panel Constituents by Mass Fraction

Constituent	*Athlon*	*Meteon*	*TopLab*	*Virtuon*
Kraft Paper	52 %	17 %	17 %	44 %
Wood	0 %	38 %	38 %	0 %
Bisphenol-A-Tar	18 %	17 %	17 %	15 %
Formaldehyde	28 %	28 %	28 %	24 %
Other Materials	2 %	0 %	0 %	18 %

The kraft paper used in the panels is recycled, so no raw material inputs are required. Wood production data represent site data for the production of pine chips.

Bisphenol-A-Tar is used as a binder in the panels. Tar is a co-product of Bisphenol A production, so a portion of the upstream burdens from Bisphenol A production are allocated to the production of the tar. Formaldehyde is also used as a binder in the panels, and is assigned the same upstream production data as that for other BEES products with formaldehyde.

Data for the transport of raw materials from the supplier to the manufacturer was provided by Trespa, with diesel truck as the mode of transportation. Figure 3.21 shows the elements of Trespa composite panel raw material production.

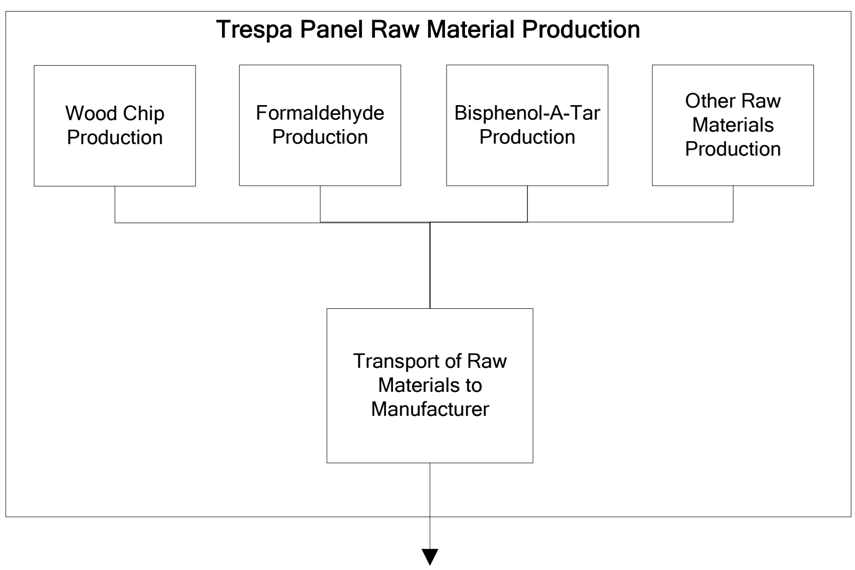

Figure 3.21 Trespa Composite Panel Raw Material Production Flow Chart

Manufacturing. Trespa composite panel manufacturing consists of bonding the core panel and the two decorative panels. The manufacturing process requires natural gas, diesel oil, and electricity as energy inputs. To produce one square meter of panel, Trespa uses 9.4 MJ (2.6 Wh) of electricity, 84.4 MJ of natural gas and 0.6 MJ of diesel oil. Trespa uses PET and Kraft paper to package its products; these inputs are included in the life cycle inventories. Figure 3.22 shows the elements of Trespa composite panel manufacturing.

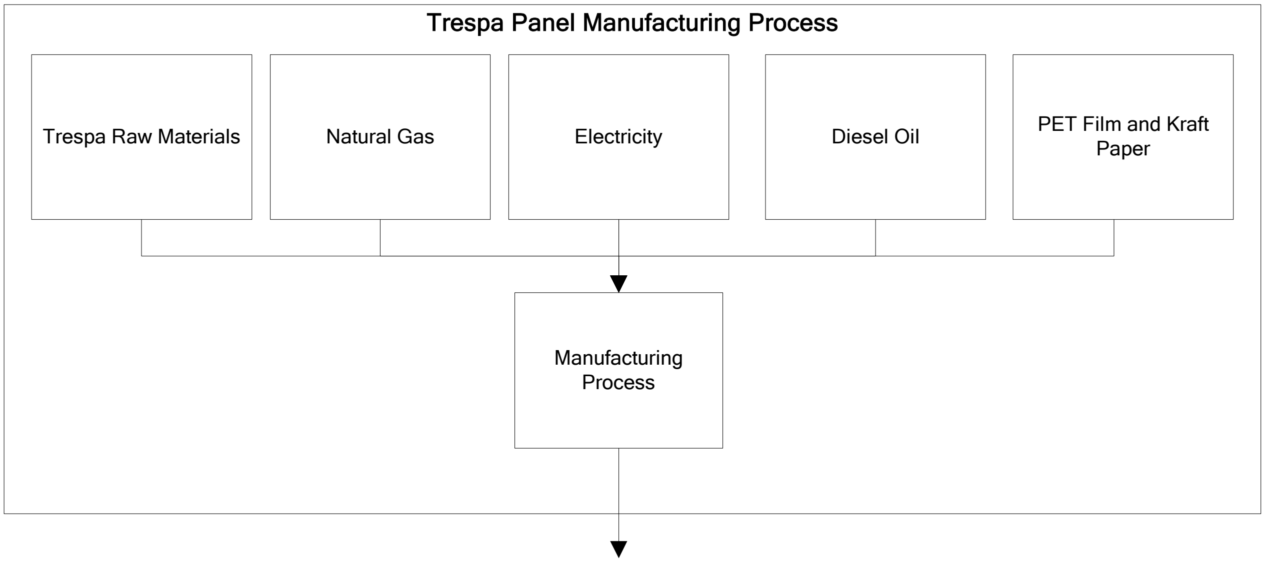

Figure 3.22 Trespa Composite Panel Manufacturing Flow Chart

Transportation. Trespa panels are shipped from the production facility in The Netherlands to a U.S. port – a distance that was modeled as 10 000 km by sea. The transportation emissions allocated to each of the four Trespa panel products depends on the overall mass of the product, as given in Table 3.40. Transportation from the U.S. port of entry to the building site, by diesel truck, is modeled as a variable in BEES.

Table 3.40 Density of Trespa Composite Panels

Product	*Mass per Applied Area (kg/m^2)*	*Density (kg/m^3)*
All products (10 mm thickness)	14	1 400

Installation. Trespa panels are installed using stainless steel bolts. On average, 0.025 kg of stainless steel bolts are required to install 1 m^2 of composite panel. Approximately 3 % of the panel is lost as waste during the installation process, due to cutting of the panels to fit the installation area.

End of Life. Trespa panels are assumed to have a lifetime of 50 years. After year 50, the panels are removed and about 50 % of the waste is reused in other products, while the remaining 50 % is sent to a landfill.

Cost. Detailed life cycle cost data for Trespa composite panels may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Their costs are listed under the following codes:

- B2011,F0—Meteon Exterior Wall Finish
- C1031,A0-- Virtuon Fabricated Toilet Partitions

- C1031,B0—Athlon Fabricated Toilet Partitions
- C1032,A0—Virtuon Lockers
- C1032,B0—Athlon Lockers
- C3030,A0—Virtuon Ceiling Finish
- C3030,B0—Athlon Ceiling Finish
- E2010,A0—Virtuon Fixed Casework
- E2010,B0—Athlon Fixed Casework
- E2021,A0--TopLab Plus Table Tops/Counter Tops/Shelving
- E2021,B0—Athlon Table Tops/Counter Tops/Shelving

Life-cycle cost data include first cost data (purchase and installation costs) and future cost data (cost and frequency of replacement) provided by Trespa.

3.9 Interior Finishes (C3012)

3.9.1 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 3.41.

Table 3.41 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)

3.9.2 Generic 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 3.23 displays the system under study for virgin latex paint.

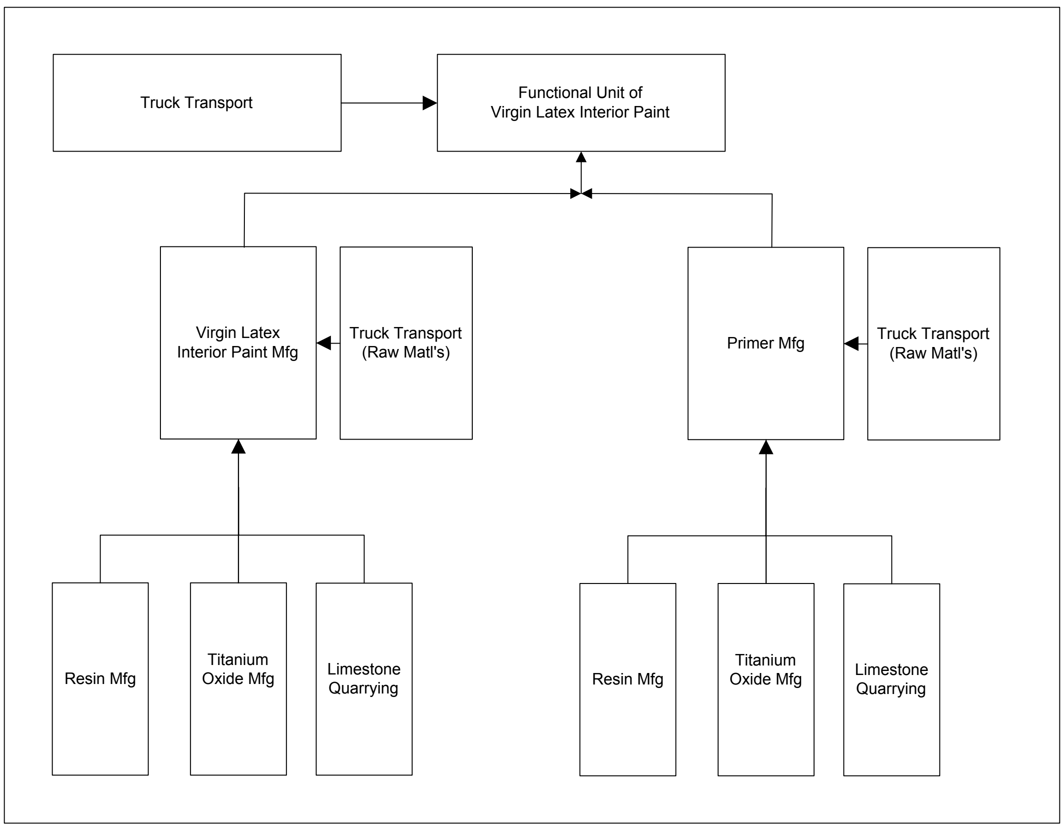

Figure 3.23 Virgin Latex Interior Paint Flow Chart

Raw Materials. The average composition of the virgin latex paint/primer system modeled in BEES is listed in Table 3.42.

Table 3.42 Virgin Latex Paint and Primer Constituents

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

Table 3.43 displays the market shares for the resins used for interior latex paint and primer.

Table 3.43 Market Shares of Resins

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

Table 3.44 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 DEAM database.

Table 3.44 Components of Paint Resins

Resin Type	***Components (Mass Fraction)***
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.

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. Cost data have been adjusted to year 2002 dollars.

3.9.3 Generic Recycled Latex Interior Paint (C3012B)

Figure 3.24 displays the BEES flow chart for recycled latex paint.

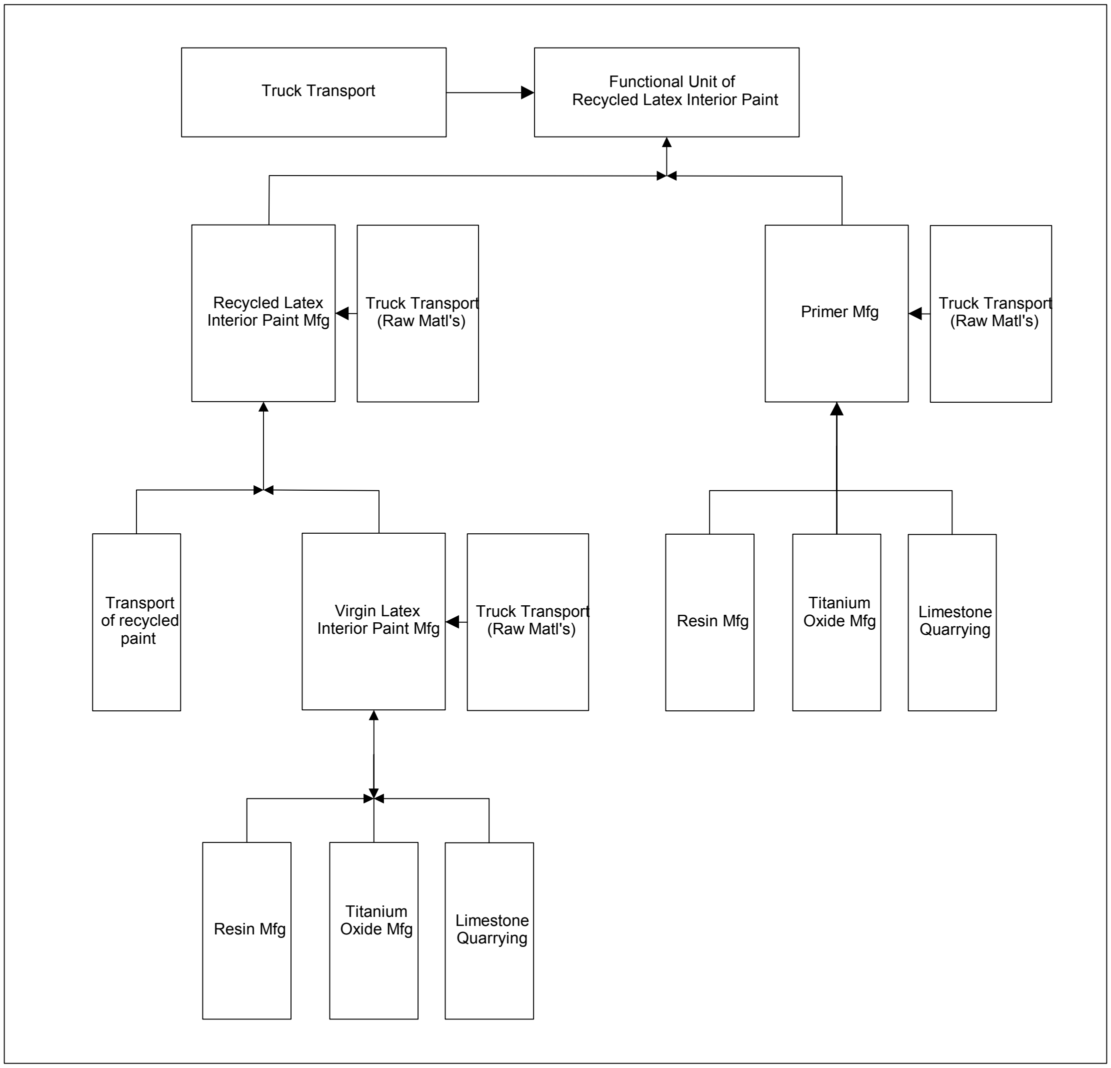

Figure 3.24 Recycled Latex Interior Paint Flow Chart

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.

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. Cost data have been adjusted to year 2002 dollars.

3.10 Floor Covering Alternatives (C3020)

3.10.1 Generic 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 3.25 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 3.45.

Table 3.45 Ceramic Tile with Recycled Glass Constituents

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

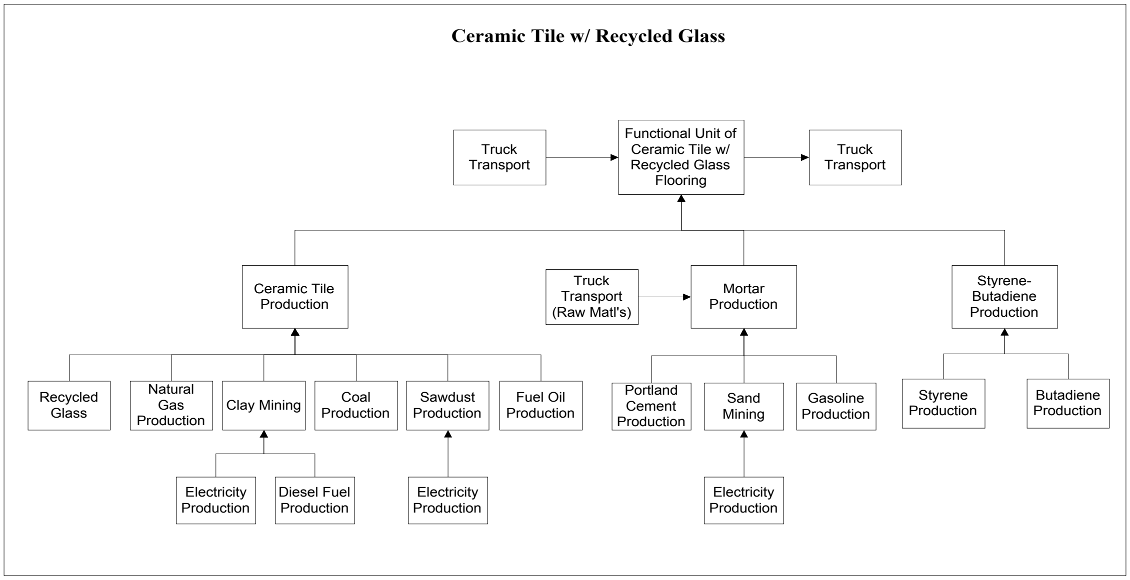

Figure 3.25 Ceramic Tile with Recycled Glass Flow Chart

Production requirements for clay are based on the DEAM 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 DEAM database.

Energy Requirements. The energy requirements for the drying and firing processes of ceramic tile production are listed in Table 3.46.

Table 3.46 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. Cost data have been adjusted to year 2002 dollars.

3.10.2 Generic Linoleum Flooring (C3020B)

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 3.26 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 3.47 lists the constituents of 2.5 mm (98 mil) linoleum and their proportions.

Table 3.47 Linoleum Constituents

Constituent	***Mass Fraction (%)****	***Mass per Applied Area***
linseed oil	23.3	670 g/m^2 (2.2 oz/ft^2)
pine rosin	7.8	224 g/m^2 (0.7 oz/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	2 874 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.

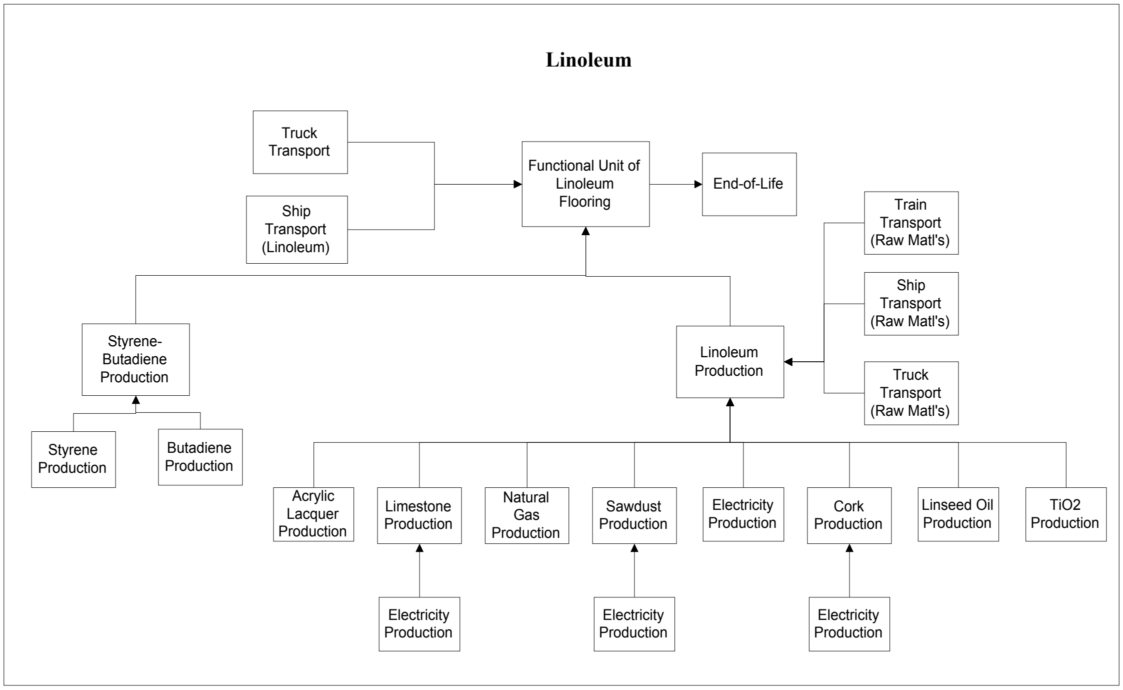

Figure 3.26 Linoleum Flow Chart

The cultivation of linseed is based on a United States agricultural model which estimates soil erosion and fertilizer run-off, [93] with the following inputs: [94]

- Fertilizer: 0.0035 kg/m^2 (31 lb/acre) nitrogen fertilizer, 17 kg/ha (15 lb/acre) phosphorous fertilizer, and 0.0014 kg/m^2 (12 lb/acre) potassium fertilizer
- Pesticides: 0.5 kg/ha (0.4 lb/acre) active compounds, with 20 % lost to air
- Diesel farm tractor: 0.65 MJ/kg (279 Btu/lb) linseed
- Linseed yield: 0.06 kg/m^2 (536 lb/acre)

The production of the fertilizers and pesticides is based on the DEAM database. The cultivation of pine trees for pine rosin is based on DEAM data for cultivated forestry, with inventory flows allocated between pine rosin and its coproduct, turpentine. The production of limestone is based on PricewaterhouseCoopers 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 DEAM 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 DEAM database. The production of acrylic lacquer is based on the DEAM database.

[93] 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.

[94] Jose Potting and Kornelis Blok, "Life-cycle Assessment of Four Types of Floor Covering," *Journal of Cleaner Production*, Vol. 3, No. 4, 1995, pp. 201-213.

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 3.48.

Table 3.48 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 3.49.

Table 3.49 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 DEAM 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 3.50.[95]

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

Table 3.50 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
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. Cost data have been adjusted to year 2002 dollars.

3.10.3 Generic 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 3.27 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 3.51 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 DEAM database.

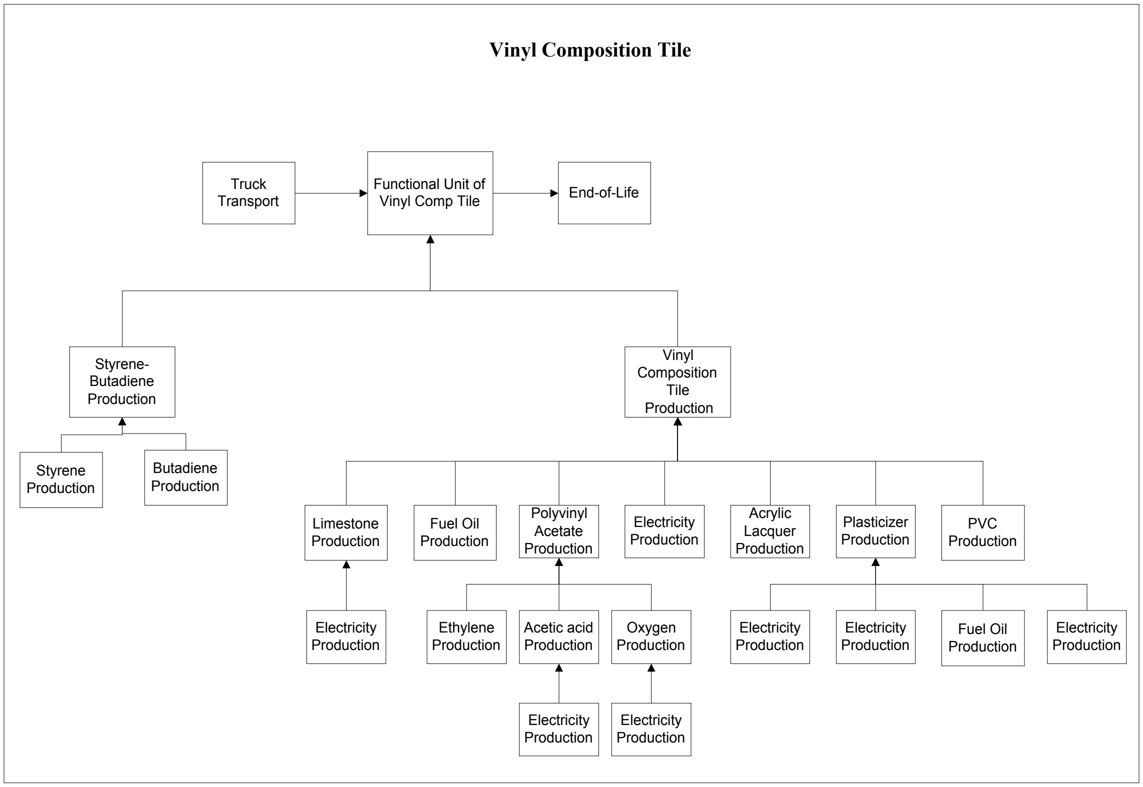

Figure 3.27 Vinyl Composition Tile Flow Chart

Table 3.51 Vinyl Composition Tile Constituents

Constituent	*Mass Fraction (%)*
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 3.52.

Table 3.52 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. Cost data have been adjusted to year 2002 dollars.

3.10.4 Generic 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 3.28 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 3.53 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 3.53 Composite Marble Tile Constituents

Constituent	*Mass Fraction (%)*
Resin	23.1
Filler	75.2
Catalyst (MEKP)	0.2
Pigment (TiO_2)	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.

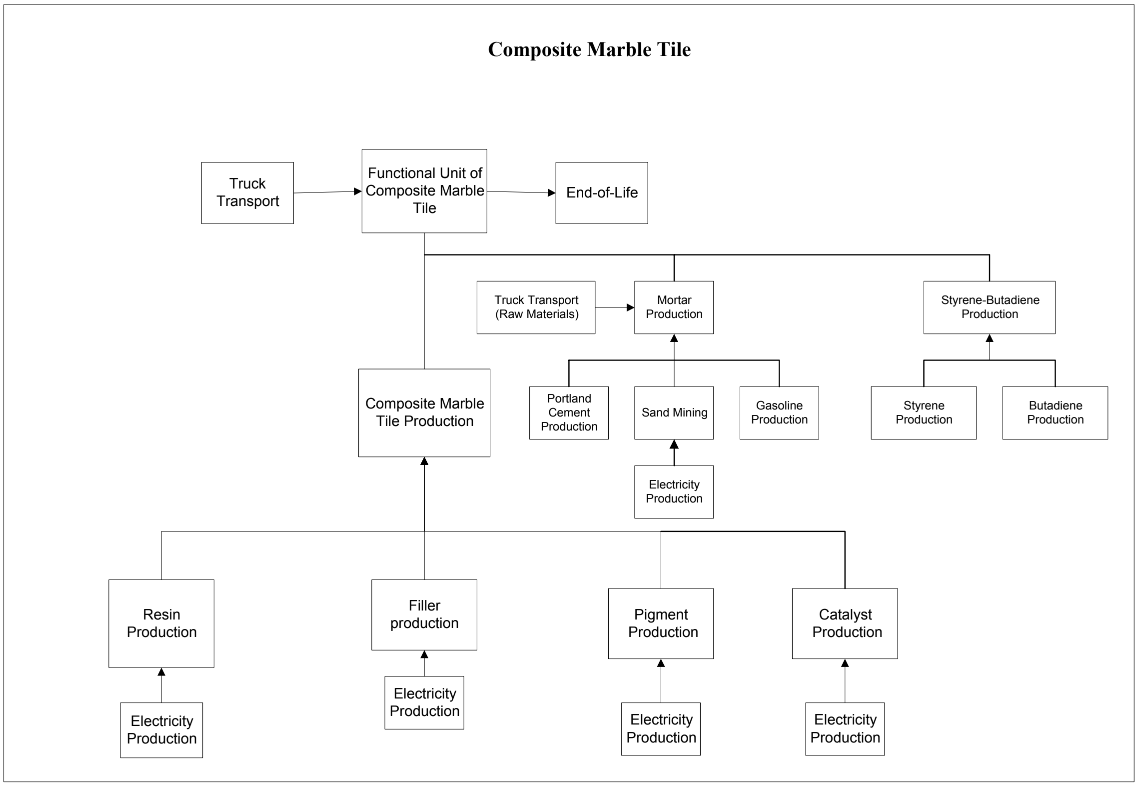

Figure 3.28 Composite Marble Tile Flow Chart

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 3.54 shows electricity use for composite marble tile manufacturing.

Table 3.54 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 25.11 kg/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. Cost data have been adjusted to year 2002 dollars.

3.10.5 Generic 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 3.29 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 3.55 lists the constituents of epoxy terrazzo and their proportions.

Table 3.55 Terrazzo Constituents

Terrazzo Constituents	*Mass Fraction (%)*
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 DEAM 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.

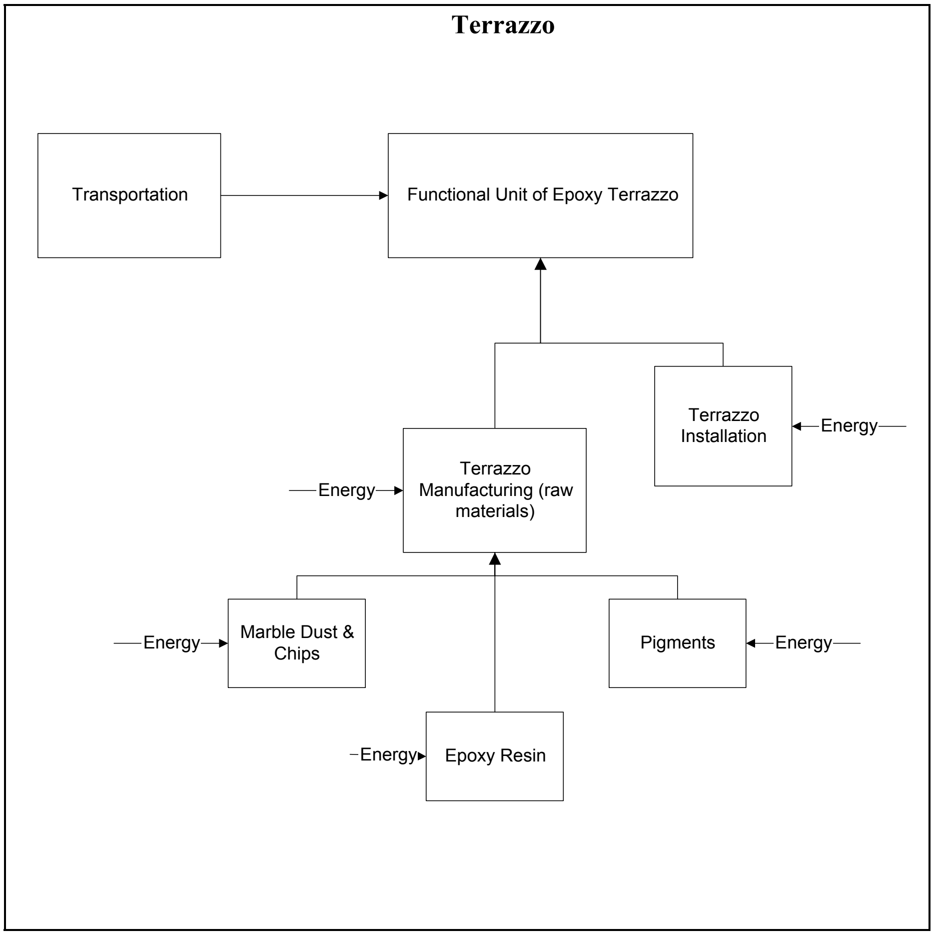

Figure 3.29 Epoxy Terrazzo Flow Chart

Energy Requirements. The energy requirements for the on-site "manufacturing" process involve mixing in a 5.97 kW (8 hp) 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. Cost data have been adjusted to year 2002 dollars.

3.10.6 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 woven slit-film polypropylene, synthetic polyester, nonwoven polypropylene, polyester/nylon, or jute. These are "yarn carrier" materials holding yarn that has been punched through them.

- Secondary backing – usually a woven or nonwoven fabric reinforcement laminated to the back of tufted carpeting to enhance dimensional stability, strength, stretch resistance, lie-flat stiffness, and handling. Examples of secondary backings are woven jute, polyester, and nonwoven polypropylene. 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".

- Laminate/Foam Coating – includes polyurethane, polyvinyl chloride (PVC), styrene butadiene (SBR) latex, and ethylene vinyl acetate (EVA). These "semi" liquids are applied to the back of the primary backing by various methods (e.g., knife over a roll, knife over a blade) and cooled, or heated and cooled, depending upon the component used. The functions of these components are to "lock in" or retain the yarn punched through the primary backing (precoat layer), and to provide stability, comfort under foot, and serve as a "glue" to bond the secondary backing to the carpet (finish coat layer).

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 3.56 displays the energy requirements for tufting carpet. [96]

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

Table 3.56 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 3.57.

Table 3.57 Carpet Installation Parameters

Parameter	***Broadloom***	***Tile***[97]
Glue application (applies to both traditional and low-VOC glues)	2 layers:[98] • 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 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 DEAM database.

3.10.7 Generic Wool Carpet (C3020G,C3020J,C3020M,C3020P)

A 1.13 kg (40 oz) wool carpet with a 25-year life is included in BEES. Figure 3.30 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

[97] Note that wool carpet tile is not currently manufactured on industrial lines.
[98] Spread rates for glue as recommended by the Carpet and Rug Institute.

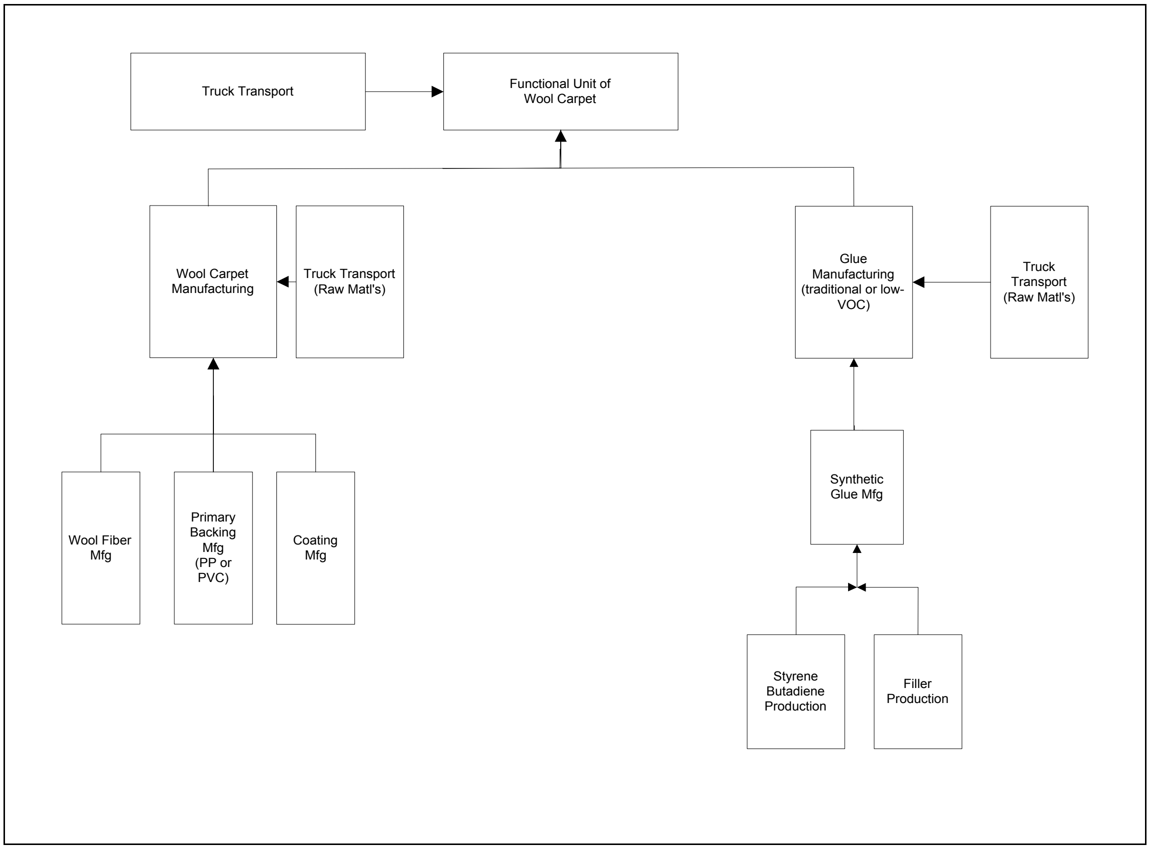

Figure 3.30 Wool Carpet Flow Chart

Raw materials. Table 3.58 lists the constituents of wool carpet and their amounts.

Table 3.58 Wool Carpet Constituents

Constituent	*Material*	*Amount* g/m^2 (oz/ft^2)
Face fiber	Wool	1 400 (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 DEAM database.

The wool fiber is produced in New Zealand, following the major production steps displayed in Figure 3.31.

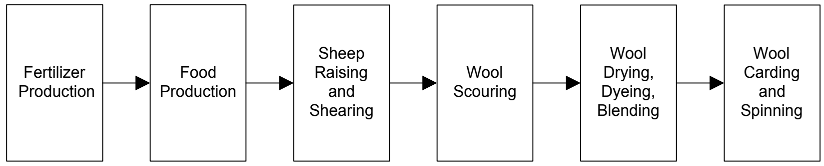

Figure 3.31 Wool Fiber Production

The material flows included for the production of raw wool are displayed in Table 3.59. [99]

Table 3.59 Raw Wool Material Flows

Flow	*Amount*
Inputs:	
- Nitrogen supply (ammonium nitrate)	29 g/kg nitrogen to raw wool (0.46 oz/lb)
- Phosphate supply (P_2O_5)	770 g/kg P_2O_5 to raw wool (12.32 oz/lb)
Outputs:	
- Raw wool	8.25 kg/year (18.20 lb/year) of raw wool
- 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/year and AP-42, Table 14-4-2, gives 8 kg/head/year.

The fertilizer inputs correspond to the production of food for the sheep. Fertilizer production is based on the DEAM 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 3.60 along with other raw wool constituents.

Table 3.60 Raw Wool Constituents

Constituent	*Mass Fraction (%)*
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 %.[100] The scoured fiber is then dried, carded, and spun. Table 3.61 lists the main inflows and outflows for the production of wool yarn from raw wool. [101] The data for raw wool processing are from the Wool Research Organisation of New Zealand (WRONZ).

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

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

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

Table 3.61 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.[102] One-fourth of the required energy (about 1MJ, or 948 Btu) is used for drying.[103] 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 3.62 displays the transportation modes and distances the wool travels before being used in the tufting process.

Table 3.62 Wool Transportation

Mode of Transportation	*Distance*
Sea Freighter	11 112 km (6000 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
- C3020, J0—Wool Carpet Tile with Low-VOC Glue

[102] This allocation is also applied to the non-energy flows for this process.
[103] Including dyeing and blending.

- 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. Cost data have been adjusted to year 2002 dollars.

3.10.8 Generic Nylon Carpet (C3020F,C3020I,C3020L,C3020O)

A 0.68 kg (24 oz) nylon carpet with an 11-year life (broadloom) or 15-year life (tile) is included in BEES. Figure 3.32 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 3.63 lists the constituents of nylon carpet and their amounts.

Table 3.63 Nylon Carpet Constituents

Constituent	*Material*	*Amount* g/m^2 (oz/ft^2)
Broadloom		
Face fiber	Nylon 6,6	810 (2.65)
Backing	Polypropylene	130 (0.43)
	Styrene butadiene latex (SBL)	930 (3.05), including 710 g (25.04 oz) of limestone as a filler
Tile		
Face fiber	Nylon 6,6	810 (2.65)
Primary Backing	Polypropylene	130 (0.43)
Precoat	EVA latex (including $CaCO_3$ filler)	930 (3.06) incl. filler: 654 (2.14)
Fiberglass	Fiberglass	68 (0.22)
Backing	Virgin PVC	3052 (10)

The production of plastic compound for backing (polypropylene and/or PVC), fiberglass, ethylene vinyl acetate (EVA) latex, styrene butadiene latex (SBL), and nylon fiber are based on the DEAM 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 3.64.

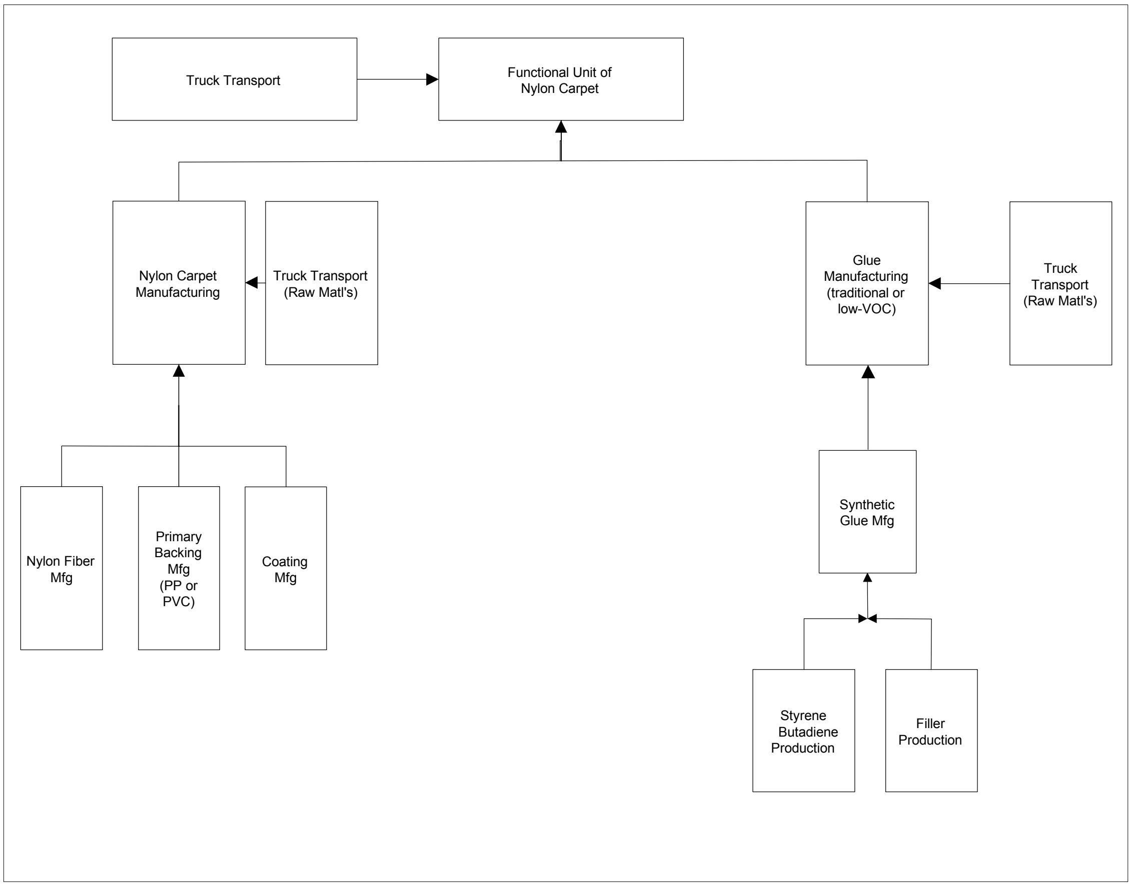

Figure 3.32 Nylon Carpet Flow Chart

Table 3.64 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. Cost data have been adjusted to year 2002 dollars.

3.10.9 Generic 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 3.33 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 3.65 lists the constituents of recycled polyester carpet and their amounts.

Table 3.65 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 DEAM database. The recycling of PET is modeled as shown in Figure 3.34.

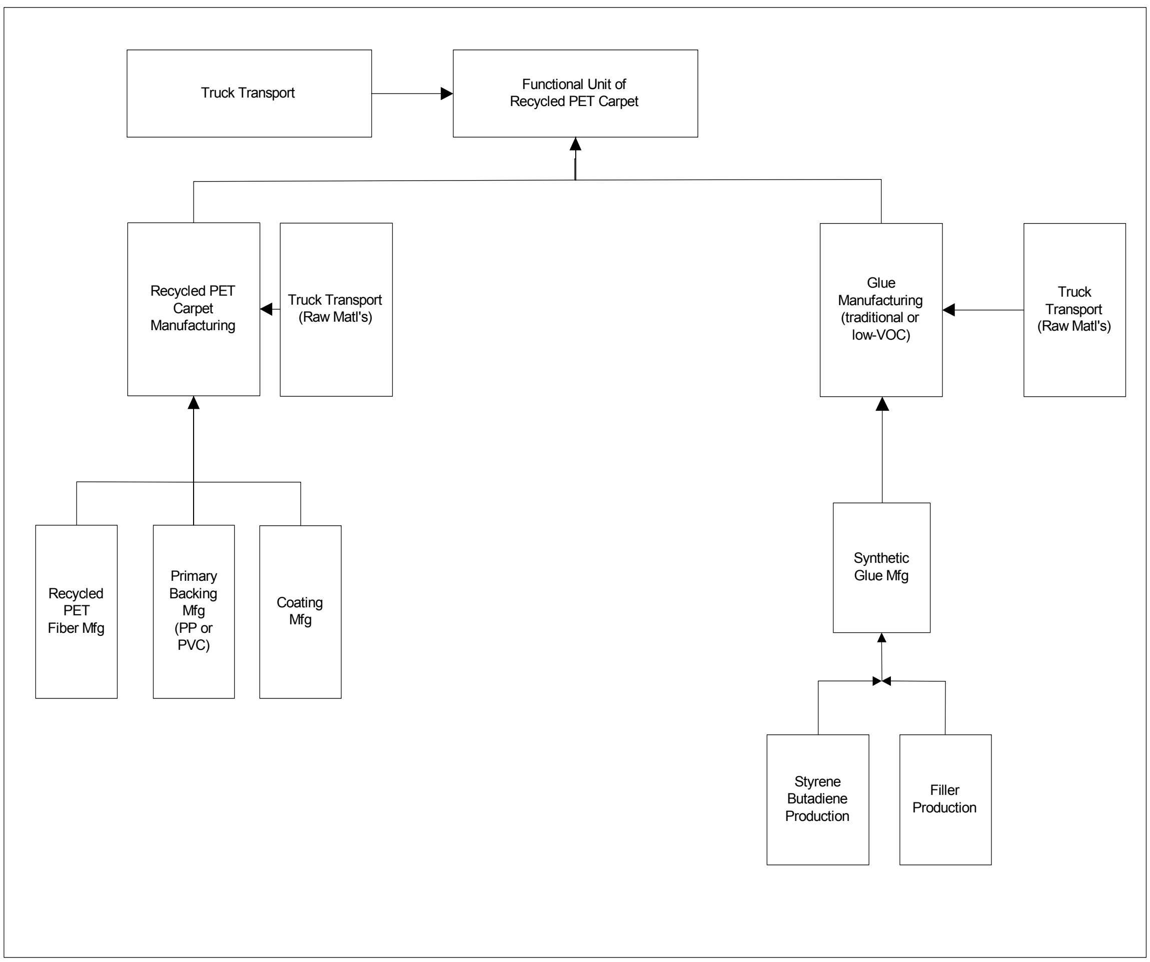

Figure 3.33 Recycled Polyester Carpet Flow Chart

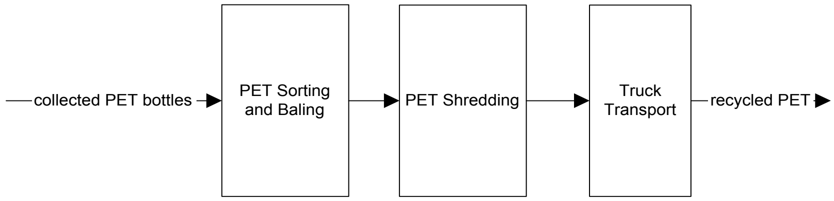

Figure 3.34 Handling and Reclamation of PET

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 3.66.

Table 3.66 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. Cost data have been adjusted to year 2002 dollars.

3.10.10 Shaw Industries EcoWorx Carpet Tile (C3020S)

A subsidiary of Berkshire Hathaway Inc., and headquartered in Dalton, Georgia, Shaw Industries sells floor covering and rugs for residential and commercial applications in the United States and abroad. Shaw's manufacturing facilities encompass every aspect of carpet and rug production, from basic chemicals and raw materials to advanced tufting, weaving, and finishing.

For commercial applications, Shaw offers carpet tiles of EcoSolution Q solution-dyed nylon fiber with EcoWorx backing substrate. In BEES, this product is referred to as Shaw EcoWorx carpet tile. The detailed environmental performance data for this product may be viewed by opening the file C3020S under the File/Open menu item in the BEES software.

Raw Materials and Manufacturing. Figure 3.35 displays the elements of Shaw EcoWorx carpet tile production. Production details for the four major elements, EcoWorx backing, nylon yarn, precoat compound, and adhesive, are shown in Figures 3.36 through 3.39, respectively.

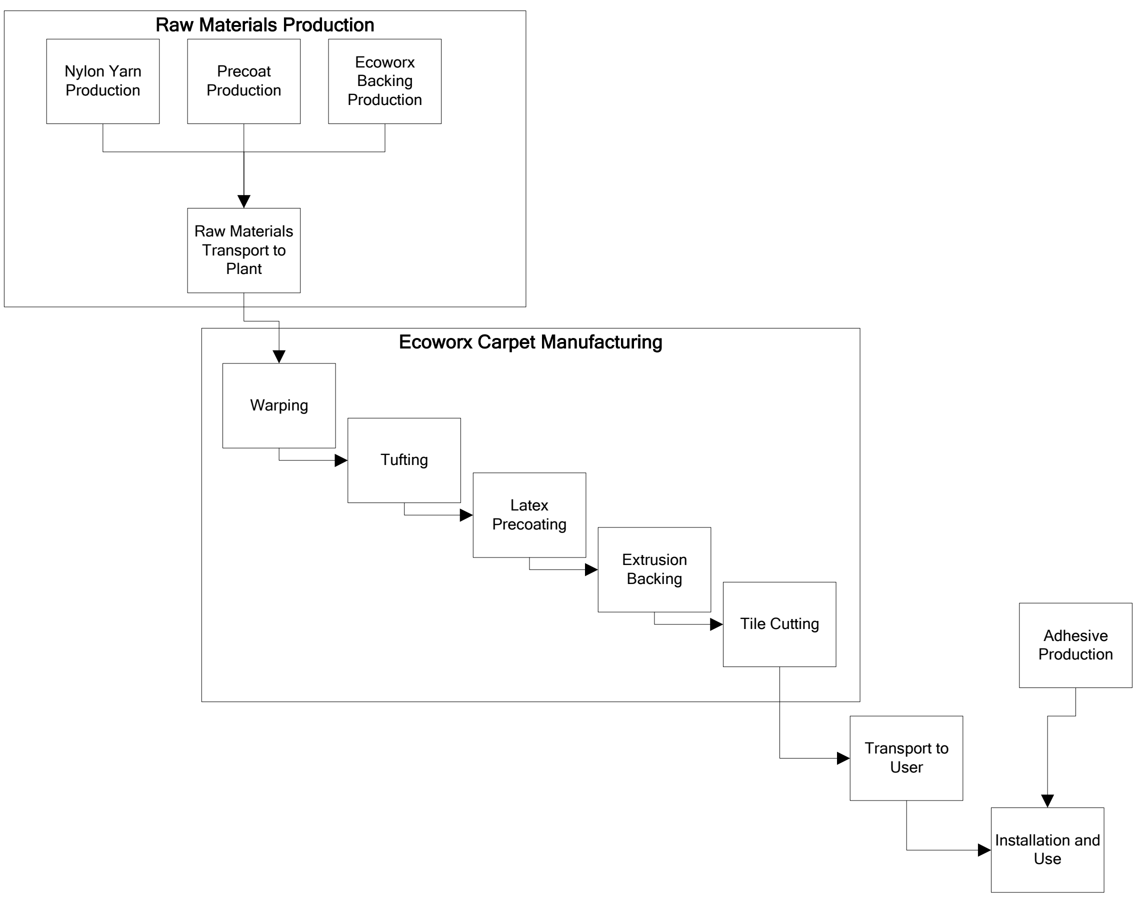

Figure 3.35 Shaw EcoWorx Carpet Tile Flow Chart

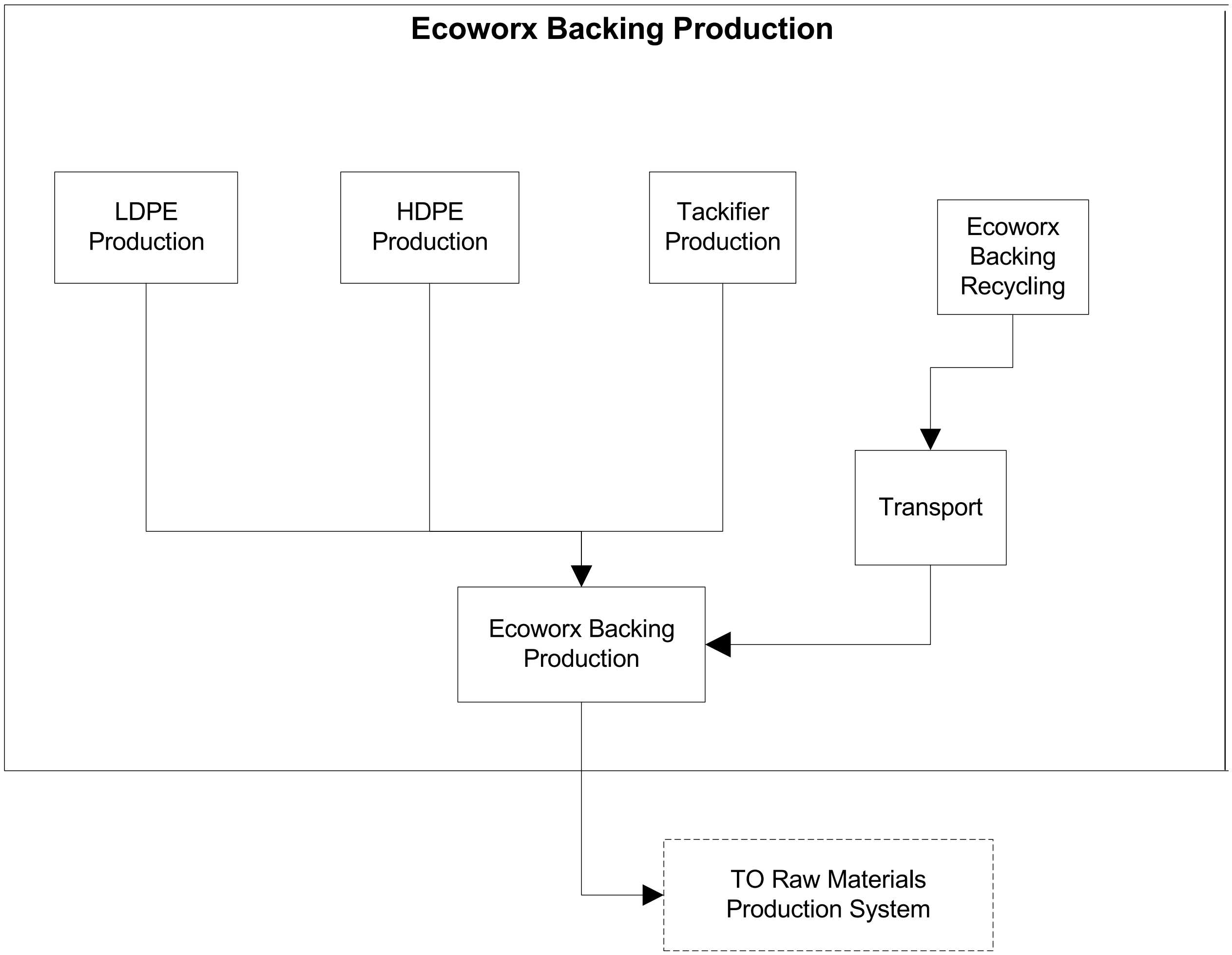

Figure 3.36 Shaw EcoWorx Backing Flow Chart

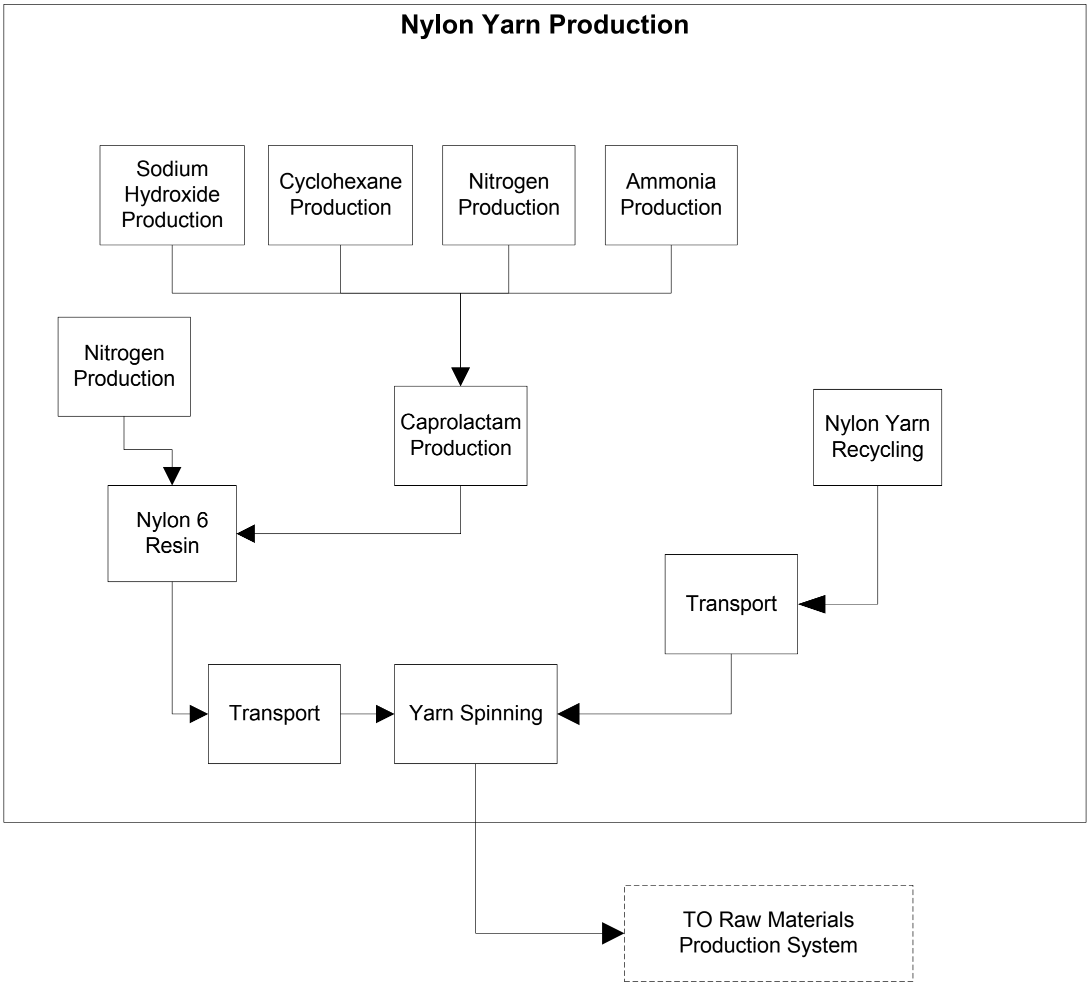

Figure 3.37 Shaw Nylon Yarn Flow Chart

Data representing the production of nylon yarn involve the following assumptions:

- For nylon yarn recycling, it is assumed that no raw materials are consumed during the recycling process and that the efficiency of the recycling process is 90 %. Electricity use for the recycling process is an average of 'yarn/backing separation' electricity use and 'contract recycling' electricity use.
- Transport for all raw materials to the manufacturing plant is set at 402 km (250 miles).
- The data for energy use for yarn spinning is based on site data. Twenty five percent (25 %) of the yarn is assumed to consist of recycled yarn.

Table 3.67 gives the production requirements for nylon yarn based on these assumptions.

Table 3.67 Nylon Yarn Production Requirements

Flow Name	*Units*	*Quantity/kg yarn*
Electricity	MJ	9.8
Natural Gas (used as fuel)	MJ	0.13
Polyamide (PA 6)	kg	0.75
Recycled Polyamide (PA 6)	kg	0.25

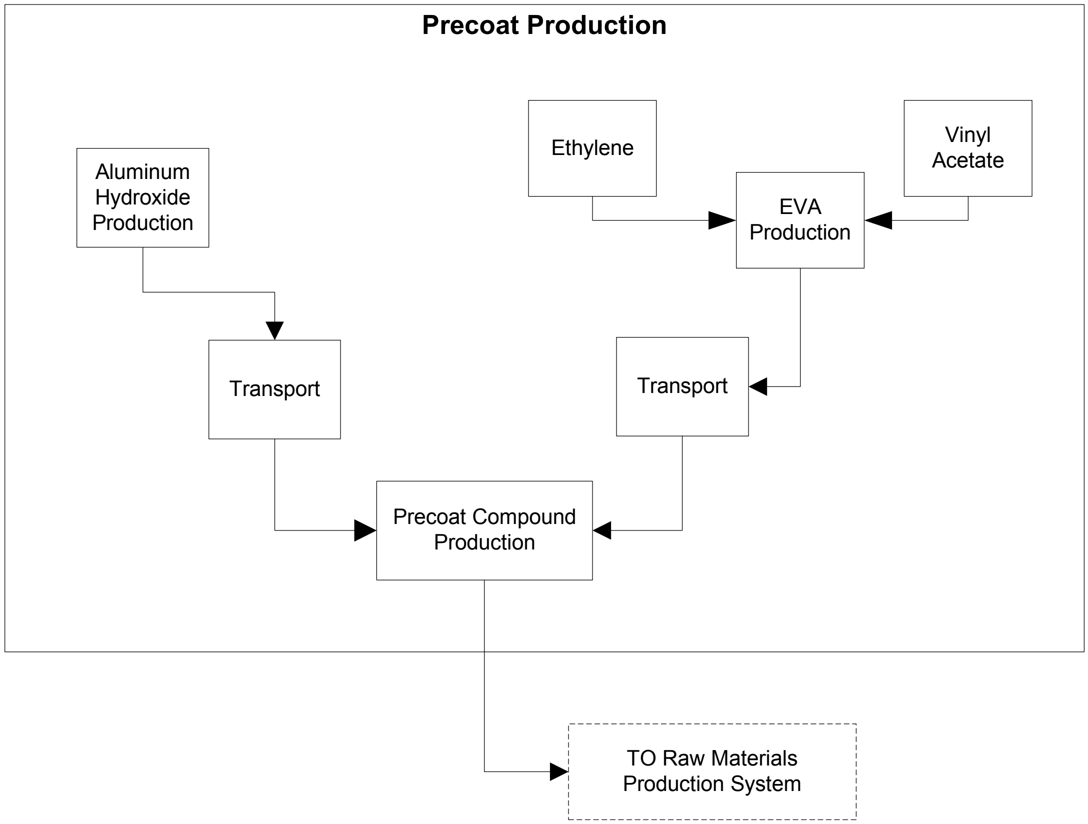

Figure 3.38 Shaw Precoat Compound Flow Chart

The amounts of aluminum hydroxide and EVA used to produce the precoat compound were provided by Shaw. The production of the rest of the precoat fillers was ignored because they contributed to less than 1 % of the total mass of the precoat compound.

The pressure-sensitive adhesive was modeled as an even blend of butyl acrylate, 2-ethylhexalacrylate (2-EHA), and methyl acrylate. Surrogate production data were used to represent these raw materials.

The mix of constituents, by mass, in 1 m^2 (1 yd^2) of carpet is 0.88 kg (1.63 lbs) of latex precoat, 0.89 kg (1.65 lbs) of yarn, and 0.14 kg (0.25 lbs) of backing.

Installation and Use. The lifetime of the carpet tile is assumed to be 15 years. While 5 % of the adhesive is wasted during installation, no carpet tiles are wasted.

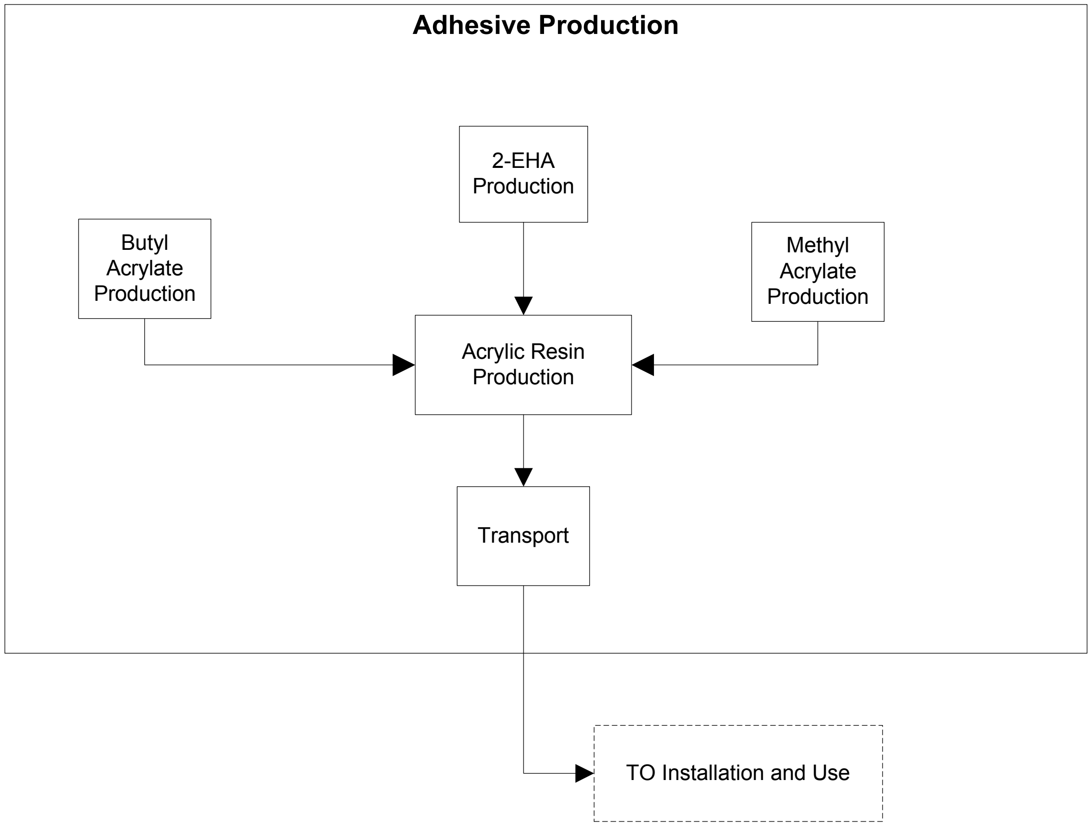

Figure 3.39 Shaw Adhesive Flow Chart

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 S0. First cost data include purchase and installation costs. Purchase costs were provided by Shaw and installation costs were collected from the R.S. Means publication, *2000 Building Construction Cost Data.* Cost data have been adjusted to year 2002 dollars.

3.10.11 Universal Textile Technologies Urethane-Backed Nylon Broadloom Carpets (C3020T, C3020U)

Universal Textile Technologies (UTT) is a carpet manufacturer based in Dalton, GA. UTT is working with Dow Chemical Company on the introduction of Dow's new product, Biobalance, a soybean-based material that can replace a portion of the inputs required to make polyurethane carpet backing. Biobalance is the result of research funded by soybean farmers to assist in developing a soy-derived polyol. The soy polyol can be used in a variety of other applications, including spray-on insulation and truck bed liners.

BEES includes two UTT nylon carpet products with different backing systems: a soy urethane backing precoat and a petroleum urethane backing precoat. The detailed environmental performance data for these products may be viewed by opening the following files under the File/Open menu item in the BEES software:

- C3020T.DBF—UTT, Petroleum Backed Nylon Carpet
- C3020U.DBF— UTT, Soy Backed Nylon Carpet

Raw Materials. A flow diagram for UTT carpet raw materials production is given in Figure 3.40. The two carpets are both made with nylon but have different additives. The mixture of constituents for each of the two products, by mass, is listed in Table 3.68.

Table 3.68 UTT Urethane-Backed Carpet Constituents by Mass Fraction

Constituent	*Carpet with Soy Urethane Backing*	*Carpet with Petroleum Urethane Backing*
Soy Polyol	2 %	--
Petroleum Polyol	7 %	9 %
Foam Backing	31 %	31 %
Nylon Yarn	30 %	30 %
Isocyanate	5 %	6 %
Other Additives and Fillers	25 %	24 %

The yarn for both carpets consists of Nylon 6,6, the data for which was taken from public data provided by the plastics industry and that are consistent with the data used to represent Nylon 6,6 in the BEES generic nylon carpet products. Data for the production of polyether polyol and isocyanate are aggregate site data provided by the plastics industry and consistent with data used in the BEES generic carpet products. Soy polyol production is represented by life cycle soybean oil production data developed for the U.S. Department of Agriculture (USDA), updated to reflect a newer manufacturing process for the oil. Data for all other fillers and additives are taken from public data.

Data for the transport of raw materials from the suppliers to the manufacturer was modeled using a diesel truck as the mode of transportation.

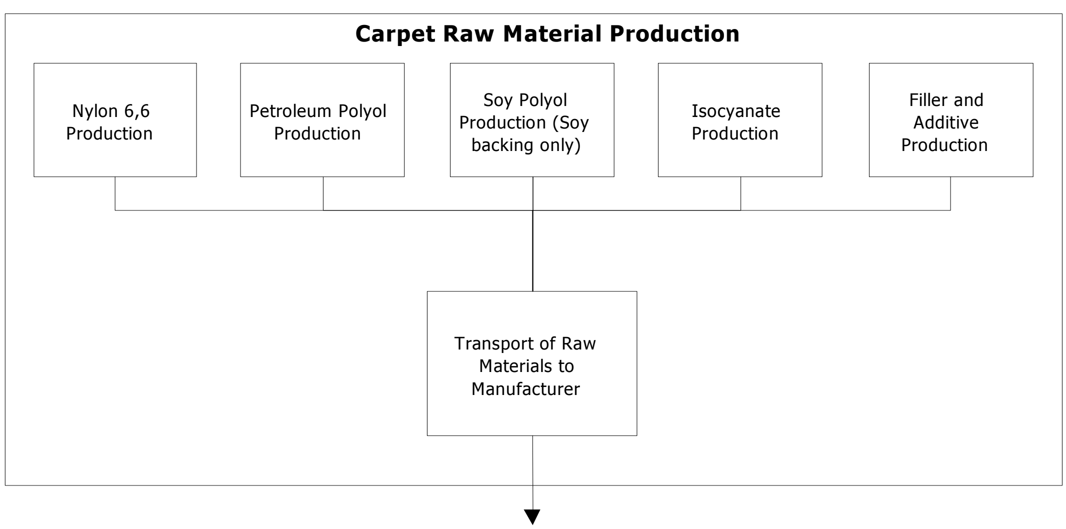

Figure 3.40 UTT Urethane Carpet Raw Materials Production Flow Chart

Manufacturing. The manufacturing process for both carpets consists of forming the polyurethane backing, curing the backing, and adhering the backing to the nylon facing. Site data are used to quantify the energy inputs to the production process, which consist of purchased electricity and natural gas. The energy input for both backing materials ranges from 0.44 MJ/m^2 to 7.78 MJ/m^2 of carpet. The manufacturing flow diagram is given in Figure 3.41.

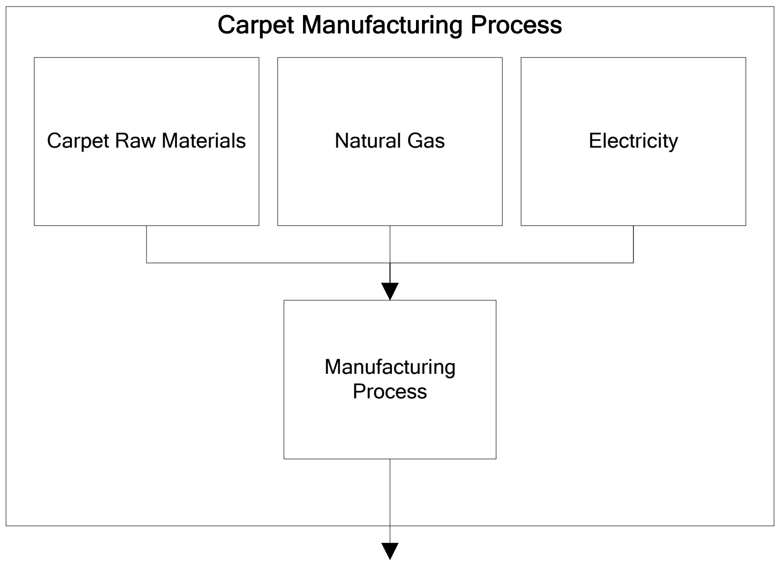

Figure 3.41 UTT Urethane Carpet Manufacturing Flow Chart

Transportation to Building Site. The transportation distance from the manufacturing plant in Dalton, Georgia to the building site is modeled as a variable in BEES. Both products are shipped by diesel truck and have the same mass per applied area and density: 3.11 kg/m^2 and 242 kg/m^3, respectively (or 0.28 kg/ft^2 and 7.27 kg/ft^3, respectively).

Installation and Use. The installation adhesive for the UTT carpet products was assumed to be the same traditional contact adhesive used to install the generic BEES carpet products. The average application was assumed to require 0.33 kg/m^2 (0.07 lb/ft^2) adhesive to carpet, again consistent with the generic BEES carpet products. No carpet waste is generated during the installation of the carpet, but 5 % of the adhesive is wasted.

End of Life. Given lifetimes of 11 years, both UTT carpet products are replaced 4 times (after the initial installation) over the 50-year BEES study period. At each replacement, it is assumed that 5 % of the carpet waste is recycled, with the remaining 95 % going to a landfill.

Cost. The detailed life-cycle cost data for the UTT products may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under BEES code C3020, product code T0 for petroleum urethane-backed carpet and BEES code C3020, product code U0 for soy urethane-backed carpet. First cost data include purchase and installation costs. Purchase costs were provided by UTT and installation costs were collected from the R.S. Means publication, *2000 Building Construction Cost Data.* Cost data have been adjusted to year 2002 dollars.

3.10.12 Collins & Aikman ER3 Carpet Tile (C3020X)

Collins and Aikman Floorcoverings (C&A) is an international manufacturer and supplier of commercial carpeting for the corporate, healthcare, education, government, and retail sectors. C&A is a leading producer of modular carpet tile and roll carpet. A commercial carpet tile product manufactured by C&A is included in BEES: style Habitat, Powerbond RS ER3 Modular carpet tile. The detailed environmental performance data for this product may be viewed by opening the file C3020X.DBF under the File/Open menu item in the BEES software:

Raw Materials. C&A carpet tile products use C&A's ER3 100 % recycled-content secondary backing as shown in Table 3.69.

Table 3.69 C&A Carpet Tile Constituents

Constituent	*Mass Fraction*
Nylon 6,6 Yarn (min. 82 % post-industrial content)	15 %
Polyester/Nylon primary backing	2 %
ER3 recycled vinyl secondary backing	36 %
Other Additives (precoat, fillers, etc.)	47 %

The yarn for the ER3 carpet tile consists primarily of post-industrial Nylon 6,6. Data for the production of Nylon 6,6 and for yarn spinning were taken from public data provided by the plastics industry; these data are consistent with the data used for the other BEES nylon carpet products.

The primary backing for the ER3 carpet tile consists of a polyester core with a Nylon 6 sheath. The data for these polymers are gathered from public data provided by the plastics industry; these data are consistent with the data used for other BEES carpet products.

For the secondary backing, modular tile products use C&A's proprietary ER3 backing system, which contains a minimum of 25 % post consumer carpet. The remaining 75 % of the mass consists of post-industrial waste generated during carpet manufacturing (50 %) and industrial waste from the automotive industry (25 %).

The most significant raw materials in terms of mass are included and are quantified using the DEAM database.

Transportation distances for shipment of the raw materials from the suppliers to the manufacturing plant were provided by C&A. Both diesel truck and rail transportation were involved, depending on the raw material. Figure 3.42 shows the elements of raw materials production for ER3 carpet tile.

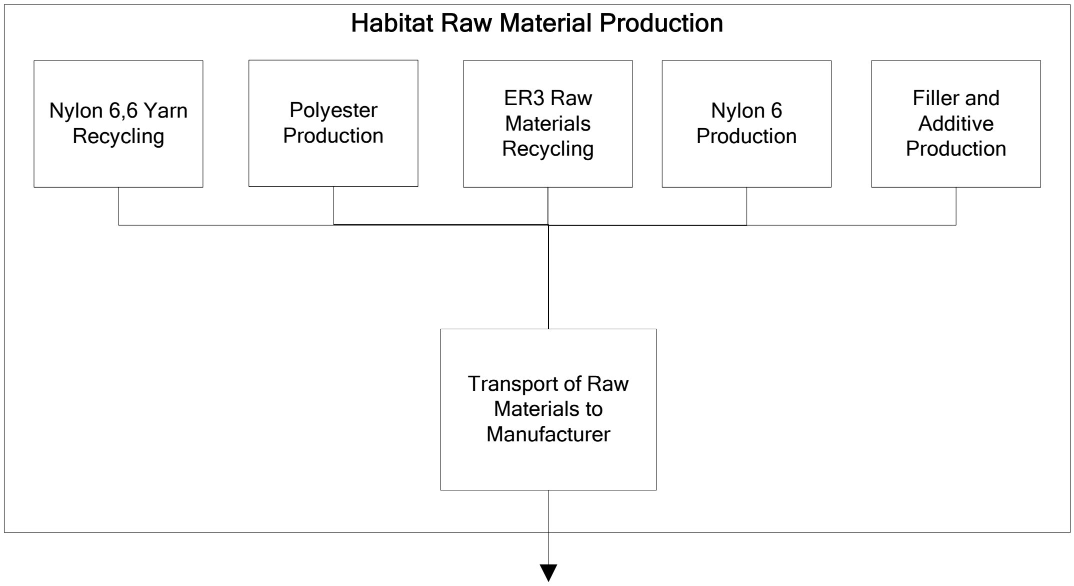

Figure 3.42 C&A ER3 Tile Raw Materials Production Flow Chart

Manufacturing. The manufacturing process for carpet tile consists of tufting the nylon yarn, applying the precoat compound, and joining the yarn to the backing materials. C&A provided information on the energy inputs and air and water emissions from the manufacturing process, as shown in Figure 3.43. Natural gas comprises 76.5 % of the energy associated with production and electricity accounts for the remaining 23.5 %. Any waste generated during the manufacturing process is recycled back into other carpet products.

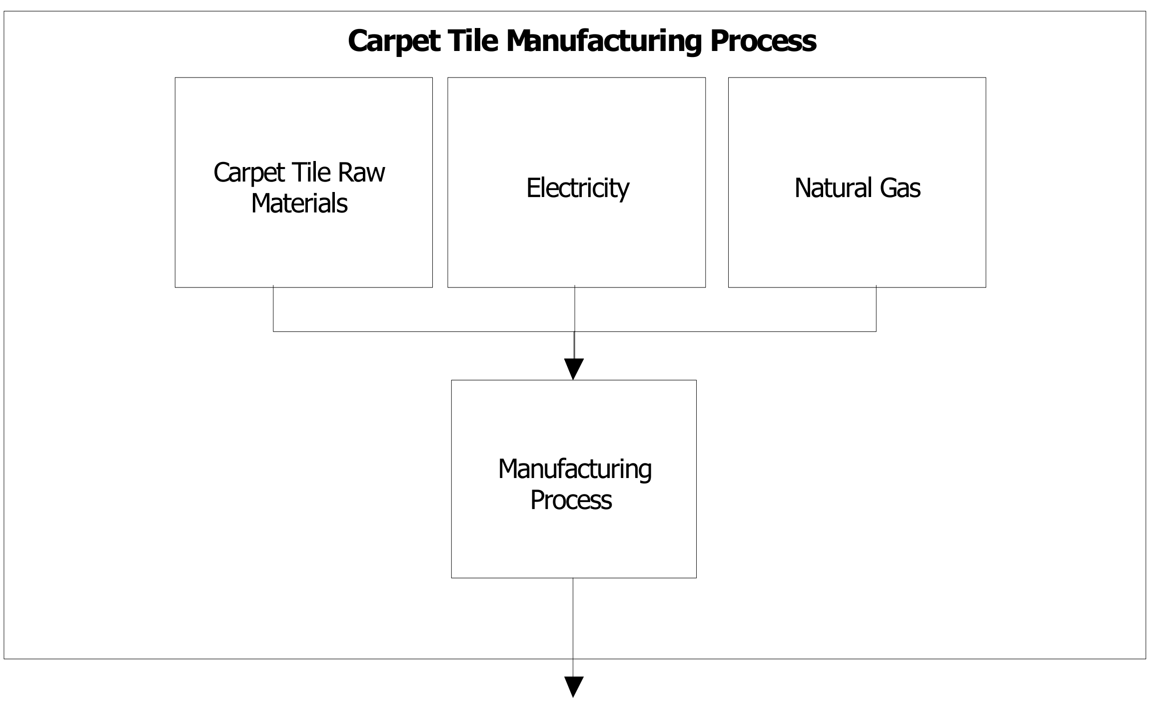

Figure 3.43 C&A Carpet Tile Manufacturing Flow Chart

Transportation to Building Site. The transportation distance from the C&A manufacturing plant in Dalton, Georgia to the building site is modeled as a variable in BEES. The product is shipped by diesel truck. The quantity of transportation emissions allocated depends on the overall mass of the product, as given in Table 3.70.

Table 3.70 C&A ER3 Carpet Tile Mass and Density

Massper Applied Area in kg/m^2 (lb/ft^2)	***Density in kg/m^3 (lb/ft^3)***
4.44 (0.88)	626 (41)

Installation and Use. C&A carpet tiles are installed with a pressure-sensitive adhesive that is applied to the back of the tiles at the manufacturing facility. According to C&A, very little carpet waste is generated during installation, and scraps are typically kept at the building site for future repairs.

End of Life. As for all BEES nylon carpet tile products, the lifetime of ER3 is set at 15 years. At end of life, 100 % of the product is recycled.

Cost. The detailed life-cycle cost data for C&A ER3 carpet tile may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under BEES code C3020, product code X0. First cost data includes purchase and installation costs. Purchase costs were provided by C&A and installation costs were collected from the R.S. Means publication, *2000 Building Construction Cost Data*. Costs have been updated to year 2002 dollars.

3.10.13 Interface Hyperion, Mercator, Prairie School, Sabi, and Transformation Carpets (C3020Y, C3020Z, C3020AA, C3020BB, C3020CC)

Based in Atlanta, Georgia, Interface is a leader in the worldwide commercial interiors market, offering modular and broadloom carpets, fabrics, interior architectural products, and specialty chemicals. Five Interface carpet products are included in BEES. They are listed below, together with the names of the BEES files containing their detailed environmental performance data:

1. Bentley Prince Street, Hyperion recycled nylon broadloom carpet (C3020Y)
2. Bentley Prince Street, Mercator recycled nylon broadloom carpet (C3020Z)
3. Interface Flooring Systems, Prairie School recycled nylon and vinyl carpet tile (C3020AA)
4. Interface Flooring Systems, Sabi recycled nylon and vinyl carpet tile (C3020BB)
5. Interface Flooring Systems, Transformation recycled nylon and vinyl carpet tile (C3020CC)

The BEES environmental performance data files for these products may be viewed by opening them under the File/Open menu item in the BEES software.

Raw Materials. Interface's Hyperion and Mercator broadloom carpets are produced from a similar mix of materials, as are its Prairie School, Sabi, and Transformation carpet tiles. The mix of constituents, by mass, for each of these products is listed in Table 3.71.

Table 3.71 Interface Carpet Constituents by Mass Fraction

Constituent	*Hyperion*	*Mercator*	*Prairie School*	*Sabi*	*Transformation*
Recycled Nylon 6,6 (77 % post-industrial)	38 %	42 %	--	9 %	11 %
Recycled Nylon 6,6 (93 % post-industrial)	--	--	11 %	--	--
Recycled vinyl (100% post-consumer)	--	--	43 %	43 %	43 %
Polypropylene	12 %	11 %	--	--	--
Styrene Butadiene Latex (SBL)	11 %	10 %	--	--	--
Ethylene Vinyl Acetate (EVA) adhesive	--	--	5 %	5 %	5 %
Other Additives	39 %	37 %	41 %	43 %	41 %

The Nylon 6,6 and vinyl used in these carpet products have significant recycled content. The recycled content nylon and vinyl carry no environmental burdens from the production of the virgin materials. However, the electricity used to grind the material down to a useable size is assigned to the products. While the recycled Nylon 6,6 comes from recycled polymer and recycled dyes, data limitations required analysis based on average U.S. data for the grinding of plastic scrap: 163 MJ of energy required to grind 907 kg, or 1 ton, of plastic. For the recycling of post-consumer vinyl, electricity data were provided by Interface. While the Nylon 6,6 virgin material comes from virgin dyes, oils, and additives, data limitations dictated that it be assessed using public data from the plastics industry for producing and spinning virgin Nylon 6,6, consistent with data used in the BEES generic carpet model.

Environmental burdens from producing the polypropylene used for backing in the Mercator and Hyperion carpets are taken from public data provided by the plastics industry. Burdens for the other polymer additives in the carpets, such as the virgin vinyl, are also taken from plastics industry data; these data are consistent with those used for other BEES carpet products.

Since the Mercator and Hyperion carpets are broadloom applications, the nylon yarn is back-coated with Styrene Butadiene latex (SBL) to provide stability. For the Prairie School, Sabi and Transformation carpet tiles, Ethylene Vinyl Acetate (EVA) is used to bind the nylon to the primary substrate. Life cycle inventory data for both materials come from public and site-specific data in the DEAM database. Data for the phthalates used in the three carpets containing vinyl comes from a recent study carried out for the European Council for Plasticizers and Intermediates.

The manufacturer provided transportation distances for shipment of the raw materials from the suppliers to the Interface plants; transportation is by diesel truck. Figures 3.44 and 3.45 show the elements of raw materials production for the Interface broadloom and tile products, respectively.

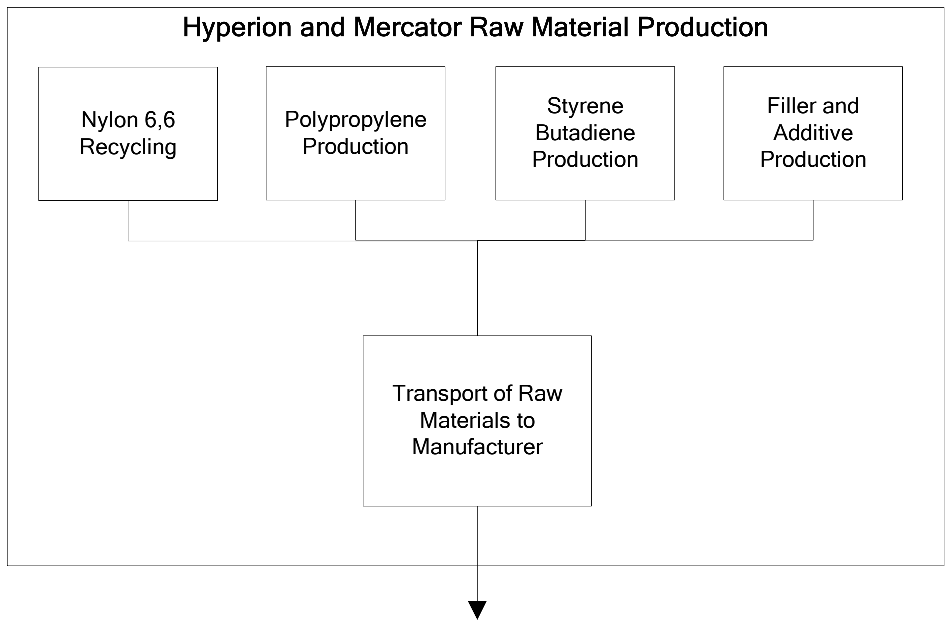

Figure 3.44 Interface Hyperion and Mercator Raw Materials Production Flow Chart

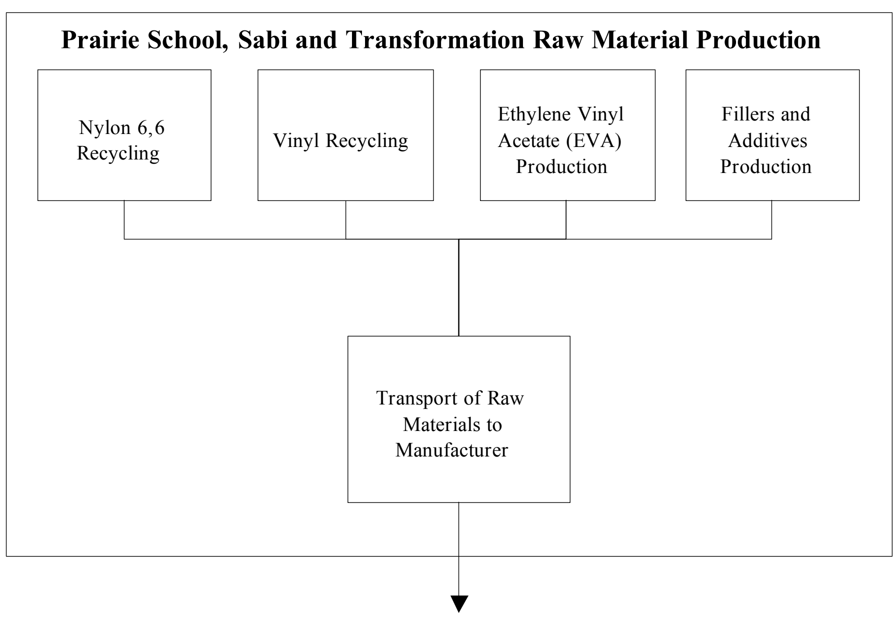

Figure 3.45 Interface Prairie School, Sabi, and Transformation Raw Materials Production Flow Chart

Manufacturing. The manufacturing process for the two broadloom carpets essentially consists of weaving the nylon yarn, applying the precoat compound, and joining the yarn to the backing. This process requires both purchased electricity and natural gas. The production of each unit of Hyperion and Mercator carpet (0.09 m^2 or 1 ft^2) requires approximately 0.1 MJ (0.03 kWh) of electricity and 0.36 MJ from natural gas.

The manufacturing process for the three carpet tile products consists of tufting the nylon yarn, applying the EVA adhesive, then joining the yarn to the backing. Producing 0.09 m^2 (1 ft^2) of each of these carpet tiles requires approximately 0.1 MJ (0.03 kWh) of electricity and 0.46 MJ (436 Btu) from natural gas.

The manufacturing flow diagram for all five Interface products is given in Figure 3.46.

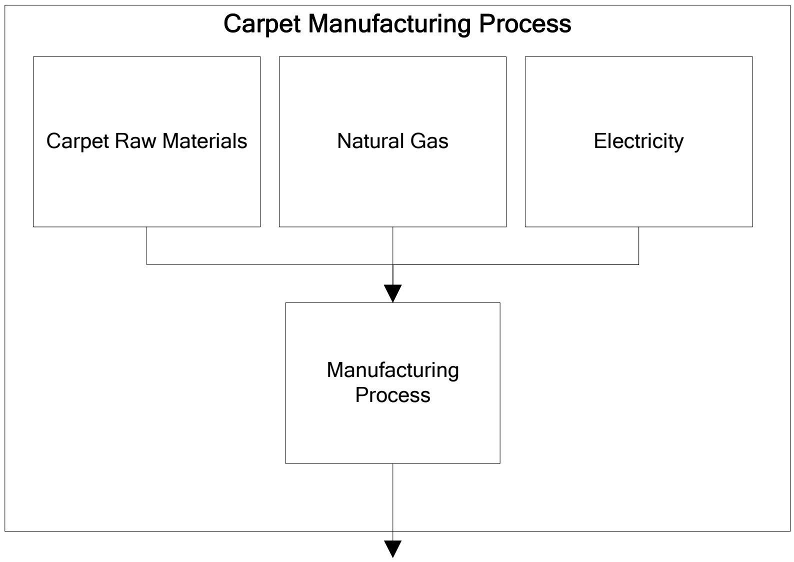

Figure 3.46 Interface Carpet Manufacturing Flow Chart

Transportation to Building Site. The transportation distance from the Interface manufacturing plant in Georgia or California to the building site is modeled as a variable in BEES. All products are shipped by diesel truck. The quantity of transportation emissions allocated to each product depends on the overall mass of the product, as given in Table 3.72.

Table 3.72 Interface Carpet Density

Product	***Massper Applied Area in kg/m^2 (lb/ft^2)***	***Density in kg/m^3 (lb/ft^3)***
Hyperion	2.00 (0.40)	356.67 (23.59)
Mercator	2.11 (0.42)	383.33 (25.36)
Prairie School	5.44 (1.08)	696.67 (46.08)
Sabi	5.33 (1.06)	870.00 (57.55)
Transformation	5.44 (1.08)	673.33 (44.54)

Installation and Use. The five Interface carpet products are installed using a contact adhesive. The following installation waste percentages are used: Hyperion – 4 %, Mercator – 2.25 %, Prairie School – 2 %, Sabi – 2 %, and Transformation – 1 %. Five percent of the adhesive is lost during installation.

End of Life. With lifetimes of 15 years, the Prairie School, Sabi, and Transformation carpet tiles are replaced three times during the 50-year BEES study period. The broadloom carpets, Hyperion and Mercator, have 11-year lives, requiring 4 replacements over the study period. As with all BEES products, life cycle environmental burdens from these replacements are included in the inventory data.

Cost. The detailed life cycle cost data for Interface carpet products 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 BEES codes:

- C3020, Y0—Hyperion
- C3020, Z0—Mercator
- C3020, AA0—Prairie School
- C3020, BB0—Sabi
- C3020, CC0—Transformation

First cost data include purchase and installation costs. Purchase costs were provided by Interface and installation costs were collected from the R.S. Means publication, *2000 Building Construction Cost Data.* Cost data have been adjusted to year 2002 dollars.

3.10.14 J&J Industries Broadloom Carpets (C3020DD, C3020EE)

J&J Industries is a privately-held manufacturer of commercial carpet, primarily for corporate interiors but also for healthcare, retail, educational, and governmental facilities. The company provided data on two 28 oz. Products: Certificate with SBR backing, and Certificate with LIFESPAN MG backing. The detailed environmental performance data for these products may be viewed by opening the following files under the File/Open menu item in the BEES software:

- C3020DD.DBF—J&J Certificate with SBR Backing
- C3020EE.DBF— J&J Certificate with LIFESPAN* MG Backing

Raw Materials. The two J&J broadloom carpets are both made with nylon but have different additives, fillers, and backing materials. The mixture of constituents, by mass, for each product is listed in Table 3.73.

Table 3.73 J&J Broadloom Carpet Constituents

Constituent	*Carpet with SBR Backing*	*Carpet with LIFESPAN Backing*
Yarn (Nylon 6)	39 %	29 %
Polyurethane	--	19 %
Styrene Butadiene Resin (SBR)	9 %	--
Other Additives	52 %	52 %

The yarn for both carpets consists of Nylon 6, which is produced from the polymerization of caprolactam. Data for Nylon 6 production and for spinning into yarn were taken from public data provided by the plastics industry; these data are consistent with those used in BEES for the generic nylon carpets.

Data for production of the polyurethane used in the carpet with LIFESPAN Backing are taken from public data released by the plastics industry. For the Styrene Butadiene Resin (SBR) used in the SBR-backed carpet, life cycle inventory data were taken from both public and site-specific data contained in the DEAM database.

Average transportation distances for shipment of raw materials from the suppliers to the J&J plant were used; transportation is by diesel truck. Figure 3.47 shows the elements of raw materials production for the two J&J carpet products.

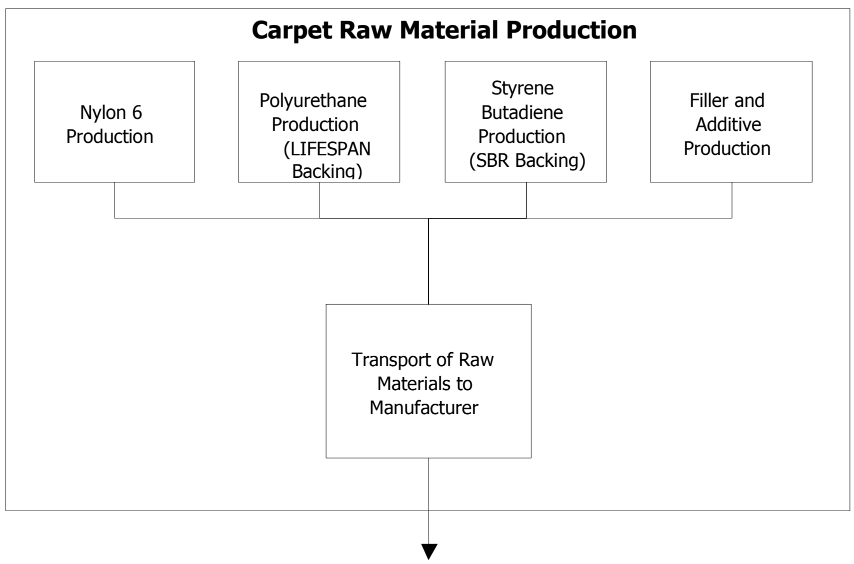

Figure 3.47 J&J Carpet Raw Materials Production Flow Chart

Manufacturing. The manufacturing process for both carpets consists of tufting the nylon yarn and joining the yarn to the backing. This process uses purchased electricity, natural gas, and other fossil fuels. For carpet with SBF Backing, the production of one unit of carpet (0.09 m^2 or 1 ft^2) requires 1.2 MJ (0.34 kWh) of electricity, 1.58 MJ of natural gas, and less than 0.03 MJ of other fossil fuels. J&J carpet with LIFESPAN Backing requires 1.3 MJ (0.35 kWh) of electricity, 1.8 MJ of natural gas, and less than 0.03 MJ of other fossil fuels per unit. The manufacturing flow diagram for both J&J carpet products is given in Figure 3.48.

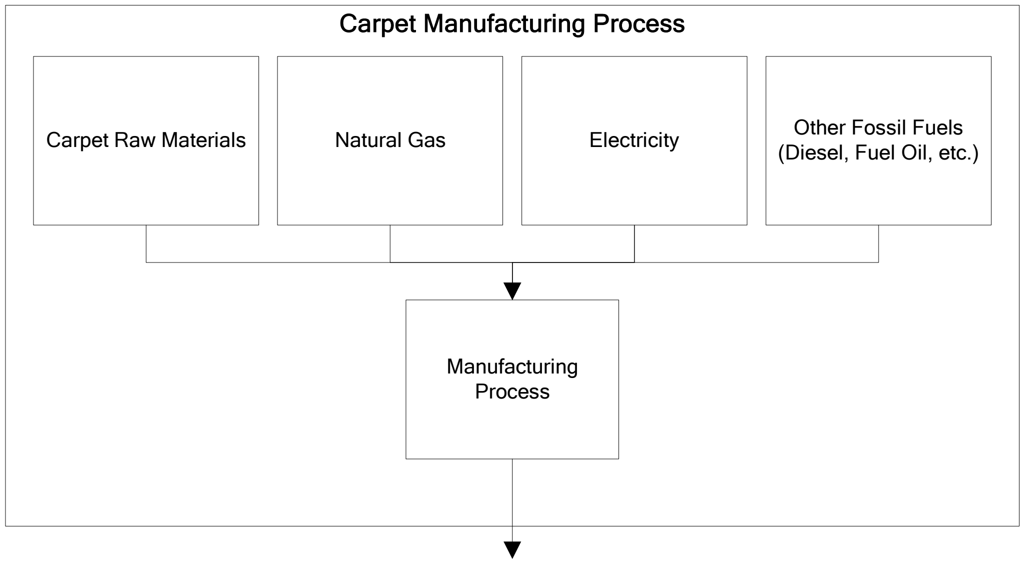

Figure 3.48 J&J Carpet Manufacturing Flow Chart

Transportation to Building Site. The transportation distance from the J&J manufacturing plant in Dalton, Georgia to the building site is modeled as a variable in BEES. Both products are shipped by diesel truck. The quantity of transportation emissions allocated to each product depends on the overall mass of the product, as given in Table 3.74.

Table 3.74 J&J Broadloom Carpet Density

Product	*Mass perApplied Area in kg/m² (lb/ft²)*	*Density in kg/ m³ (lb/ft³)*
Carpet with SBR Backing	2.41 (0.48)	346.67 (22.93)
Carpet with LIFETIME Backing	3.16 (0.63)	453.33 (29.99)

Installation and Use. The J&J broadloom carpets are assumed to be installed using a low VOC adhesive. The average application is assumed to require 0.03 kg (0.07 lb) of adhesive per unit of carpet (0.09 m^2 or 1 ft^2), consistent with other BEES carpet products. On average, 7 % of the carpet and 5 % of the adhesive are lost during installation.

End of Life. With lifetimes of 11 years, both carpets are replaced 4 times over the 50-year BEES study period. As with all BEES products, life cycle environmental burdens from these replacements are included in the inventory data.

Cost. The detailed life-cycle cost data for these two J&J broadloom carpet products 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 BEES codes:

- C3020, DD0—J&J Broadloom Carpet with SBR Backing
- C3020, EE0— J&J Broadloom Carpet with LIFETIME Backing

First cost data include purchase and installation costs. Purchase costs were provided by J&J and installation costs were collected from the R.S. Means publication, *2000 Building Construction Cost Data.* Cost data have been adjusted to year 2002 dollars.

3.10.15 Mohawk Regents Row and Meritage Broadloom Carpets (C3020FF, C3020GG)

Mohawk Industries is the second-largest manufacturer of commercial and residential carpets and rugs in the United States, and one of the largest carpet manufacturers in the world. Mohawk is involved in all aspects of carpet and rug production, from raw materials to advanced tufting, weaving, and finishing. The company provided data on two broadloom carpets: Regents Row, a woven commercial carpet; and Meritage, a tufted commercial carpet. The detailed environmental performance data for these products may be viewed by opening the following files under the File/Open menu item in the BEES software:

- C3020FF.DBF—Mohawk Regents Row
- C3020GG.DBF—Mohawk Meritage

Raw Materials. The two Mohawk carpets are produced from different materials and have different ratios of backing to yarn. The mixture of the main constituents of each carpet is listed in Table 3.75.

Table 3.75 Mohawk Broadloom Carpet Constituents by Mass Fraction

Constituent	*Regents Row*	*Meritage*
Yarn (Nylon 6)	--	48 %
Yarn (Nylon 6,6)	51 %	--
Backing	16 %	9 %
Other Additives (back coating, adhesives, etc.)	33 %	43 %

The yarn for Regents Row carpet consists of woven Nylon 6,6. Data for Nylon 6,6 production and for spinning into yarn are taken from public data provided by the plastics industry; these data are consistent with those used in BEES for the generic nylon carpets. The yarn for Meritage carpet is Nylon 6, which is produced from the polymerization of caprolactam. As with the Regents Row carpet, the data for Nylon 6 production and for extruding into yarn are taken from public data provided by the plastics industry and are consistent with those for similar BEES products.

The backing for the Regents Row carpet is a 50/50 mix of polypropylene and polyester fibers. The Meritage carpet only uses polypropylene for the backing material. Data for the backing materials are taken from public data provided by the plastics industry.

Since the Regents Row carpet is woven, the nylon yarn is back-coated with Styrene Butadiene latex to provide stability. For the Meritage carpet, Ethylene Vinyl Acetate (EVA) is used to adhere the backing to the tufted nylon. Life cycle inventory data for both materials are taken from public and site-specific data in the DEAM database.

Transportation distances for shipment of the raw materials from the suppliers to the Mohawk plants were provided by Mohawk; transportation is by diesel truck. Figures 3.49 and 3.50 show the elements of raw materials production for the Mohawk Regents Row and Meritage carpets, respectively.

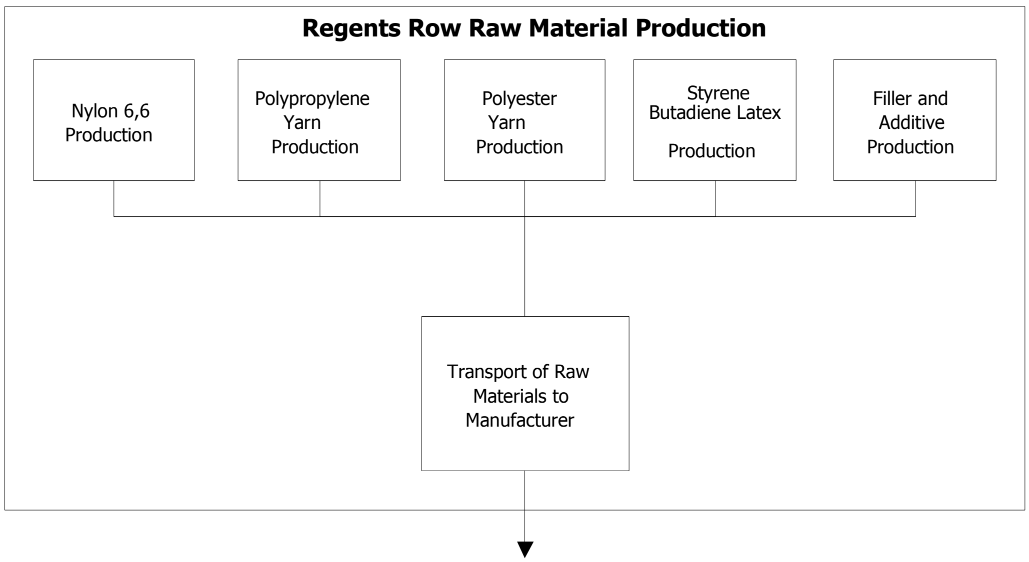

Figure 3.49 Mohawk Regents Row Raw Materials Production Flow Chart

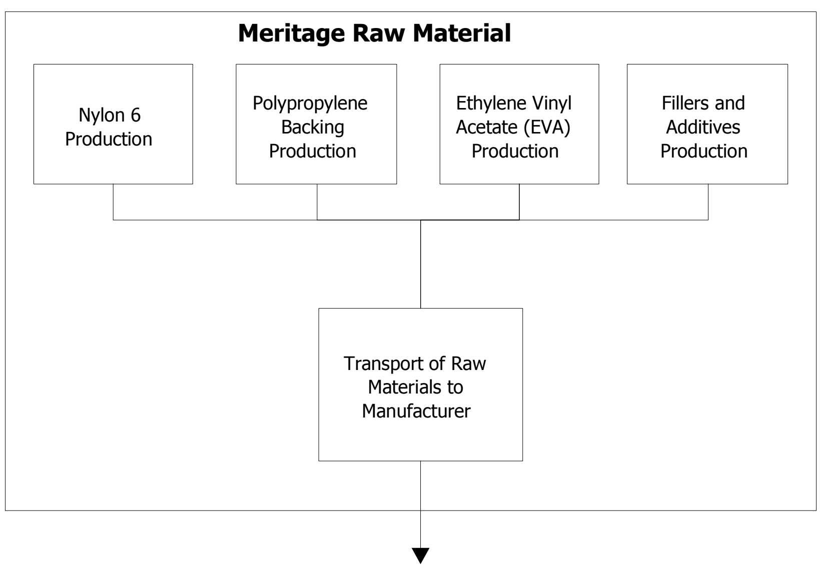

Figure 3.50 Mohawk Meritage Raw Materials Production Flow Chart

Manufacturing. The manufacturing process for Mohawk Regents Row carpet consists of interlacing face yarns with backing yarns which are then coated with finish chemicals. This process requires both purchased electricity and natural gas. The production of each unit of Regents Row carpet (0.09 m^2 or 1 ft^2) requires 0.4 MJ (0.1 kWh) of electricity and 0.73 MJ (0.20 kWh) of natural gas. The manufacturing process for Mohawk Meritage carpet consists of tufting the nylon yarn into the backing foundation and coating the fabric with an EVA chemical system. This process requires 0.6 MJ (0.18 kWh) of electricity and 0.71 MJ of natural gas per unit. The manufacturing flow diagram for both Mohawk carpets is given in Figure 3.51.

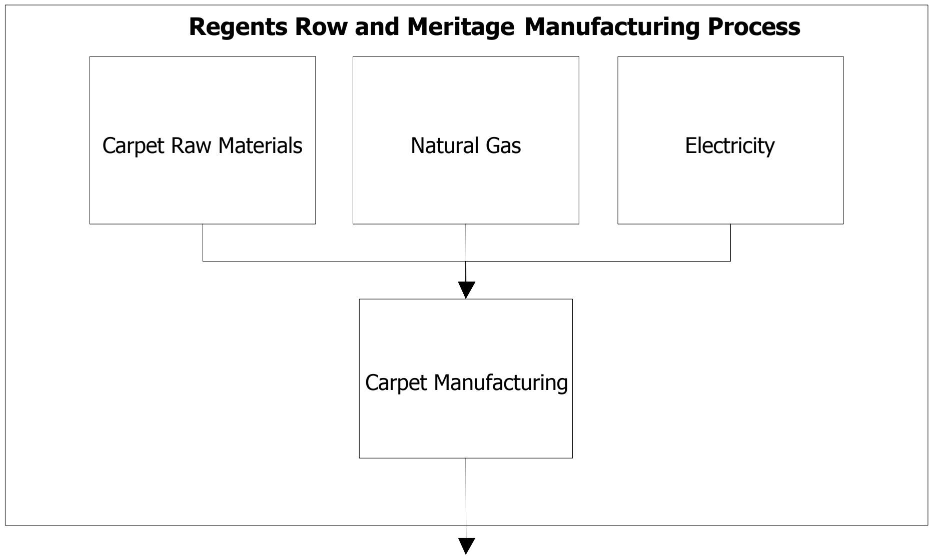

Figure 3.51 Mohawk Carpet Manufacturing Flow Chart

Transportation to Building Site. The transportation distance from the Mohawk manufacturing plant in South Carolina or Georgia to the building site is modeled as a variable in BEES. Both products are shipped by diesel truck. The quantity of transportation emissions allocated to each product depends on the overall mass of the product, as given in Table 3.76.

Table 3.76 Mohawk Carpet Density

Product	***Mass in kg/m² (lb/ft²)***	***Density in kg/m³ (lb/ft³)***
Regents Row	2.34 (0.47)	336.67 (22.27)
Meritage	2.41 (0.48)	346.67 (22.93)

Installation and Use. Both Mohawk carpets are installed using a low-VOC adhesive given the Green Seal by the Carpet Research Institute. The average application requires about 0.04 kg of adhesive per unit of carpet (0.09 m^2 or 1 ft^2). For the two carpets, approximately 5 % of both the carpet and the adhesive is wasted during installation.

End of Life. All BEES nylon broadloom carpets are assumed to have lifetimes of 11 years. Thus, both Mohawk broadloom carpets are assumed to be replaced four times over the 50-year BEES study period. As with all BEES products, life cycle environmental burdens from these replacements are included in the inventory data.

Cost. The detailed life-cycle cost data for Mohawk broadloom carpet products 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 BEES codes:

- C3020, FF0—Mohawk Regents Row
- C3020, GG0—Mohawk Meritage

First cost data include purchase and installation costs. Purchase costs were provided by Mohawk and installation costs were collected from the R.S. Means publication, *2000 Building Construction Cost Data.* Cost data have been adjusted to year 2002 dollars.

3.10.16 Natural Cork Parquet Tile and Floating Floor Plank (C3020HH, C3020II)

Natural Cork is a U.S. supplier of cork flooring and wall coverings. It distributes products manufactured by Granorte, a Portuguese company that recycles cork waste from the production of cork bottle stoppers. The energy used to produce the cork tiles comes mainly from waste cork powder. Natural Cork provided data on two of its products: cork parquet tile and cork floating floor plank. The detailed environmental performance data for these products may be viewed by opening the following files under the File/Open menu item in the BEES software:

- C3020HH.DBF—Natural Cork Parquet Floor Tile
- C3020II.DBF—Natural Cork Floating Floor Plank

Raw Materials. Both Natural Cork floor tile products use a cork sheet made from a combination of recycled cork waste and urethane binder. The floating floor plank also includes a layer of High Density Fiberboard (HDF) cut into a tongue-and-groove pattern. The mixture of the main constituents of each floor tile is listed in Table 3.77.

Table 3.77 Natural Cork Floor Tile Constituents by Mass Fraction

Constituent	***Cork Parquet Floor Tile***	***Cork Floating Floor Plank***
Recycled Cork Waste	93 %	58 %
Binder	7 %	3 %
High Density Fiberboard (HDF)	--	39 %

Since the cork constituent is a waste product, the environmental burdens from virgin production of the cork are not included. The energy used to grind the cork, however, is included as manufacturing energy. High Density Fiberboard (HDF) burdens are based on data from a public study on particleboard and fiberboard production. HDF is produced mostly from recovered wood waste – only 14 % of the wood going into HDF is harvested directly. Manufacturing one unit of HDF (0.09 m^2 or 1 ft^2) requires 2.2 MJ (0.6 kWh) of fuel energy and 1.3 MJ (0.36 kWh) of electricity. Most of the fuel energy comes from the combustion of wood waste generated from the production line.

The binder for Natural Cork flooring is a moisture-cured urethane, produced from a reaction between polyisocyanate and moisture present in the atmosphere. Polyisocyanate production data are based on publicly available plastics industry data.

Average distances for transport of the raw materials from the suppliers to the manufacturing facility were used, with diesel truck as the mode of transportation. Figure 3.52 shows the elements of raw materials production for both Natural Cork floor products.

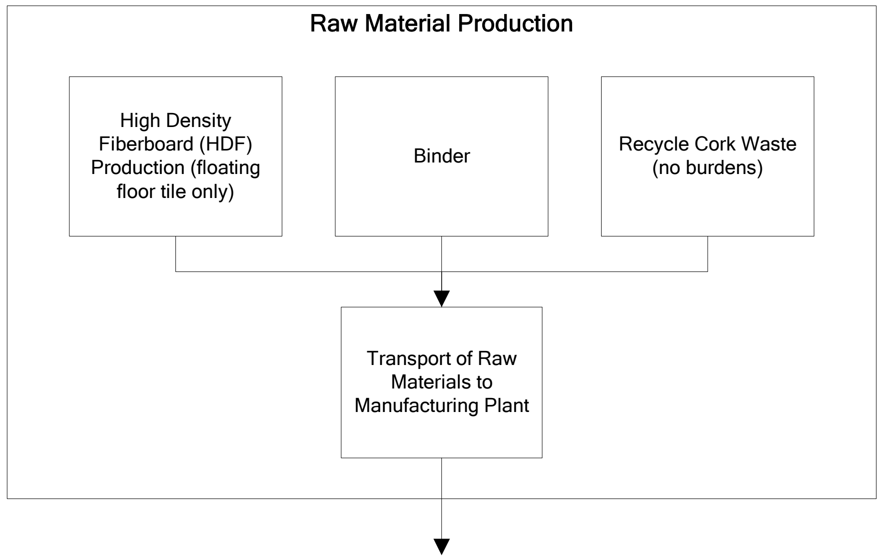

Figure 3.52 Natural Cork Raw Materials Production Flow Chart

Manufacturing. The manufacturing processes for the two cork floor products are essentially the same. Cork waste is ground and blended with the urethane binder, then cured. For the floating floor plank, the HDF is sandwiched between two layers of cork sheet and then cured.

Electricity and an on-site boiler are used to blend and cure both products. The boiler uses cork powder generated during the production process to produce steam and electricity. Manufacturing the parquet flooring requires about 0.8 MJ of both thermal and electrical energy per unit produced (0.09 m^2 or 1 ft^2); the floating floor plank requires about 1 MJ of electricity and 0.9 MJ of thermal energy per unit. Water is also used in the production process, but it is recycled and recovered by the plant. Producing each unit of product generates about 1 kg of waste, 94 % of which is used to produce energy and 3 % of which is recycled. The recycled material is accounted for in the BEES life cycle inventory. The manufacturing flow diagram for both Natural Cork floor products is given in Figure 3.53.

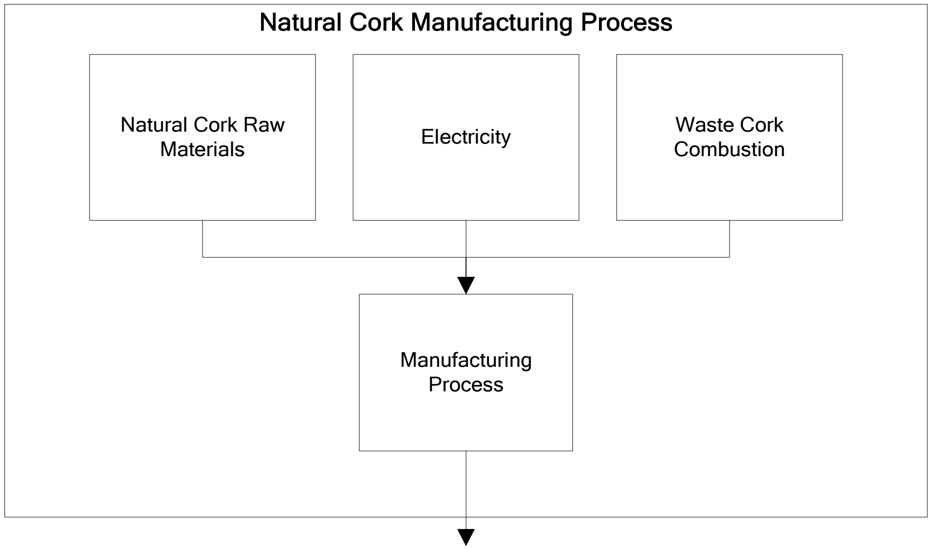

Figure 3.53 Natural Cork Manufacturing Flow Chart

Transportation to Building Site. The finished cork products are shipped first from the manufacturing facility in Portugal to the Natural Cork warehouse in Georgia–a distance of about 6437 km (4000 mi). Environmental burdens from this leg of the journey are built into the manufacturing portion of the BEES life-cycle inventory and are evaluated based on transport by ocean tanker using fuel oil. The transportation distance from the Natural Cork warehouse in Augusta, Georgia to the building site is modeled as a variable in BEES. Both products are shipped from Augusta by diesel truck; the quantity of transportation emissions allocated to each product depends on the overall mass of the product, as given in Table 3.78.

Table 3.78 Natural Cork Floor Tile Density

Product	***Massper Applied Area in kg/m^2 (lb/ft^2)***	***Density in kg/m^3 (lb/ft^3)***
Cork Parquet Tile	2.56 (0.51)	516.67 (34.18)
Cork Floating Floor	7.44 (1.48)	563.33 (37.26)

Installation and Use. Natural Cork parquet tile is installed using a water-based contact adhesive. The average application requires about 0.009 kg of adhesive per unit of flooring (0.09 m^2 or 1 ft^2). The Natural Cork floating floor requires only a minimal amount of tongue-and-groove adhesive to bond the individual planks together. On average, 5 % of the adhesive is wasted during installation, but none of the flooring is lost.

End of Life. Based on information from Natural Cork, its flooring does not require replacement over the 50-year BEES study period. At year 50, all of the waste is sent to a landfill, since according to the manufacturer none is currently being recycled.

Cost. The detailed life-cycle cost data for Natural Cork Parquet and Floating Floor 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 BEES codes:

- C3020, HH0—Natural Cork Parquet Floor Tile

- C3020, II0—Natural Cork Floating Floor Plank

First cost data include purchase and installation costs. Purchase costs were provided by Natural Cork and installation costs were collected from the R.S. Means publication, *2000 Building Construction Cost Data.* Cost data have been adjusted to year 2002 dollars.

3.10.17 Forbo Industries Marmoleum Linoleum (C3020R, C3020NN)

Linoleum is a resilient, organic-based floor covering consisting of a backing covered with a thick wearing surface. Oxidized linseed oil and rosin are mixed with the other natural ingredients to form linoleum granules. These granules are then calendared onto a jute backing, making a continuous long sheet. The sheets are hung in drying rooms to allow the naturally occurring process to continue until the product reaches the required flexibility and resilience. The sheets are then removed from the drying rooms, cut into rolls, and prepared for shipment.

Forbo Marmoleum may be installed using either a styrene-butadiene or a low-VOC adhesive. Both installation options are included in BEES. The detailed environmental performance data for these products may be viewed by opening the files C3020R. DBF (styrene-butadiene adhesive) and C3020NN.DBF (no-VOC adhesive) under the File/Open menu item in the BEES software. Figure 3.54 shows the elements of Forbo Marmoleum production.

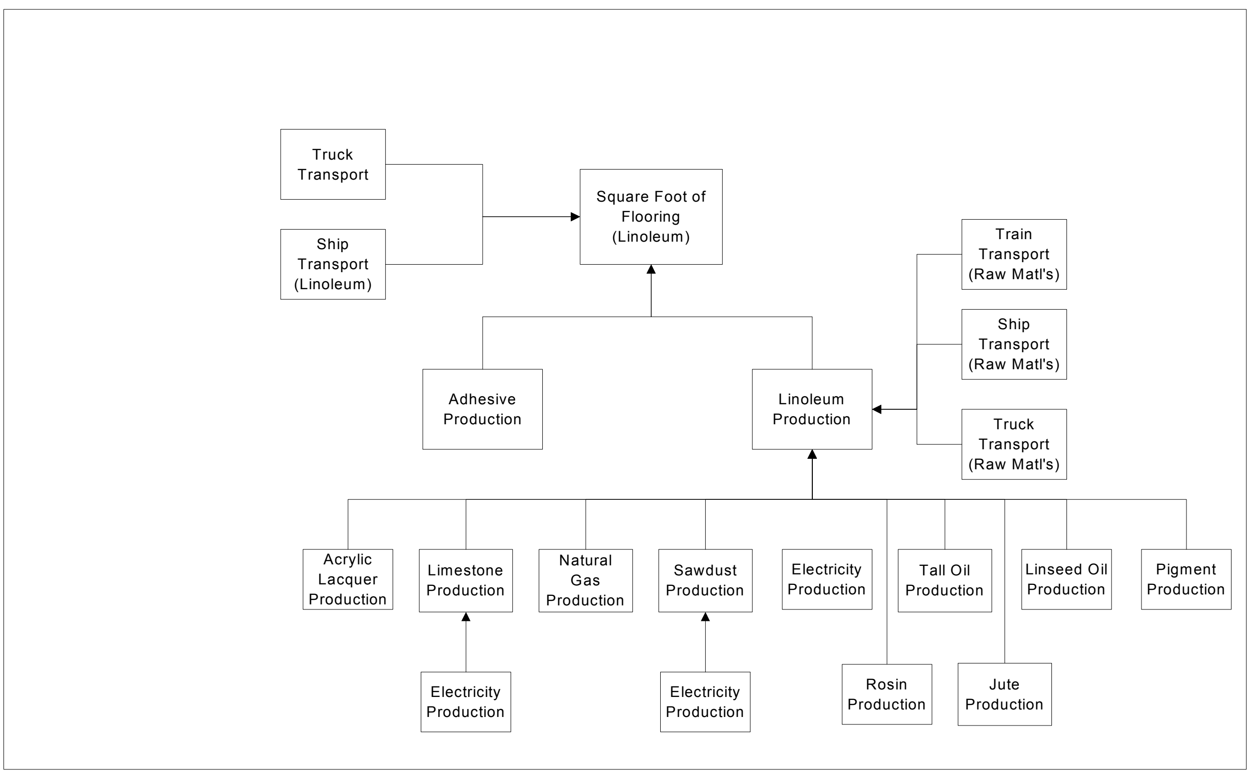

Figure 354 Marmoleum Flow Chart

Raw Materials. Table 3.79 lists the constituents of 2.5 mm (0.10 in) linoleum and their proportions.

Table 3.79 Linoleum Constituents

Linoleum Constituents	*Mass Fraction (%)*[104]	*Mass per Applied Area in g/m^2 (lb/ft^2)*
linseed oil	25	588 (0.12)
tall oil	17	398 (0.08)
pine rosin	3	76 (0.02)
limestone	26	592 (0.12)
wood flour	39	901 (0.18)
pigment	4	101 (0.02)
backing (jute)	10	233 (0.05)
acrylic lacquer	1	12 (0.00)
Total:	100	2 901 (0.59)

The cultivation of linseed (in Canada) is based on supplier data provided by Forbo. Data on inputs to the cultivation of linseed and production of pesticides are not available. The production of fertilizer is based on data from a Chalmers University Study.[105]

Pine rosin production is assumed to have no burdens, since the harvesting of raw pine rosin is done mainly by hand, according to Forbo.

The production of limestone is based on supplier data for limestone quarrying and grinding.

The burdens for tall oil production were allocated from the production of paper based on economic value. The production of tall oil is assumed to produce 1 % of the value of the paper production system.

Wood flour is sawdust produced as a coproduct of wood processing; its burdens are based on data from Forbo suppliers. Fifteen percent (15 %) of the burdens for wood processing are allocated to the production of sawdust, based on the economic value of sawdust.

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

Jute used in linoleum manufacturing is mostly grown in India and Bangladesh. Data representing its production are based on supplier data provided by Forbo.

Data for the production of acrylic lacquer are based on supplier data.

Use. The installation of linoleum may be done using either a styrene-butadiene or a low-VOC

[104] Marieke Goree, Jeroen Guinée, Gjalt Huppes, Lauran van Oers, *Environmental Life Cycle Assessment of Linoleum*, Leiden University, Netherlands, 2000.

[105] J. Davis and C. Haglund, *SIK Report No. 654: Life Cycle Inventory (LCI) of Fertilizer Production*, Chalmers University of Technology, Sweden, 1999

adhesive. Both options are available in BEES.

Forbo Marmoleum flooring is assumed to have a useful life of 18 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 codes R0 (styrene-butadiene installation adhesive) and NN0 (no-VOC adhesive). Cost data were provided by Forbo.

3.11 Office Chair Alternatives (E2020)

3.11.1 Herman Miller Aeron Office Chair (E2020A)

The Herman Miller Aeron chair consists of more than 50 different components and subassemblies from more than 15 direct suppliers. These components and subassemblies are constructed from four major materials: plastics, aluminum, steel, and foams/fabrics. The detailed environmental performance data for this product can be viewed by opening the file E2020A.DBF under the File/Open menu item in the BEES software. The flow diagram in Figure 3.55 shows the elements involved in the production of the Herman Miller Aeron chair.

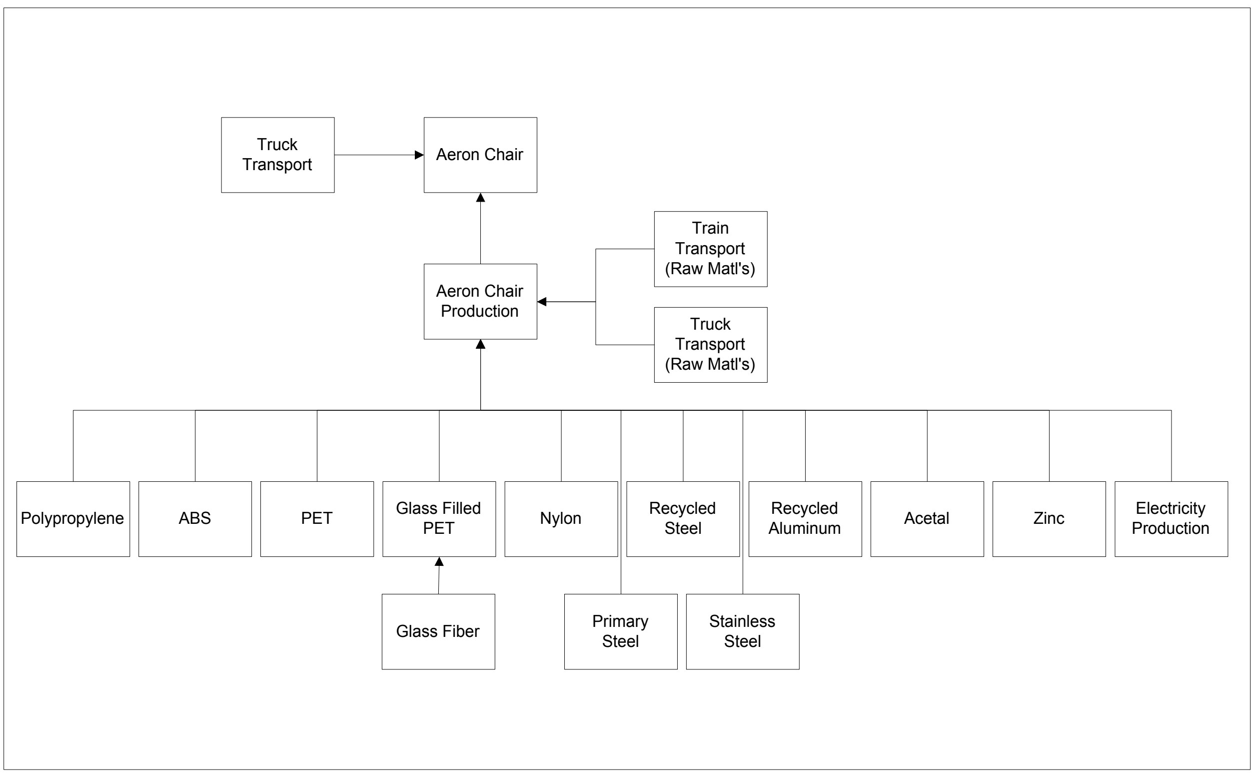

Figure 3.55 Herman Miller Aeron Flow Chart

Raw Materials. Of the Aeron chair materials that come from nonrenewable sources (petrochemicals and metals), over two-thirds are made from recycled materials and can be further recycled. The Aeron chair contains approximately 60 % mass fraction recycled content, including steel, polypropylene, glass-filled nylon, 30 % glass-filled PET, and aluminum. The mixture of constituents, by mass fraction, is given in Table 3.80.

Table 3.80 Herman Miller Aeron Chair Constituents

Constituent	***Description***
Plastics (polypropylene, ABS, PET, nylon, glass-filled nylons	27 % for all plastics (24 % for seat & back frame assemblies, 9 % for knobs, levers, bushings, covers)
Aluminum	35 % for aluminum base, swing arms, seat links, arm yokes
Steel	23.5 % for tilt assembly, 2 % for nuts, bolts, other components
Foam/fabric (arm rests, lumbar supports)	Less than 4 %; Pellicle seat & back suspension system is a combination of synthetic fibers & elastomers
Composite subassemblies	3 % for 5 casters; 6.7 % for pneumatic cylinder; 6.2 % for moving components of tilt assembly

Plastics. The main plastics used in the Aeron chair include polypropylene, ABS, PET, nylon, and glass-filled nylons. Roughly one-fourth (27 %) of the chair, by mass fraction, is made with plastic materials. The seat and back frame assemblies make up 23.6 % of the chair's weight. The seat and back frames are made of glass-filled PET, which contains two-thirds post-industrial recycled materials. The Pellicle suspension system (approximately 2 % of the chair weight) can be removed for replacement or for recycling of the seat and back frames. The remaining plastic components are various knobs, levers, bushings, and covers.

Aluminum. Roughly 35 % of the Aeron chair is made from aluminum. Major components include the base, swing arms, seat links, and arm yokes. All these components are made from 100 % post-consumer recycled aluminum. In the manufacture of these aluminum die cast components, there is no waste. All trim flash and defect materials are recycled within the manufacturing process. Aluminum components from a finished Aeron chair can be segregated and entered back into the recycling stream to be made into the same or other components at the end of their useful life. A material that can be recycled repeatedly (typically into the same product) is considered part of a closed-loop recycling system.

Steel. The tilt assembly, approximately 23.5 % of the chair's weight, is largely made up of steel stampings and screw-machined components. These steel components represent 74 % of the tilt by mass fraction or 17.3 % of the mass of the chair. The steel components in the tilt are made from 7 % to 50 % recycled materials. The remaining steel materials (less than 2 % of the chair) are nuts, bolts, and other components that require the high strength properties of steel.

Foam/Fabric. The armrests and lumbar supports are the only Aeron chair components made from foams or fabrics. The Pellicle seat and back suspension system is a combination of synthetic fibers and elastomers. These materials comprise a small percentage of the chair. Fabric scraps from Herman Miller's production facilities are recycled into automobile headliners and other similar components. Foam scraps are recycled into carpet padding.

Composite Subassemblies. The Aeron chair has three composite subassemblies of multiple material types. They consist of the five casters, the pneumatic cylinder, and the moving components of the tilt assembly. The pneumatic cylinder can be returned to the manufacturer for disassembly and recycling.

Installation and Use. Packaging materials for the Herman Miller Aeron chair include corrugated paper and a polyethylene plastic bag to protect the product from soiling and dust. Each of these materials is part of a closed-loop recycling system. On larger shipments within North America, disposable packaging can be eliminated through use of reusable shipping blankets.

End-of-Life. The Herman Miller Aeron chair is designed to last at least 12.5 years under normal use conditions. Thus, the chair is replaced three times over the 50-year BEES study period. As with all BEES products, life cycle environmental burdens from these replacements are included in the inventory data.

Cost. The detailed life-cycle cost data for the Herman Miller Aeron chair may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under BEES code E2020, product code A0. First cost data include purchase and installation costs provided by Herman Miller.

3.11.2 Herman Miller Ambi and Generic Office Chairs (E2020B)

A typical chair for office use is a compilation of many different components and subassemblies from multiple suppliers. The Herman Miller Ambi chair is typical of the industry average office chair, and is used in BEES to represent a generic office chair. The detailed environmental performance data for this product can be viewed by opening the file E2020B.DBF under the File/Open menu item in the BEES software. The flow diagram in Figure 3.56 shows the elements involved in the production of the Herman Miller Ambi chair.

Raw Materials. The Herman Miller Ambi chair consists of more than 50 different components and subassemblies from more than 15 direct suppliers. The components and subassemblies are constructed from three major materials: plastics, steel, and foams/fabrics. Of the materials produced from nonrenewable sources (petrochemicals and metals), over two-thirds are made from recycled materials and can be further recycled. The Ambi chair contains approximately 20 % recycled content by weight, including steel, polypropylene, nylon, glass-filled nylon, polystyrene, foam, and fabric. The mixture of constituents, by mass fraction, is given in Table 3.81.

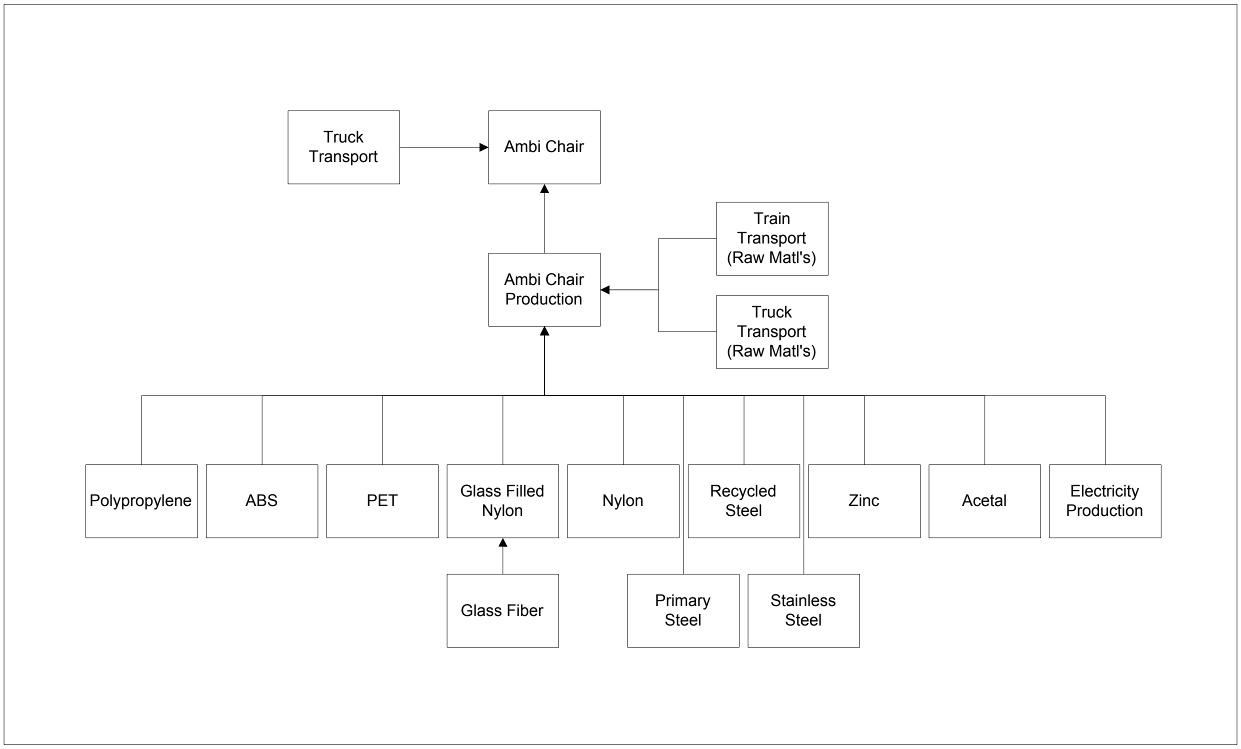

Figure 3.56 Herman Miller Ambi Flow Chart

Table 3.81 Herman Miller Ambi Chair Constituents

Constituent	***Description***
Plastics (polypropylene, PVC, nylon, glass-filled nylons)	33 % for all plastics (24 % for seat shells, 9 % for knobs, levers, bushings, covers)
Steel	63 % for tilt assembly and base; 2 % for nuts, bolts, other components
Foams/fabrics	Less than 4 %; included in open-loop recycling systems
Composite subassemblies	3 % for five casters; 6.7 % for pneumatic cylinder; 6.3 % for moving components of tilt assembly

Plastics. The main plastics used in the Herman Miller Ambi chair include polypropylene, PVC, nylon, and glass-filled nylons. Roughly one-third of the chair, by weight, is made with plastic materials. The seat shells make up 24 % of the chair's weight. The seat shells are made of polypropylene, which contains 10 % post-industrial recycled materials. The remaining plastic components are various knobs, levers, bushings, and covers. These single-material plastic components used in the Ambi chair are identified with ISO recycling symbols and ASTM material designations to help channel them back into the recycling stream.

Steel. The tilt assembly and base, constituting approximately 63 % of the chair's weight, are largely made of steel stampings and screw-machined components. These steel components are 74 % of the tilt assembly by weight or 50 % of the weight of the chair. The steel components in the tilt assembly are made from 28 % to 50 % recycled-content materials. The remaining steel materials (less than 2 % of the chair's mass) are nuts, bolts, and other components that require the high-strength properties of steel. The steel components of the Ambi chair can be segregated and entered back into the recycling stream.

Foam/Fabric. These materials are part of an open-loop system; they can be transformed into other products. Fabric scraps from Herman Miller's current production facilities are made into automobile headliners and other similar components. Foam scraps are used in carpet padding.

Composite Subassemblies. There are three composite subassemblies of multiple material types. They are the five casters (3 % of the chair mass), the pneumatic cylinder (6.7 % of the chair mass), and the moving components of the tilt assembly (6.3 % of the chair mass). The pneumatic cylinder can be returned to the manufacturer for disassembly and recycling.

Installation and Use. Packaging materials for the Herman Miller Ambi chair include corrugated paper and a polyethylene plastic bag to protect the product from soiling and dust. Each of these materials is part of a closed-loop recycling system. On larger shipments within North America, disposable packaging can be eliminated through use of reusable shipping blankets.

End-of-Life. The Herman Miller Ambi chair is designed to last at least 12.5 years under normal use conditions. Thus, the chair is replaced three times over the 50-year BEES study period. As with all BEES products, life cycle environmental burdens from these replacements are included in the inventory data.

Cost. The detailed life-cycle cost data for the Herman Miller Ambi and generic office chairs may be viewed by opening the file LCCOSTS.DBF under the File/Open menu item in the BEES software. Costs are listed under BEES code E2020, product code B0. First cost data include purchase and installation costs provided by Herman Miller.

3.12 Parking Lot Paving Alternatives (G2022)

3.12.1 Generic Concrete Paving (G2022A, G2022B, G2022C)

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 (3 000 lb/in^2) is used. The flow diagram shown in Figure 3.57 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

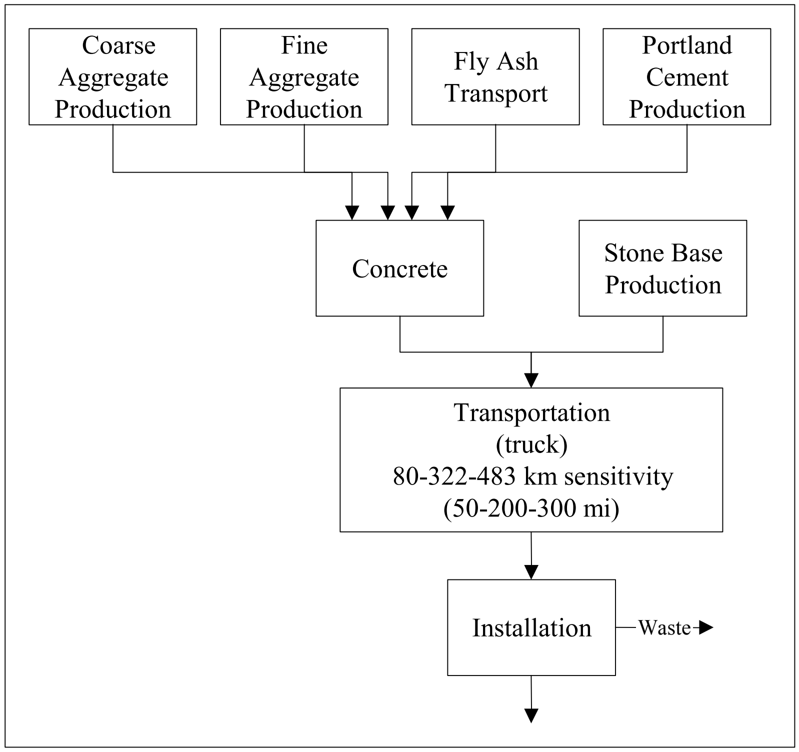

Figure 3.57 Concrete Paving Flow Chart

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.

Concrete paving is assumed to last 30 years.

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

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. Cost data have been adjusted to year 2002 dollars.

3.12.2 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.[106] 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 3.58 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 3.82. The production of the raw materials required for the pavement and the emulsifier is based on the PricewaterhouseCoopers 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 asphalt emulsion maintenance over 50 years).

[106] 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.

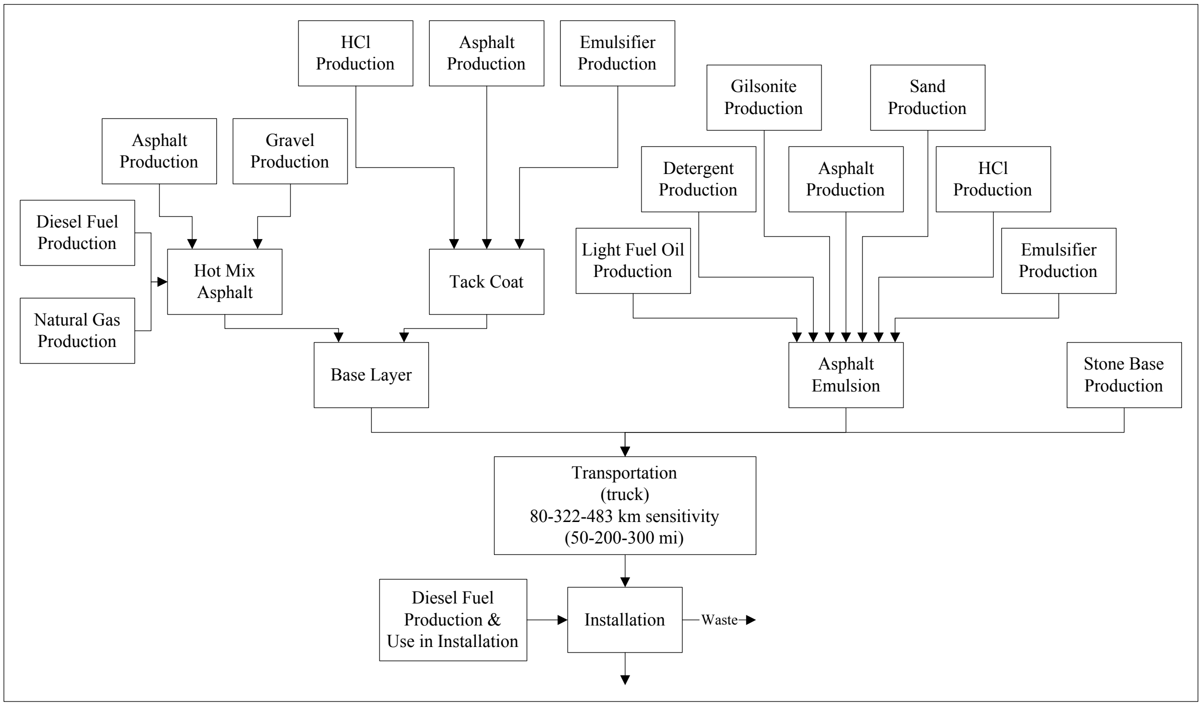

Figure 3.58 Asphalt with GSB88 Emulsion Maintenance Flow Chart

Table 3.82 Raw Materials for Asphalt Base Layer

Constituent	***Base Layer (mass fraction %)***	***Component (mass fraction %)***
- 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

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 3.83.

Table 3.83 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 PricewaterhouseCoopers 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. Cost data have been adjusted to year 2002 dollars.

3.12.3 Generic 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.[107] 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 3.59 shows the elements of

[107] 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.

asphalt paving with asphalt cement maintenance. The detailed environmental performance data for this product may be viewed by opening the file G2022E.DBF under the File/Open menu item in the BEES software.

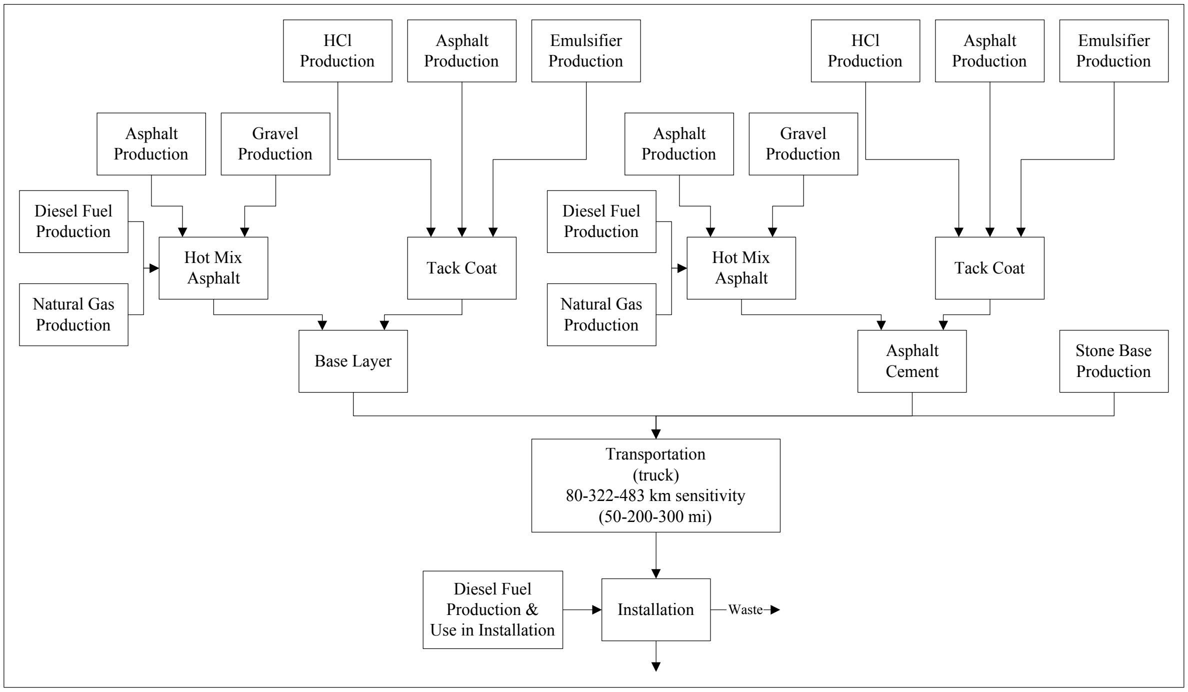

Figure 3.59 Asphalt with Asphalt Cement Maintenance Flow Chart

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 3.84.

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

Table 3.84 Raw Materials for Asphalt Cement Maintenance

Constituent	*Base Layer (mass fraction %)*	*Component (mass fraction %)*
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 3.82. The energy requirements for the asphalt cement maintenance are listed in Table 3.85.

Table 3.85 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 PricewaterhouseCoopers 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. Cost data have been adjusted to year 2002 dollars.

3.13 Transformer Oil Alternatives (G4010)

3.13.1 Generic Mineral Oil-Based Transformer Oil (G4010A)

Mineral oil-based transformer oil can be made from either naphtha or paraffin. Since the naphthenic-based mineral oil carries a larger market share, it is used as the mineral oil-base for BEES.[108] The production of naphthenic-based transformer oil consists of four main components: extraction of crude oil, crude oil transport to refinery, crude oil refining and refining into transformer oil, and transportation to the transformer for use. Figure 3.60 shows the elements of mineral oil-based transformer oil production. The detailed environmental performance data for this product may be viewed by opening the file G4010A.DBF under the File/Open menu item in the BEES software. Requirements for the four components of mineral oil-based transformer oil are based on the DEAM database, as detailed below.

[108] 2001 telephone conversation with United Power Services, an independent transformer oil testing laboratory.

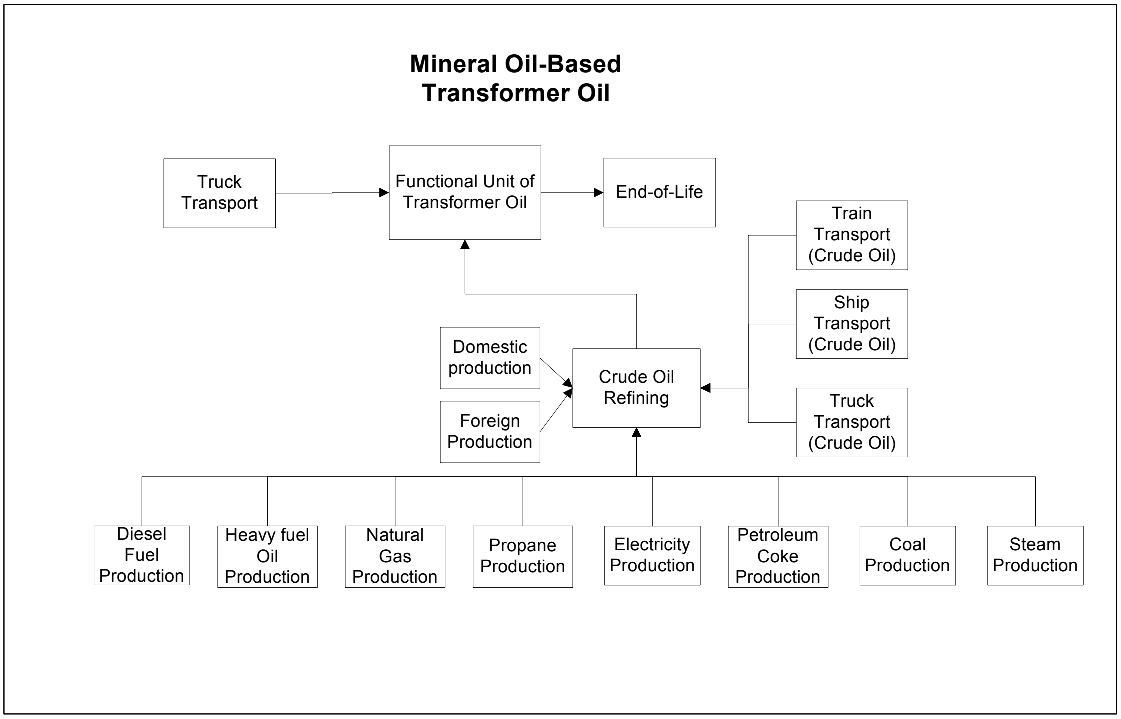

Figure 3.60 Mineral Oil-Based Transformer Oil Flow Chart

Crude Oil Extraction. This production component includes the process flows associated with the extraction of crude oil from the ground. Three separate technologies for crude oil extraction are modeled: conventional onshore recovery, conventional offshore recovery, and advanced onshore recovery, the latter entailing the underground injection of steam (produced by natural gas boilers) or carbon dioxide to enhance the extraction of crude oil. Percentages of total crude oil extraction by technology for domestic and foreign production are given in Table 3.86.[109]

Table 3.86 Extraction of Crude Oil by Technology and Origin

Technology	***Domestic Crude Oil Extraction***	***Foreign Crude Oil Extraction***
Conventional Onshore Recovery	69 %	77 %
Conventional Offshore Recovery	20 %	20 %
Advanced Onshore Recovery	11 %	3 %

Natural gas is produced as a coproduct of crude oil extraction. The energy use and emissions associated with extraction are allocated between crude oil and natural gas on a mass basis.

Crude Oil Transport to Refinery. Crude oil transport to the refinery is regionalized by the five

[109] Shares of each technology are based on 1994 data in *Oil & Gas Journal Database.* Note that the advanced recovery category includes all advanced crude oil extraction techniques except water flooding. It is assumed that steam flooding and carbon dioxide injection represent the largest portion of the advanced recovery category.

U.S. Petroleum Administration Defense Districts (PADDs). Transportation distances are specified and allocated for the different modes for transport of crude oil. Figure 3.61 illustrates this procedure by showing the results for PADD District II.

Crude Oil Refining. Crude oil refining involves raw materials and energy use as well as emissions. Crude oil refining is based on an average U.S. refinery as opposed to a PADD-specific refinery. It is assumed that the material required by the refinery includes crude oil and other petroleum-based feedstocks, purchased energy inputs, and process catalysts.

Crude oil refineries draw most of their energy requirements from the crude oil stream in the form of still gas and catalyst coke as shown in Table 3.87. Additional energy requirements and process needs are fulfilled by the other inputs shown in Table 3.87.[110]

The emissions and energy requirements associated with the production of these fuels are accounted for. Emissions are based on the U.S. Environmental Protection Agency AP-42 emission factors.

Crude oil refineries produce a number of different petroleum products from crude oil. The method for allocating total refinery energy use and total refinery emissions to the production of naphtha is complicated by the fact that the refinery product mix is variable, both among refineries and even with time for a given integrated refinery. The following method is used to allocate refinery flows to naphtha production:

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[110] Energy Information Administration, *Petroleum Supply Annual 1994*, Report No. DOE/EIA-0340(94)/1, May 1995.

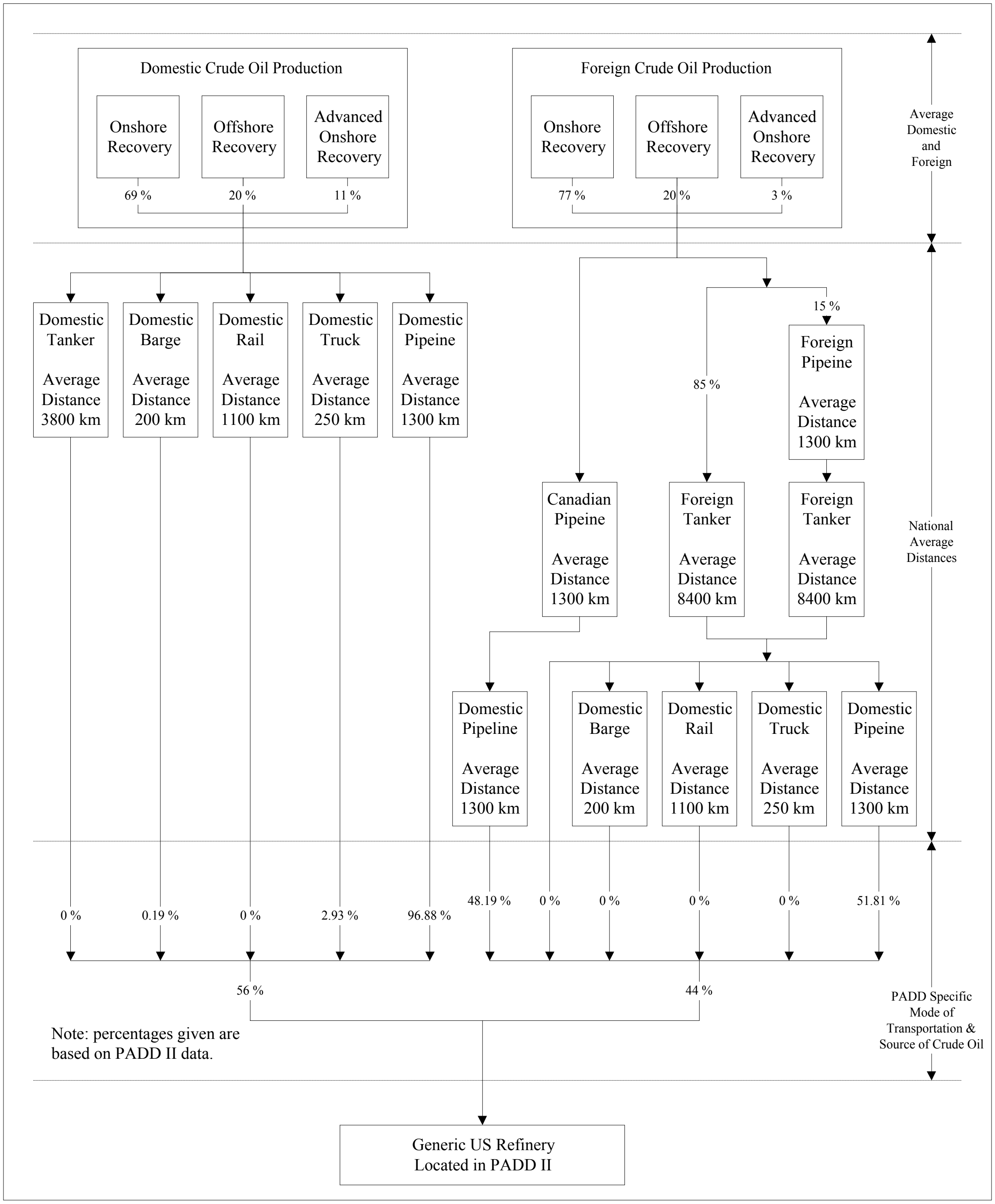

Figure 3.61 Crude Oil Transportation for U.S. Petroleum Administration Defense District II (PADD II)

Table 3.87 U.S. Average Refinery Energy Use

Flow	*Units*	*Annual Quantity*
Still Gas	MJ	1.52E+12
Catalyst Coke	MJ	5.14E+11
Natural Gas	MJ	7.66E+11
Coal	MJ	3.27E+09
Steam	MJ	3.8E+10
Electricity	MJ	1.43E+11
Propane (C3H8, kg)	MJ	6.21E+10
Diesel Oil (kg)	MJ	3.16E+09
Heavy Fuel Oil	MJ	6.13E+10
Coke	MJ	1.77E+10
Other	MJ	8.8E+09

1. Calculate the percentage of total refinery energy use by refinery process.

2. Calculate naphtha's share of each process's energy consumption.

3. For each refinery process, multiply the corresponding results from steps 1 and 2 to get the percentage of total refinery energy use allocated to naphtha refinery energy allocated to naphtha production (from step 3 above).

After producing naphtha, pour-point depressives and other additives are added to enhance the transformer oil. Data are not available on these additives since for many transformer oil producers, these data are proprietary. Thus, flows associated with additives could not be estimated.

Transportation. Truck transportation is used to represent transportation from the transformer oil production plant to the transformer to be filled at the point of use. The transportation distance is modeled as a variable of the BEES system. Only the truck is modeled—and not, for example, pipeline transportation—since transformer oil is a specialty petroleum product with a tiny market as compared to other petroleum products.

Use. The amount of oil used in a transformer depends on the size of the transformer. A relatively small-sized (1 000 kV·A) transformer is assumed, which requires about 1.89 m^3 (500 gal) of fluid to cool. It is assumed that the use phase of the transformer oil lasts the lifetime of the transformer, approximately 30 years. The functional unit for all BEES transformer oil data is "cooling for one 1 000 kilovolt-ampere transformer for 30 years." Included in the modeling is the electricity required to recondition the oil when dissolved gas analysis tests indicate the need. Reconditioning is assumed to occur every five years.[111]

[111] Information on dissolved gas analysis testing can be found in the U.S. Bureau of Reclamation (USBR) website's Facilities Instructions Standards and Techniques (FIST) document, http://www.usbr.gov/power/data/fist/fist3-30. Energy information on reconditioning was provided during telephone conversations with S.D. Myers, a transformer and transformer fluid contractor, November 2001.

There is a tiny (5 % of 1 %, or 0.05 %) chance of an abnormal or catastrophic event in which transformer oil spills disastrously and impacts the surrounding ecosystem and human health. The BEES life-cycle data account for the possibility of such oil spill impacts, though with significant limitations. Oil spills have little impact on the BEES results for transformer oils.

End of Life. After the 30-year life of the transformer, mineral oil-based transformer fluid is often in good enough condition to be reconditioned and used in another transformer. The mineral oil is assumed to be reconditioned and reused in another transformer 75 % of the time. Transformer oil may also be incinerated, with and without energy recovery. For this study, it is assumed that half of the remaining 25 % of mineral oil that is too contaminated to be reprocessed to an effective state is incinerated without energy recovery and half is incinerated with energy recovery. The credit gained for energy recovery--producing energy in an industrial boiler--is accounted for. The end-of-life options for transformer oil do not include disposable waste, as it is generally a well-maintained product and can be used in other applications. Therefore, none of the product is assumed to be landfilled.

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 G4010, product code A0. Life-cycle cost data for mineral-based transformer oil include first cost data (excluding installation costs) and future cost data (cost and frequency of oil reconditioning). First cost data are collected from Waverly Light & Power and future cost data from the U.S. Bureau of Reclamation.

3.13.2 BioTrans Transformer Oil (G4010B)

BioTrans Transformer oil is a soy-based oil relatively new on the market. Results of independent tests on the performance for BioTrans Transformer oil are comparable to results for other Transformer oils (such as the mineral-based and silicone-based fluids discussed above). BioTrans Transformer oil is produced from soybean feedstock. The flow diagram in Figure 3.62 shows the elements of BioTrans Transformer oil production**.** The detailed environmental performance data for this product may be viewed by opening the file G4010B.DBF under the File/Open menu item in the BEES software.

Production. BioTrans Transformer oil is composed of the materials listed in Table 3.88.

After producing soy-based oil, pour-point depressives and other additives are added to enhance the oil. No data are available on these additives since this data is proprietary for many Transformer oil producers.

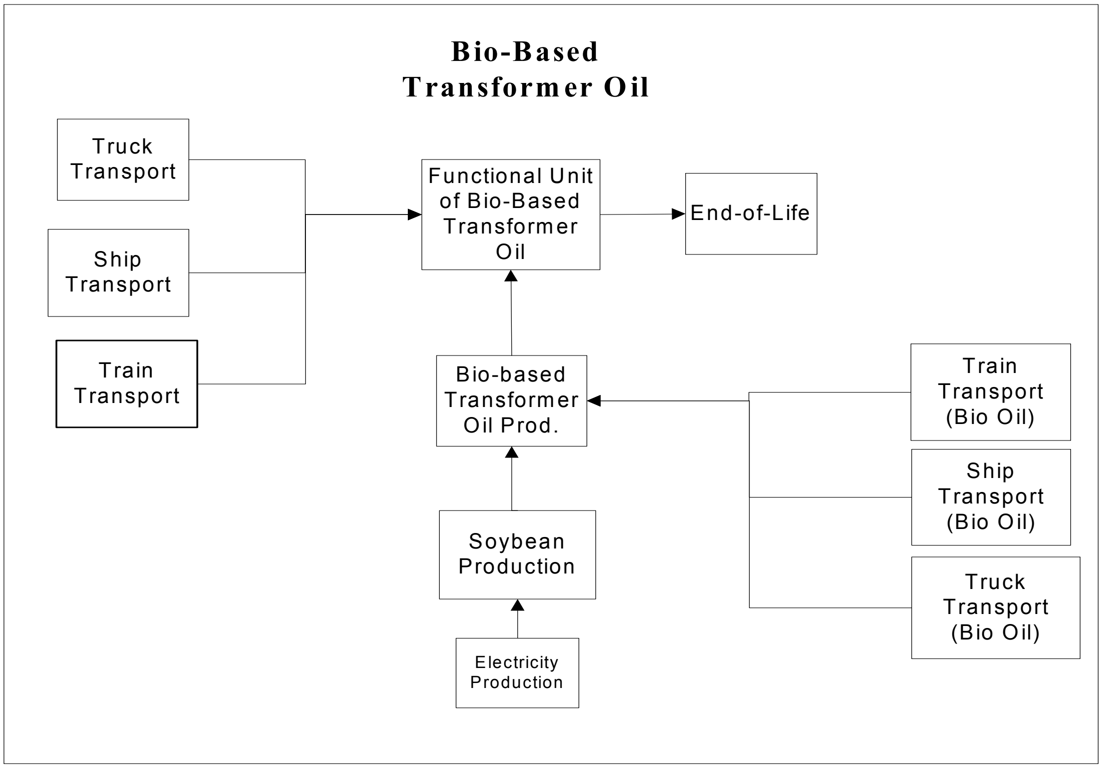

Figure 3.62 BioTrans Transformer Oil Flow Chart

Table 3.88 BioTrans Transformer Oil Constituents

BioTrans Oil Constituents	***Mass (kg/kg oil)***
Soybeans (dry)	0.90
Hexane	0.002
Water	0.0035
Additives and pour-point depressives	< 0.1

The energy requirements for BioTrans Transformer oil production are listed in Table 3.89.

Table 3.89 Energy Requirements for BioTrans Transformer Oil Production

Fuel Use	***Production Energy (per kg oil)***
Electricity	0.27 MJ
Natural Gas	1.2 MJ
Steam	0.38 kg

Emissions from BioTrans Transformer oil production consist of fugitive hexane emissions as well as emissions arising from energy production.

Transportation. Truck Transportation is used to represent Transportation from the Transformer oil production plant to the Transformer to be filled at the point of use. The Transportation distance is modeled as a variable of the BEES system. Only the truck is modeled--and not, for example, pipeline Transportation--since Transformer oil is a specialty petroleum product with a tiny market as compared to other petroleum products

Use. The amount of oil used in a Transformer depends on the size of the Transformer. A relatively small-sized (1 000 kV·A) transformer is assumed, which requires about 1.89 m^3 (500 gal) of fluid to cool. It is assumed that the use phase of the Transformer oil lasts the lifetime of the Transformer, approximately 30 years. The functional unit for all BEES Transformer oil data is "cooling for one 1 000 kilovolt-ampere Transformer for 30 years." Included in the modeling is the electricity required to recondition the oil when dissolved gas analysis tests indicate the need. Reconditioning is assumed to occur every five years.[112]

There is a tiny (5 % of 1 %, or 0.05 %) chance of an abnormal or catastrophic event in which Transformer oil spills disastrously and impacts the surrounding ecosystem and human health. The BEES life-cycle data account for the possibility of such oil spill impacts, though with significant limitations. Oil spills have little impact on the BEES results for Transformer oils.

End of Life. BioTrans oil has not been in use long enough to assess its fate after 30 years. It is assumed to be treated the same as mineral oil. Thus, after the 30-year life of the Transformer, it is assumed to be reconditioned and reused in another Transformer 75 % of the time. Using the same modeling assumptions as for mineral-based oil, half of the remaining 25 % of the BioTrans oil that is too contaminated to be reprocessed to an effective state is incinerated without energy recovery and half is incinerated with energy recovery. The credit gained for energy recovery--producing energy in an industrial boiler--is accounted for. The end-of-life options for Transformer oil do not include disposable waste, as it is generally a well-maintained product and can be used in other applications. Therefore, none of the product is assumed to be landfilled.

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 G4010, product code B0. Life-cycle cost data for BioTrans Transformer oil include first cost data (excluding installation costs) and future cost data (cost and frequency of oil reconditioning). First cost data are collected from Waverly Light & Power and future cost data from the U.S. Bureau of Reclamation.

3.13.3 Generic Silicone-Based Transformer Fluid (G4010C)

Silicone-based transformer fluid is a synthetic transformer oil composed primarily of dimethylsiloxane polymers, and following a very different series of production steps than that described above for mineral oil-based transformer oil production. Figure 3.63 shows the elements of silicone fluid production**.** The detailed environmental performance data for this product may be viewed by opening the file G4010C.DBF under the File/Open menu item in the BEES software.

[112] Information on dissolved gas analysis testing can be found in the U.S. Bureau of Reclamation (USBR) website's Facilities Instructions Standards and Techniques (FIST) document, http://www.usbr.gov/power/data/fist/fist3-30. Energy information on reconditioning was provided during telephone conversations with S.D. Myers, a Transformer and Transformer fluid contractor, November 2001.

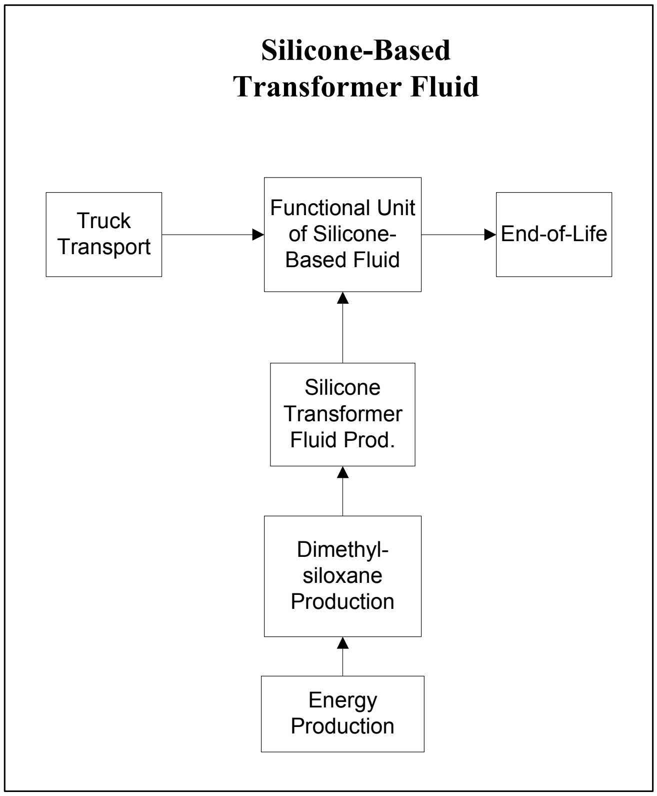

Figure 3.63 Silicone-Fluid Flow Chart

Production. While silicone-based fluid is produced in the United States and abroad, the only publicly-available data are European. Thus, European data are used to model the main component, cyclical siloxane, as described below[113].

The production of demethylsiloxane starts with the production of dimethylchlorosilane using chloromethane and silicon. Dimethylchlorosilane undergoes hydrolysis reactions to produce dimethylsilanediol, which undergoes another series of hydrolysis reactions to condense into cyclical siloxane. No data are available to model production of the dimethylsiloxane polymer from the cyclical siloxane, or the final stages required to produce the transformer fluid. Thus, only production flows for the main component, cyclical siloxane, are included in the BEES data.

Transportation. Truck transportation is used to represent transportation from the transformer oil production plant to the transformer to be filled at the point of use. The transportation distance is modeled as a variable of the BEES system.

Use. The amount of oil used in a transformer depends on the size of the transformer. A relatively small-sized (1 000 kV•A) transformer is assumed, which requires about 1.89 m^3 (500 gal) of fluid to cool. It is assumed that the use phase of the transformer oil lasts the lifetime of the transformer, approximately 30 years. The functional unit for all BEES transformer oil data is "cooling for one 1 000 kilovolt-ampere transformer for 30 years." Included in the modeling is the electricity required to recondition the oil when dissolved gas analysis tests indicate the need.

[113] Silicon production: JL Vignes, Données Industrielles, économiques, géographiques sur des produits chimiques (minéraux et organiques) Metaux et Matériaux, pp. 134, ed. 1994, Union des Physiciens; Dimethylchlorosilane production: "Silicones", Rhône-Poulenc département silicones, Techno-Nathan edition, Nouvelle Librairie, 1988; Dimethylsilanediol and cyclic siloxane production: Carette, Pouchol (RP Silicones) , Techniques de l'ingénieur, vol. A 3475, p.3.

Reconditioning is assumed to occur every five years.[114]

There is a tiny (5 % of 1 %, or 0.05 %) chance of an abnormal or catastrophic event in which transformer oil spills disastrously and impacts the surrounding ecosystem and human health. The BEES life-cycle data account for the possibility of such oil spill impacts, though with significant limitations. Oil spills have little impact on the BEES results for transformer oils.

End of Life. Silicone fluid is well maintained during the life of the transformer due to its sensitive-area uses and its higher cost[115]. It is assumed therefore that 90 % of the time it is suitable for reconditioning and reuse at the end of the 30 year life of the transformer. Of the remaining 10 %, half is incinerated with energy recovery, with credit given for energy production in an industrial boiler. The other half is sent back to the manufacturer for restructuring for production into other silicone-based products[116]. The end-of-life options for transformer oil do not include disposable waste, as it is generally a well-maintained product and can be used in other applications. Therefore, none of the product is assumed to be landfilled.

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 G4010, product code C0. Life-cycle cost data for silicone-based transformer fluid include first cost data (excluding installation costs) and future cost data (cost and frequency of oil reconditioning). First cost data are collected from Waverly Light & Power and future cost data from the U.S. Bureau of Reclamation.

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[114] Information on dissolved gas analysis testing can be found in the U.S. Bureau of Reclamation (USBR) website's Facilities Instructions Standards and Techniques (FIST) document, http://www.usbr.gov/power/data/fist/fist3-30. Energy information on reconditioning was provided during telephone conversations with S.D. Myers, a transformer and transformer fluid contractor, November 2001.

[115] Contact at S.D. Myers company, November 2001.

[116] Information from Dow Corning, http://www.dowcorning.com, "Reuse, recycle, or disposal of transformer fluid", 2001.

4. BEES Tutorial

To select environmentally-friendly, cost-effective 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, and economic performance scores 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 importance 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 importance weight is automatically computed. Next you are asked to select your relative importance weights for the environmental impact categories included in the BEES environmental performance score: Global Warming, Acidification, Eutrophication, Fossil Fuel Depletion, Indoor Air Quality, Habitat Alteration, Water Intake, Criteria Air Pollutants, Smog, Ecological Toxicity, Ozone Depletion, and Human Health. (There are a limited number of BEES products for which Smog, Ecological Toxicity, Human Toxicity, and Ozone Depletion are excluded from the evaluation due to resource constraints. Whenever any of these products are selected, *all* products under analysis are automatically evaluated with respect to the reduced impact set. Refer to table 4.1 for a listing of the number of impacts evaluated for each product.) You are presented with four sets of alternative weights. You may choose to define your own set of weights or to select a built-in weight set derived from an EPA Science Advisory Board study, a Harvard University study, or a set of equal weights.[117] 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 under analysis, as shown in

[117] So that the set of equal weights would appropriately sum to 100, individual weights have been rounded up or down. These arbitrary settings may be changed by using the user-defined weighting option.

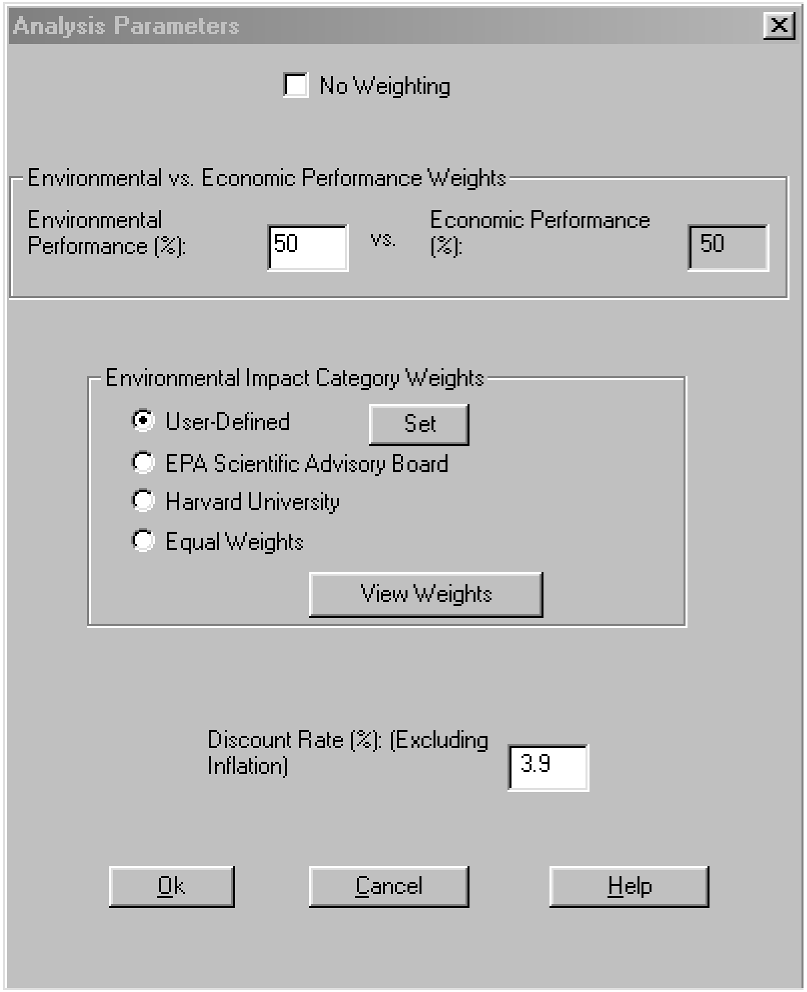


Figure 4.1 Setting Analysis Parameters

Figure 4.3. These weights must sum to 100.

Environmental Impact Category Weights

Weight Set:	Globalwarm	Acidifcatn	Eutrophctn	Natresdepn	Indoor_Air	Habit_altn	Water_Intk	Crit_Air_P	Smog	Ecolog_Tox	Ozone_Depl	Human_Hlth
User-Defined	9	9	9	9	8	8	8	8	8	8	8	8
EPA Science Advisory Boa	16	5	5	5	11	16	5	5	5	11	5	11
Harvard University Study-b	11	9	9	7	7	6	9	10	9	6	11	6
Equal Weights	9	9	9	9	8	8	8	8	8	8	8	8

Figure 4.2 Viewing Impact Category Weights

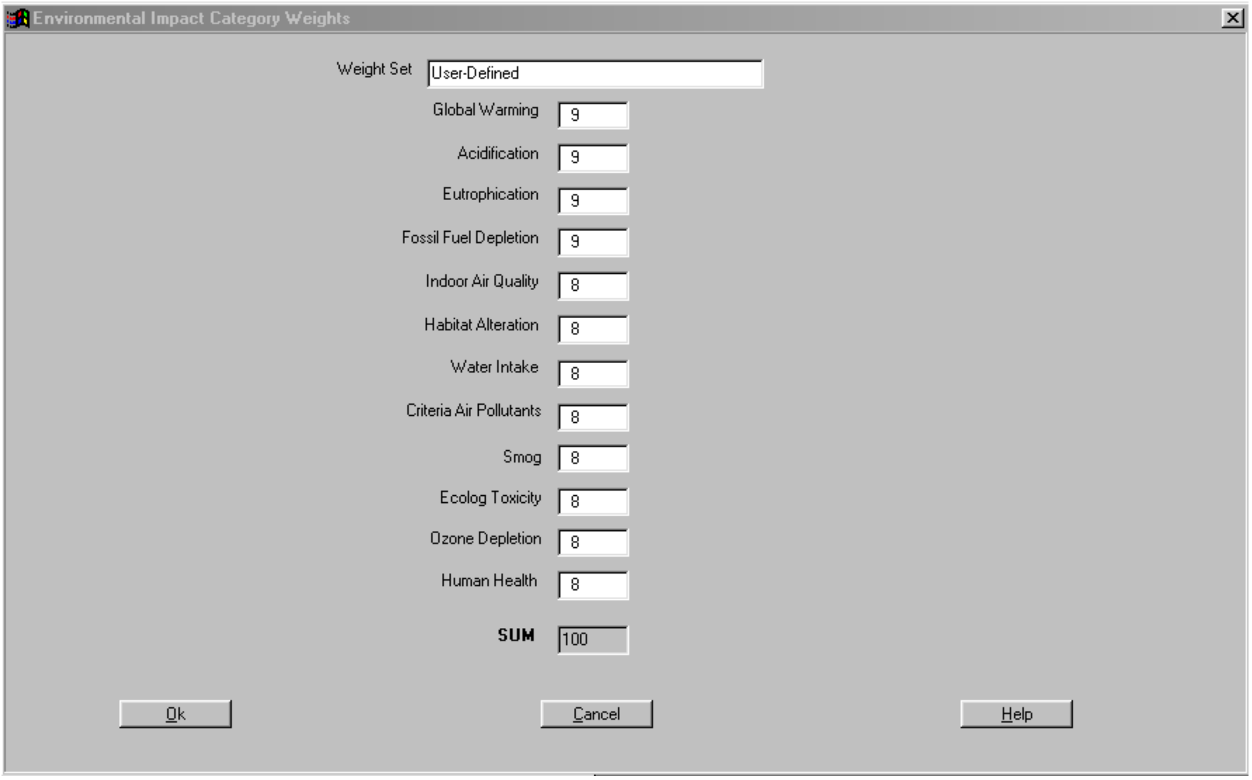


Figure 4.3 Entering User-Defined Weights

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 2002 rate mandated by the U.S. Office of Management and Budget for most Federal projects, 3.9 %, is provided as a default value.[118]

[118] U.S. 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, Washington, DC, 2002.

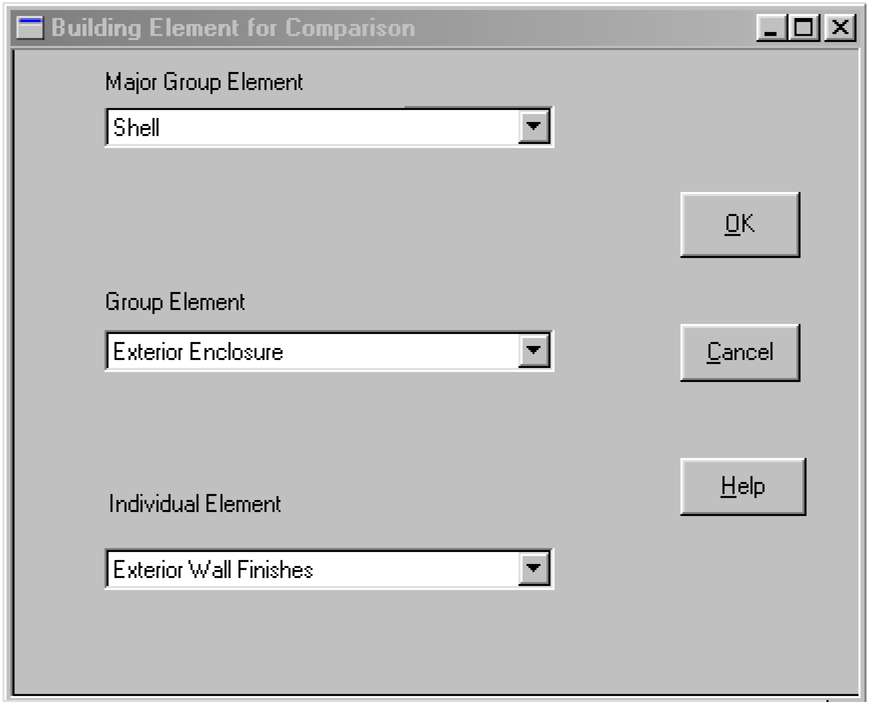


Figure 4.4 Selecting Building Element for BEES Analysis

4.2 Defining Alternatives

Select Analysis/Define Alternatives from the Main Menu to choose the building products you want to compare. A window appears as in Figure 4.4. Selecting alternatives is a two-step process.

1. Select the specific building element for which you want to compare alternatives. Building elements are organized using the hierarchical structure of the ASTM standard UNIFORMAT II classification system: by Major Group Element, Group Element, and Individual Element.[119] Click on the down arrows to display the complete lists of available choices at each level of the hierarchy.

   BEES 3.0 contains environmental and economic performance data for nearly 200 products across 23 building elements including beams, columns, roof sheathing, exterior wall finishes, wall insulation, framing, roof coverings, partitions, ceiling finishes, interior wall finishes, floor coverings, chairs, and parking lot paving. Press Ok to select the choice in view.

[119] ASTM International, *Standard Classification for Building Elements and Related Sitework--UNIFORMAT II,* ASTM Designation E 1557-97, West Conshohocken, PA, 1997.

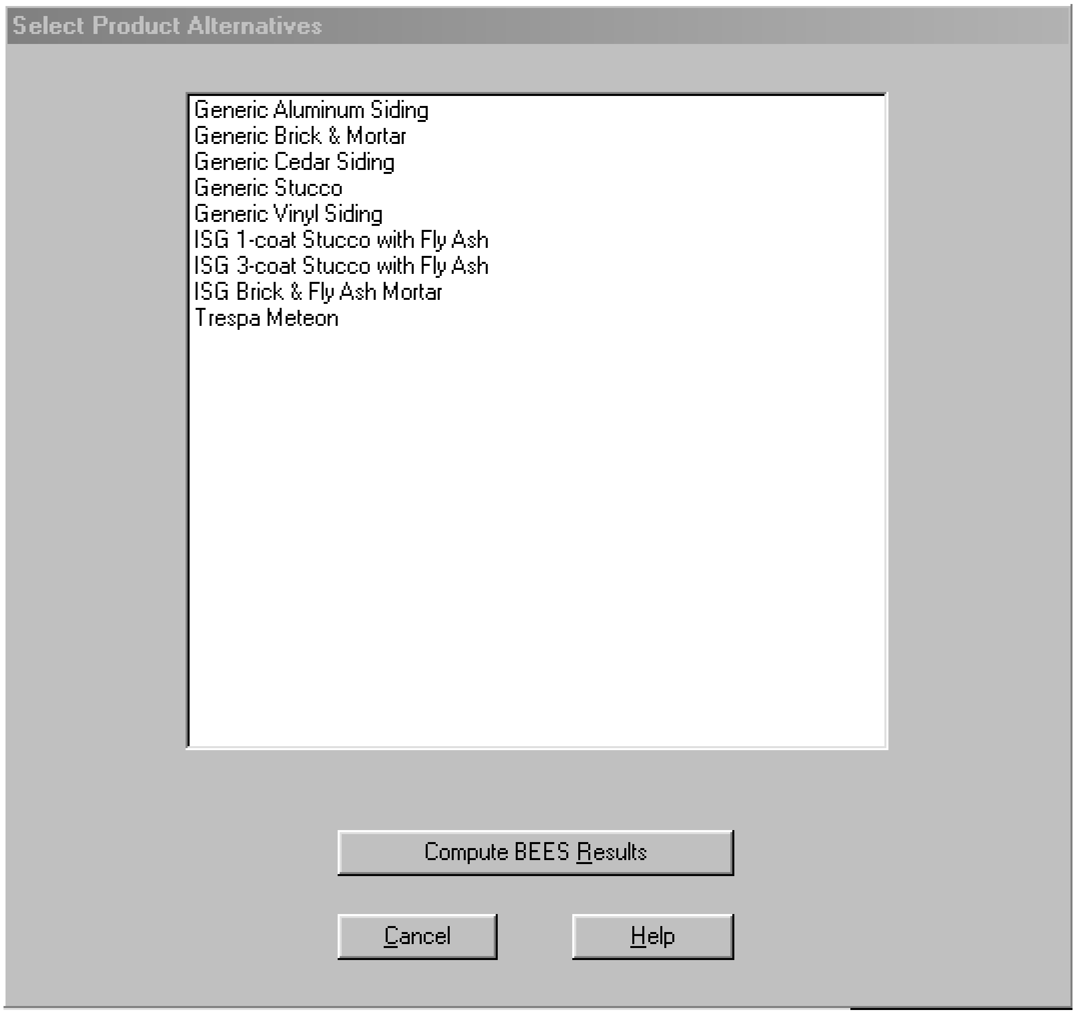


Figure 4.5 Selecting Building Product Alternatives

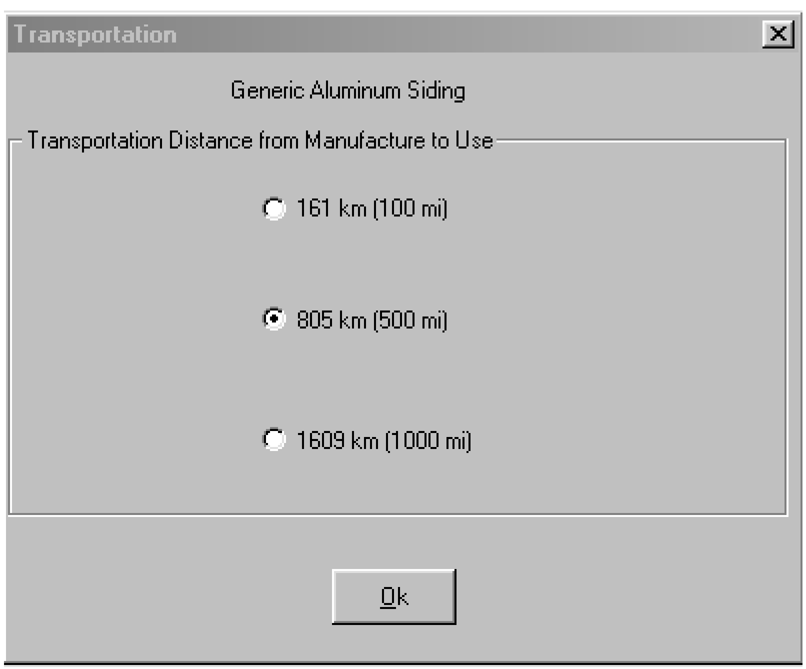


Figure 4.6 Setting Transportation Parameters

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. After selecting each alternative, you will be presented with a window, such as in Figure 4.6, asking for the distance required to transport the product from the manufacturing plant to your building site.[120] If the product is exclusively manufactured in another country (e.g., linoleum flooring), this setting should reflect the transportation distance from the U.S. distribution facility to your building site (transport *to* the distribution facility has already been built into the BEES data).

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. Press Display to view the three graphs. 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. Because this graph displays scores for unit quantities of individual building products that have been normalized (i.e., placed on a common scale) by reference to total U.S. impacts, they appear as very small numbers. If you chose not to weight, this graph is not available.
3. The Economic Performance Results graph displays the first cost, discounted future costs and their sum, the life-cycle cost.

[120] 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 for 50-year heating and cooling energy use based on roof covering color.

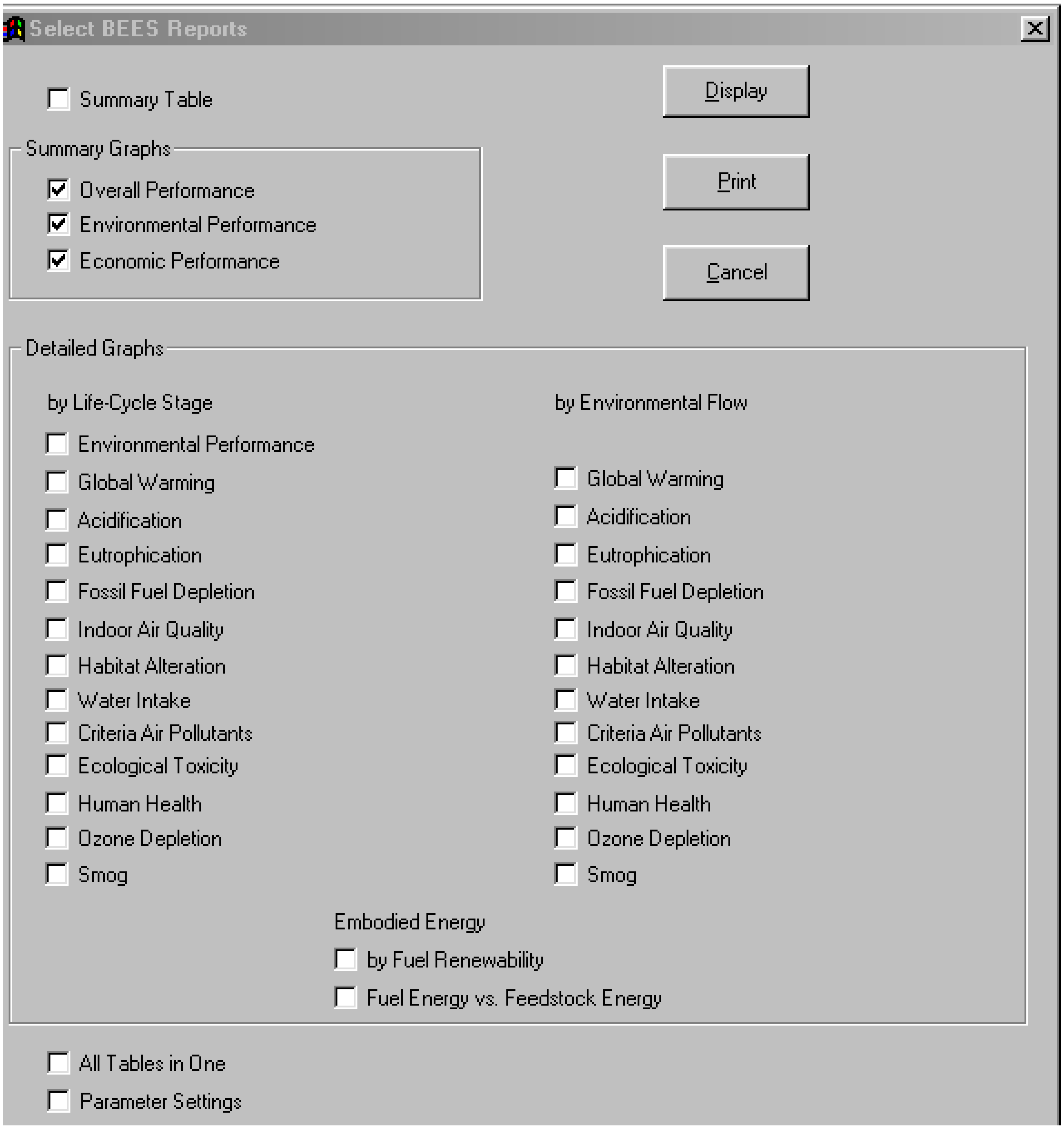
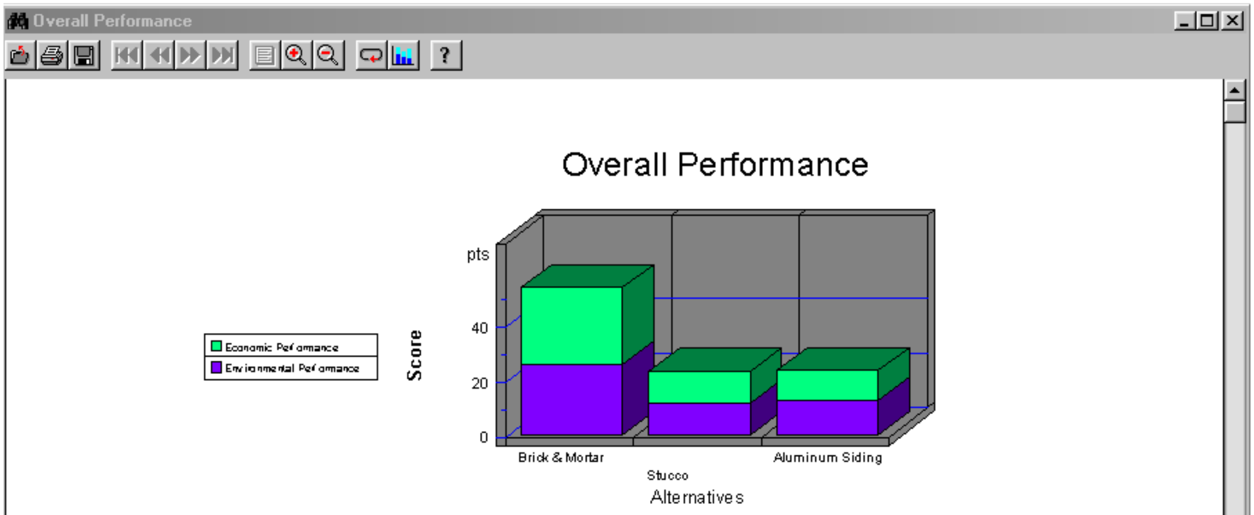


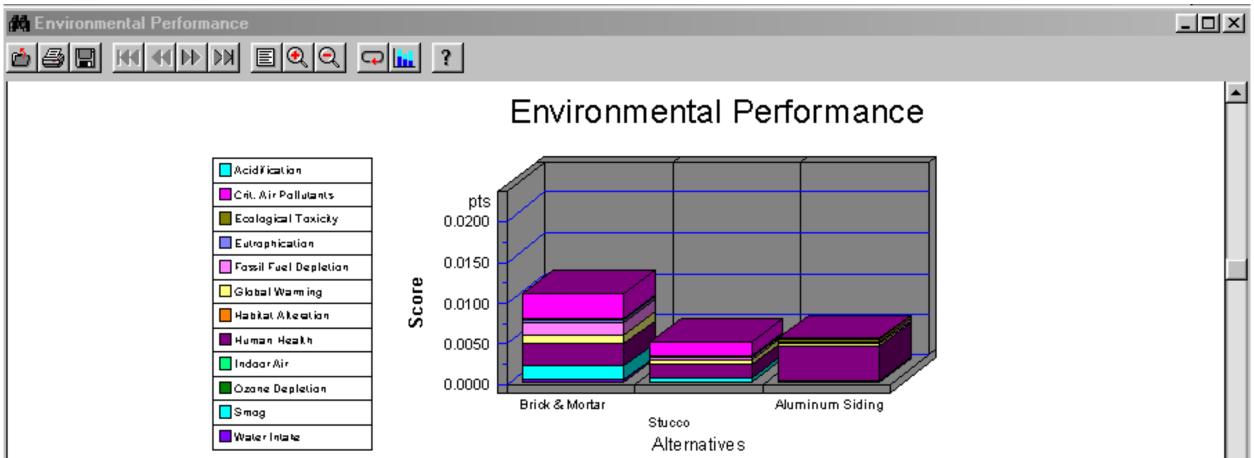
Figure 4.7 Selecting BEES Reports



Note: Lower values are better

Category	Brick	Stucco	Aluminum
Economic Perform.–50%	28.0	11.2	10.9
Environ. Perform.–50%	25.6	11.9	12.6
Sum	53.6	23.1	23.5

Figure 4.8 Viewing BEES Overall Performance Results

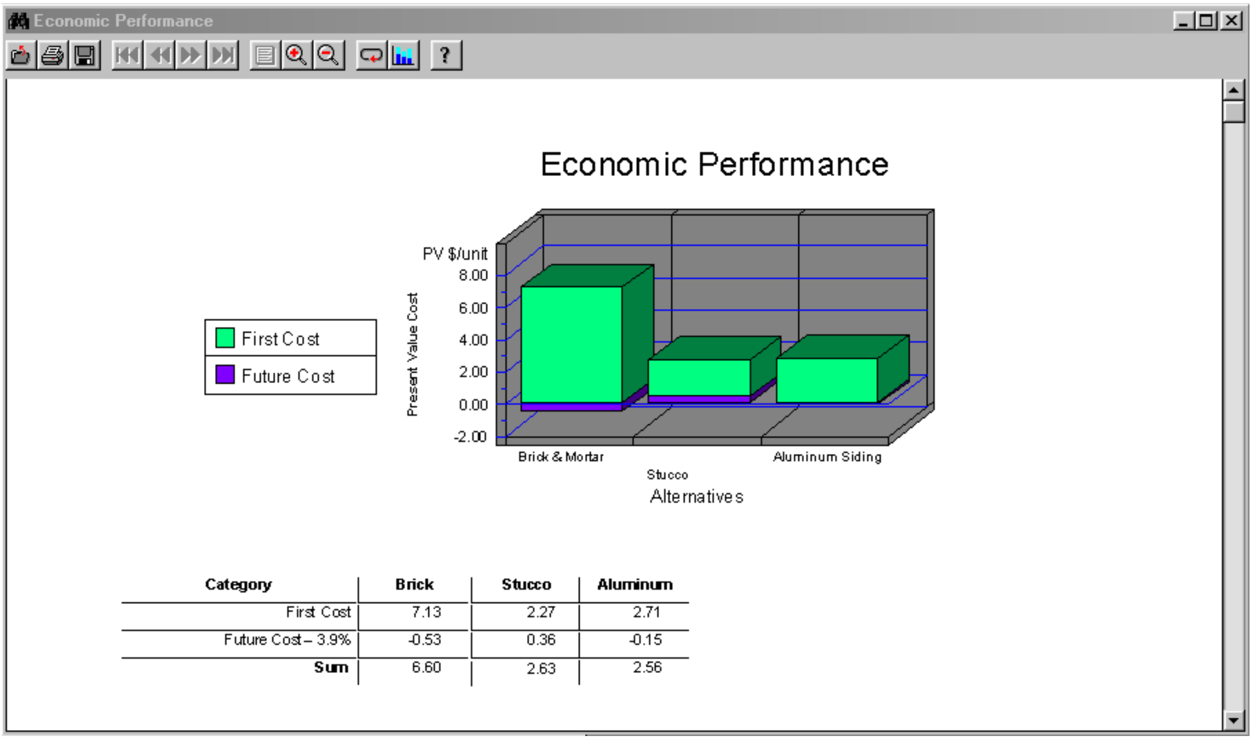


Note: Lower values are better

Category	Brick	Stucco	Aluminum
Acidification–9%	0.0000	0.0000	0.0000
Crit. Air Pollutants–8%	0.0031	0.0018	0.0001
Ecolog. Toxicity–8%	0.0001	0.0001	0.0002
Eutrophication–9%	0.0004	0.0001	0.0001
Fossil Fuel Depl.–9%	0.0015	0.0003	0.0002
Global Warming–9%	0.0011	0.0006	0.0003
Habitat Alteration–8%	0.0000	0.0000	0.0000

Press PageDown for more results..

Figure 4.9 Viewing BEES Environmental Performance Results



Category	Brick	Stucco	Aluminum
First Cost	7.13	2.27	2.71
Future Cost – 3.9%	-0.53	0.36	-0.15
Sum	6.60	2.63	2.56

Figure 4.10 Viewing BEES Economic Performance Results

BEES results are derived by using the BEES model to combine environmental and economic performance data using your study parameters. The method 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* report giving all the detailed results in a single tabular report. Figures 4.11 through 4.15 illustrate each of these options.

Once you have displayed any BEES report, you may select additional reports for display by selecting Tools/Select Reports from the menu.[121] To compare BEES results based on different parameter settings, either select Tools/Change Parameters from the menu, or if the Summary Table is in focus, press the *Change Parameters* button. Change your parameters, and press Ok. You may now display reports based on your new parameters. Then you may find it convenient to view reports with different parameter settings side-by-side by selecting Window/Tile from the 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

[121] This feature is not available from the menu displayed with the BEES Summary Table.

a single economic data file, LCCOSTS.DBF, with cost data for all products. As noted in section 3, some environmental data files map to a product in more than one application, while the economic data typically 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.

The environmental performance data files are similarly structured, with 3 simulations in each. The first column in all these files, XPORT, shows the assumed transportation distance from manufacture to use (in miles). 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)" radioactive air emissions, "(s)" releases to soil, "(w)" water effluents, "(wr)" radioactive water effluents, and "E" energy usage. All quantities are expressed in terms of the product's functional units, typically 0.09 m^2 (1 ft^2) of product service for 50 years.[122] The column labeled "Total" is the primary data column, giving total cradle-to-grave 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 roughly 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 constant 2002 dollars) per functional unit.

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.

[122] The functional unit for concrete beams and columns is 0.76 cubic meters (1 cubic yard) of product service for 50 years, for chairs is office seating for 1 person for 50 years, for soil treatment is 1 kilogram of soil improver over 50 years, and for transformer oil is cooling for one 1000 kilovolt-ampere transformer for 30 years.

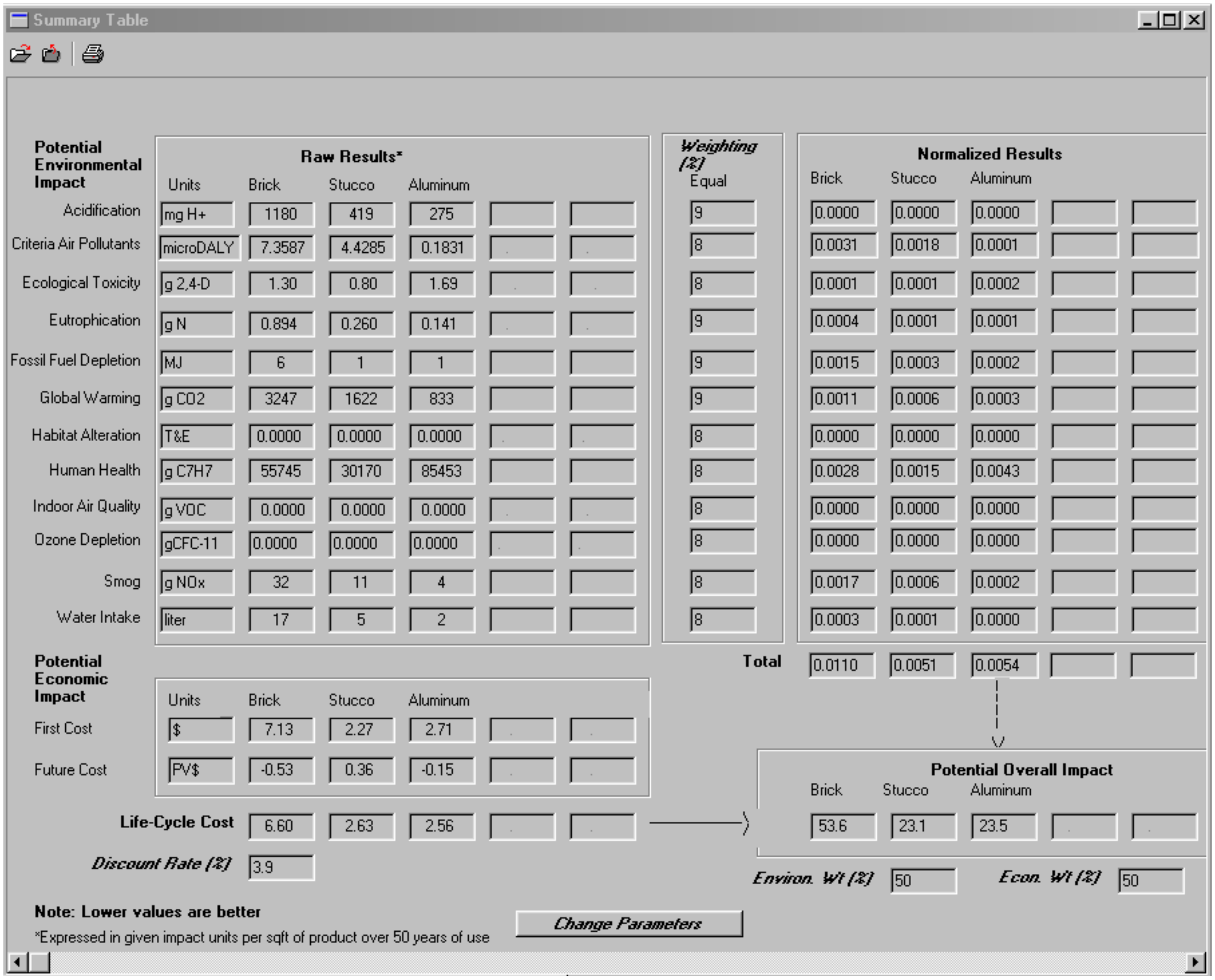
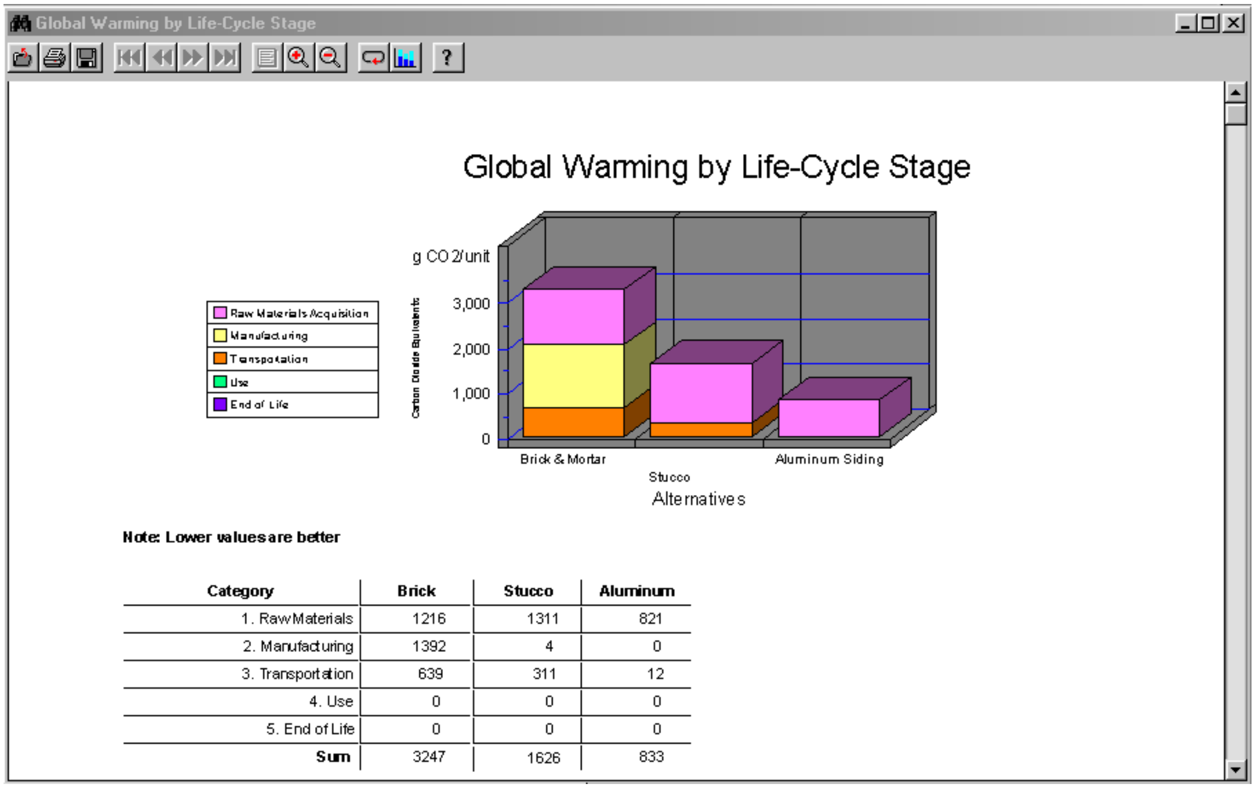
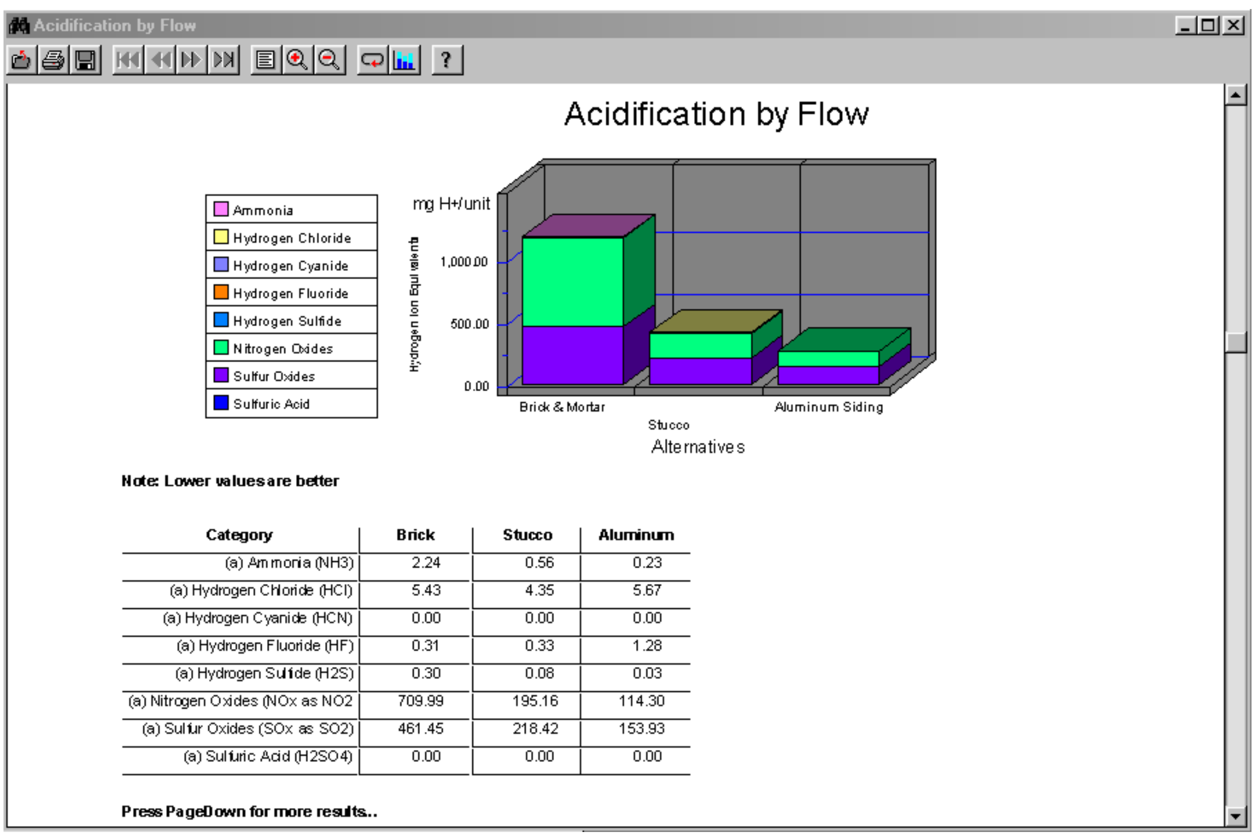


Figure 4.11 Viewing BEES Summary Table



Category	Brick	Stucco	Aluminum
1. Raw Materials	1216	1311	821
2. Manufacturing	1392	4	0
3. Transportation	639	311	12
4. Use	0	0	0
5. End of Life	0	0	0
Sum	3247	1626	833

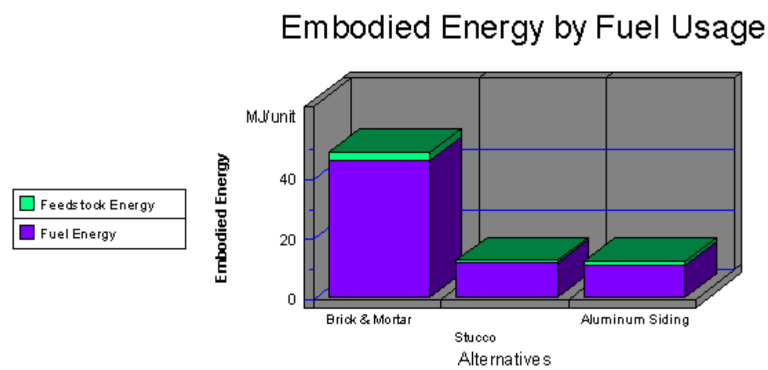
Figure 4.12 Viewing BEES Environmental Impact Category Performance Results by Life-Cycle Stage



Category	Brick	Stucco	Aluminum
(a) Ammonia (NH3)	2.24	0.56	0.23
(a) Hydrogen Chloride (HCl)	5.43	4.35	5.67
(a) Hydrogen Cyanide (HCN)	0.00	0.00	0.00
(a) Hydrogen Fluoride (HF)	0.31	0.33	1.28
(a) Hydrogen Sulfide (H2S)	0.30	0.08	0.03
(a) Nitrogen Oxides (NOx as NO2	709.99	195.16	114.30
(a) Sulfur Oxides (SOx as SO2)	461.45	218.42	153.93
(a) Sulfuric Acid (H2SO4)	0.00	0.00	0.00

Press PageDown for more results..

Figure 4.13 Viewing BEES Environmental Impact Category Performance Results by Flow



Category	Brick	Stucco	Aluminum
Feedstock Energy	2.70	0.81	1.28
Fuel Energy	45.69	11.49	10.80
Sum	48.39	12.30	12.08

Figure 4.14 Viewing BEES Embodied Energy Results

Criteria Air Pollutants by Flow (micro disability-adjusted life years/unit)

Category	Brick	Stucco	Aluminum
(a) Nitrogen Oxides (NOx as NO2	0.04	0.01	0.01
(a) Particulates (greater than	0.00	0.00	0.00
(a) Particulates (PM 10)	0.00	0.00	0.00
(a) Particulates (unspecified)	7.19	4.36	0.13
(a) Sulfur Oxides (SOx as SO2)	0.13	0.06	0.04
Sum	7.36	4.43	0.18

Criteria Air Pollutants by Life-Cycle Stage (micro disability-adjusted life years/unit)

Category	Brick	Stucco	Aluminum
1. Raw Materials	6.07	4.39	0.18
2. Manufacturing	1.22	0.00	0.00
3. Transportation	0.07	0.04	0.00
4. Use	0.00	0.00	0.00
5. End of Life	0.00	0.00	0.00
Sum	7.36	4.43	0.18

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	No. Impacts	Environ-mental Data File Name	Economic Data Code
Slab on Grade	Generic 100 % Portland Cement	12	A1030A	A1030,A0
Slab on Grade	Generic 15 % Fly Ash Cement	12	A1030B	A1030,B0
Slab on Grade	Generic 20 % Fly Ash Cement	12	A1030C	A1030,C0
Slab on Grade	Generic 20 % Slag Cement	12	A1030D	A1030,D0
Slab on Grade	Generic 35 % Slag Cement	12	A1030E	A1030,E0
Slab on Grade	Generic 50 % Slag Cement	12	A1030F	A1030,F0
Slab on Grade	Generic 5 % Limestone Cement	12	A1030G	A1030,G0
Slab on Grade	Generic 10 % Limestone Cement	12	A1030H	A1030,H0
Slab on Grade	Generic 20 % Limestone Cement	12	A1030I	A1030,I0
Slab on Grade	Lafarge Silica Fume Cement	12	A1030J	A1030,J0
Slab on Grade	ISG IP Cement	12	A1030K	A1030,K0
Slab on Grade	Lafarge NewCem Slag Cement (20 %)	12	A1030L	A1030,L0
Slab on Grade	Lafarge NewCem Slag Cement (35 %)	12	A1030M	A1030,M0
Slab on Grade	Lafarge NewCem Slag Cement (50 %)	12	A1030N	A1030,N0
Slab on Grade	Generic 35 % Fly Ash Cement	12	A1030O	A1030,O0
Slab on Grade	Lafarge Portland Type I Cement	12	A1030P	A1030,P0
Basement Walls	Generic 100 % Portland Cement	12	A2020A	A2020,A0
Basement Walls	Generic 15 % Fly Ash Cement	12	A2020B	A2020,B0
Basement Walls	Generic 20 % Fly Ash Cement	12	A2020C	A2020,C0
Basement Walls	Generic 20 % Slag Cement	12	A2020D	A2020,D0
Basement Walls	Generic 35 % Slag Cement	12	A2020E	A2020,E0
Basement Walls	Generic 50 % Slag Cement	12	A2020F	A2020,F0
Basement Walls	Generic 5 % Limestone Cement	12	A2020G	A2020,G0
Basement Walls	Generic 10 % Limestone Cement	12	A2020H	A2020,H0
Basement Walls	Generic 20 % Limestone Cement	12	A2020I	A2020,I0
Basement Walls	Lafarge Silica Fume Cement	12	A2020J	A2020,J0
Basement Walls	ISG IP Cement	12	A2020K	A2020,K0
Basement Walls	Lafarge NewCem Slag Cement (20 %)	12	A2020L	A2020,L0
Basement Walls	Lafarge NewCem Slag Cement (35 %)	12	A2020M	A2020,M0
Basement Walls	Lafarge NewCem Slag Cement (50 %)	12	A2020N	A2020,N0
Basement Walls	Lafarge BlockSet	12	A2020O	A2020,O0
Basement Walls	Lafarge Portland Type I Cement	12	A2020P	A2020,P0
Beams	Generic 100 % Portland Cement 4KSI	12	B1011A	B1011,A0
Beams	Generic 15 % Fly Ash Cement 4KSI	12	B1011B	B1011,B0
Beams	Generic 20 % Fly Ash Cement 4KSI	12	B1011C	B1011,C0
Beams	Generic 20 % Slag Cement 4KSI	12	B1011D	B1011,D0
Beams	Generic 35 % Slag Cement 4KSI	12	B1011E	B1011,E0
Beams	Generic 50 % Slag Cement 4KSI	12	B1011F	B1011,F0
Beams	Generic 5 % Limestone Cement 4KSI	12	B1011G	B1011,G0
Beams	Generic 10 % Limestone Cement 4KSI	12	B1011H	B1011,H0
Beams	Generic 20 % Limestone Cement 4KSI	12	B1011I	B1011,I0
Beams	Generic 100 % Portland Cement 5KSI	12	B1011J	B1011,J0
Beams	Generic 15 % Fly Ash Cement 5KSI	12	B1011K	B1011,K0

Beams	Generic 20 % Fly Ash Cement 5KSI	12	B1011L	B1011,L0
Beams	Generic 20 % Slag Cement 5KSI	12	B1011M	B1011,M0
Beams	Generic 35 % Slag Cement 5KSI	12	B1011N	B1011,N0
Beams	Generic 50 % Slag Cement 5KSI	12	B1011O	B1011,O0
Beams	Generic 5 % Limestone Cement 5KSI	12	B1011P	B1011,P0
Beams	Generic 10 % Limestone Cement 5KSI	12	B1011Q	B1011,Q0
Beams	Generic 20 % Limestone Cement 5KSI	12	B1011R	B1011,R0
Beams	Lafarge Silica Fume Cement (4KSI)	12	B1011S	B1011,S0
Beams	ISG IP Cement 4KSI	12	B1011T	B1011,T0
Beams	Lafarge NewCem Slag Cement 4KSI (20 %)	12	B1011U	B1011,U0
Beams	Lafarge NewCem Slag Cement 4KSI (35 %)	12	B1011V	B1011,V0
Beams	Lafarge NewCem Slag Cement 4KSI (50 %)	12	B1011W	B1011,W0
Beams	Lafarge Silica Fume Cement (5KSI)	12	B1011X	B1011,X0
Beams	ISG IP Cement 5KSI	12	B1011Y	B1011,Y0
Beams	Lafarge NewCem Slag Cement 5KSI (20 %)	12	B1011Z	B1011,Z0
Beams	Lafarge NewCem Slag Cement 5KSI (35 %)	12	B1011AA	B1011,AA0
Beams	Lafarge NewCem Slag Cement 5KSI (50 %)	12	B1011BB	B1011,BB0
Beams	Lafarge Portland Type I Cement 4KSI	12	B1011CC	B1011,CC0
Beams	Lafarge Portland Type I Cement 5KSI	12	B1011DD	B1011,DD0
Columns	Generic 100 % Portland Cement 4KSI	12	B1012A	B1012,A0
Columns	Generic 15 % Fly Ash Cement 4KSI	12	B1012B	B1012,B0
Columns	Generic 20 % Fly Ash Cement 4KSI	12	B1012C	B1012,C0
Columns	Generic 20 % Slag Cement	12	B1012D	B1012,D0
Columns	Generic 35 % Slag Cement 4KSI	12	B1012E	B1012,E0
Columns	Generic 50 % Slag Cement 4KSI	12	B1012F	B1012,F0
Columns	Generic 5 % Limestone Cement 4KSI	12	B1012G	B1012,G0
Columns	Generic 10 % Limestone Cement 4KSI	12	B1012H	B1012,H0
Columns	Generic 20 % Limestone Cement 4KSI	12	B1012I	B1012,I0
Columns	Generic 100 % Portland Cement 5KSI	12	B1012J	B1012,J0
Columns	Generic 15 % Fly Ash Cement 5KSI	12	B1012K	B1012,K0
Columns	Generic 20 % Fly Ash Cement 5KSI	12	B1012L	B1012,L0
Columns	Generic 20 % Slag Cement 5KSI	12	B1012M	B1012,M0
Columns	Generic 35 % Slag Cement 5KSI	12	B1012N	B1012,N0
Columns	Generic 50 % Slag Cement 5KSI	12	B1012O	B1012,O0
Columns	Generic 5 % Limestone Cement 5KSI	12	B1012P	B1012,P0
Columns	Generic 10 % Limestone Cement 5KSI	12	B1012Q	B1012,Q0
Columns	Generic 20 % Limestone Cement 5KSI	12	B1012R	B1012,R0
Columns	Lafarge Silica Fume Cement (4KSI)	12	B1012S	B1012,S0
Columns	ISG IP Cement 4KSI	12	B1012T	B1012,T0
Columns	Lafarge NewCem Slag Cement 4KSI (20 %)	12	B1012U	B1012,U0
Columns	Lafarge NewCem Slag Cement 4KSI (35 %)	12	B1012V	B1012,V0
Columns	Lafarge NewCem Slag Cement 4KSI (50 %)	12	B1012W	B1012,W0
Columns	Lafarge Silica Fume Cement (5KSI)	12	B1012X	B1012,X0
Columns	ISG IP Cement 5KSI	12	B1012Y	B1012,Y0
Columns	Lafarge NewCem Slag Cement 5KSI (20 %)	12	B1012Z	B1012,Z0
Columns	Lafarge NewCem Slag Cement 5KSI (35 %)	12	B1012AA	B1012,AA0
Columns	Lafarge NewCem Slag Cement 5KSI (50 %)	12	B1012BB	B1012,BB0
Columns	Lafarge Portland Type I Cement 4KSI	12	B1012CC	B1012,CC0
Columns	Lafarge Portland Type I Cement 5KSI	12	B1012DD	B1012,DD0
Roof Sheathing	Generic Oriented Strand Board Sheathing	8	B1020A	B1020,A0
Roof Sheathing	Generic Plywood Sheathing	8	B1020B	B1020,B0

Exterior Wall Finishes	Generic Brick & Mortar	12	B2011A	B2011,A0
Exterior Wall Finishes	Generic Stucco	12	B2011B	B2011,B0
Exterior Wall Finishes	Generic Aluminum Siding	12	B2011C	B2011,C0
Exterior Wall Finishes	Generic Cedar Siding	8	B2011D	B2011,D0
Exterior Wall Finishes	Generic Vinyl Siding	8	B2011E	B2011,E0
Exterior Wall Finishes	Trespa Meteon	12	B2011F	B2011,F0
Exterior Wall Finishes	ISG Brick & Fly Ash Mortar	12	B2011G	B2011,G0
Exterior Wall Finishes	ISG 3-coat Stucco with Fly Ash	12	B2011H	B2011,H0
Exterior Wall Finishes	ISG 1-coat Stucco with Fly Ash	12	B2011I	B2011,I0
Wall Insulation	Generic R-13 Blown Cellulose	8	B2012A	B2012,A0
Wall Insulation	Generic R-11 Fiberglass Batt	8	B2012B	B2012,B0
Wall Insulation	Generic R-15 Fiberglass Batt	8	B2012C	B2012,C0
Wall Insulation	Generic R-12 Blown Mineral Wool	8	B2012D	B2012,D0
Wall Insulation	Generic R-13 Fiberglass Batt	8	B2012E	B2012,E0
Framing	Generic Steel Framing	8	B2013A	B2013,A0
Framing	Generic Wood Framing--Treated	8	B2013B	B2013,B0
Framing	Generic Wood Framing--Untreated	12	B2013C	B2013,C0
Wall Sheathing	Generic Oriented Strand Board Sheathing	8	B1020A	B2015,A0
Wall Sheathing	Generic Plywood Sheathing	8	B1020B	B2015,B0
Roof Coverings	Generic Asphalt Shingles--Black	12	B3011A	B3011,A0
Roof Coverings	Generic Asphalt Shingles--Coral	12	B3011A	B3011,A0
Roof Coverings	Generic Asphalt Shingles--Dk Brown	12	B3011A	B3011,A0
Roof Coverings	Generic Asphalt Shingles--Dk Gray	12	B3011A	B3011,A0
Roof Coverings	Generic Asphalt Shingles--Green	12	B3011A	B3011,A0
Roof Coverings	Generic Asphalt Shingles--Lt Brown	12	B3011A	B3011,A0
Roof Coverings	Generic Asphalt Shingles--Lt Gray	12	B3011A	B3011,A0
Roof Coverings	Generic Asphalt Shingles--Tan	12	B3011A	B3011,A0
Roof Coverings	Generic Asphalt Shingles--White	12	B3011A	B3011,A0
Roof Coverings	Generic Asphalt Shingles	12	B3011A	B3011,A0
Roof Coverings	Generic Clay Tile	12	B3011B	B3011,B0
Roof Coverings	Generic Clay Tile--Red	12	B3011B	B3011,B0
Roof Coverings	Generic Fiber Cement--Lt Gray/Lt Brown	12	B3011C	B3011,C0
Roof Coverings	Generic Fiber Cement Shingles	12	B3011C	B3011,C0
Roof Coverings	Generic Fiber Cement--Dk Color	12	B3011C	B3011,C0
Roof Coverings	Generic Fiber Cement--Med Color	12	B3011C	B3011,C0
Ceiling Insulation	Generic R-30 Blown Cellulose Insulation	8	B3012A	B3012,A0
Ceiling Insulation	Generic R-30 Fiberglass Batt Insulation	8	B3012B	B3012,B0
Ceiling Insulation	Generic R-30 Blown Mineral Wool Insulation	8	B3012C	B3012,C0
Ceiling Insulation	Generic R-30 Blown Fiberglass Insulation	8	B3012D	B3012,D0
Partitions	Generic Drywall	12	C1011A	C1011,A0
Partitions	Trespa Virtuon	12	C3030A	C1011,B0
Partitions	Trespa Athlon	12	C3030B	C1011,C0
Fabricated Toilet Partitions	Trespa Virtuon	12	C3030A	C1031,A0
Fabricated Toilet Partitions	Trespa Athlon	12	C3030B	C1031,B0
Lockers	Trespa Virtuon	12	C3030A	C1030,A0
Lockers	Trespa Athlon	12	C3030B	C1030,B0
Wall Finishes to Interior Walls	Generic Virgin Latex Paint	8	C3012A	C3012,A0
Wall Finishes to	Generic Recycled Latex Paint	8	C3012B	C3012,B0

Interior Walls				
Floor Coverings	Generic Ceramic Tile w/ Recycled Glass	12	C3020A	C3020,A0
Floor Coverings	Generic Linoleum	12	C3020B	C3020,B0
Floor Coverings	Generic Vinyl Composition Tile	12	C3020C	C3020,C0
Floor Coverings	Generic Composite Marble Tile	12	C3020D	C3020,D0
Floor Coverings	Generic Terrazzo	12	C3020E	C3020,E0
Floor Coverings	Generic Nylon Carpet	12	C3020F	C3020,F0
Floor Coverings	Generic Wool Carpet	12	C3020G	C3020,G0
Floor Coverings	Generic Recycled PET Carpet	12	C3020H	C3020,H0
Floor Coverings	Generic Nylon Carpet Tile/Low-VOC Glue	12	C3020I	C3020,I0
Floor Coverings	Generic Wool Carpet Tile/Low-VOC Glue	12	C3020J	C3020,J0
Floor Coverings	Generic Recycled PET Carpet Tile/Low-VOC	12	C3020K	C3020,K0
Floor Coverings	Generic Nylon Carpet Broadloom/Std.Glue	8	C3020L	C3020,L0
Floor Coverings	Generic Wool Carpet Broadloom/Std.Glue	8	C3020M	C3020,M0
Floor Coverings	Generic Recycled PET Carpet Brdlm/Std.Gl	8	C3020N	C3020,N0
Floor Coverings	Generic Nylon Carpet Broadloom/Low-VOC	8	C3020O	C3020,O0
Floor Coverings	Generic Wool Carpet Broadloom/Low-VOC	8	C3020P	C3020,P0
Floor Coverings	Generic Recycled PET Carpet Brdlm/LowVOC	8	C3020Q	C3020,Q0
Floor Coverings	Forbo Linoleum/Std Glue	12	C3020R	C3020,R0
Floor Coverings	Shaw Ecoworx Carpet Tile	12	C3020S	C3020,S0
Floor Coverings	Universal Textile Tech Petrol Backed Carpet	12	C3020T	C3020,T0
Floor Coverings	Universal Textile Tech Soy Backed Carpet	12	C3020U	C3020,U0
Floor Coverings	C&A Floorcoverings, ER3 Carpet Tile	12	C3020X	C3020,X0
Floor Coverings	Bentley Prince Street, Hyperion	12	C3020Y	C3020,Y0
Floor Coverings	Bentley Prince Street, Mercator	12	C3020Z	C3020,Z0
Floor Coverings	Interface Flooring Systems, Prairie School	12	C3020AA	C3020,AA0
Floor Coverings	Interface Flooring Systems, Sabi	12	C3020BB	C3020,BB0
Floor Coverings	Interface Flooring Systems, Transformation	12	C3020CC	C3020,CC0
Floor Coverings	J&J Industries, Certificate- SBR Latex	12	C3020DD	C3020,DD0
Floor Coverings	J&J Industries, Certificate- LIFESPAN*MG	12	C3020EE	C3020,EE0
Floor Coverings	Mohawk Regents Row	12	C3020FF	C3020,FF0
Floor Coverings	Mohawk Meritage	12	C3020GG	C3020,GG0
Floor Coverings	Natural Cork Parquet Tile	12	C3020HH	C3020,HH0
Floor Coverings	Natural Cork Floating Floor Plank	12	C3020II	C3020,II0
Floor Coverings	Forbo Linoleum/No-VOC Glue	12	C3020NN	C3020,NN0
Ceiling Finishes	Trespa Virtuon	12	C3030A	C3030,A0
Ceiling Finishes	Trespa Athlon	12	C3030B	C3030,B0
Fixed Casework	Trespa Virtuon	12	C3030A	E2010,A0
Fixed Casework	Trespa Athlon	12	C3030B	E2010,B0
Chairs	Herman Miller Aeron Office Chair	12	E2020A	E2020,A0
Chairs	Herman Miller Ambi Office Chair	12	E2020B	E2020,B0
Chairs	Generic Office Chair	12	E2020B	E2020,B0
Table Tops, Counter Tops, Shelving	Trespa Toplab Plus	12	E2021A	E2021,A0
Table Tops, Counter Tops, Shelving	Trespa Athlon	12	C3030B	E2021,B0
Soil Treatment	Lafarge CKD Soil Enhancer	12	G1030A	G1030,A0
Soil Treatment	Generic Portland Cement	12	G1030B	G1030,B0
Parking Lot Paving	Generic 100 % Portland Cement	12	G2022A	G2022,A0
Parking Lot Paving	Generic 15 % Fly Ash Cement	12	G2022B	G2022,B0

Parking Lot Paving	Generic 20 % Fly Ash Cement	12	G2022C	G2022,C0
Parking Lot Paving	Asphalt with GSB88 Seal-Bind Maintenance	12	G2022D	G2022,D0
Parking Lot Paving	Asphalt with Cement Maintenance	12	G2022E	G2022,E0
Parking Lot Paving	ISG 100 % IP Cement	12	G2022F	G2022,F0
Parking Lot Paving	Lafarge Portland Type I Cement	12	G2022G	G2022,G0
Transformer Oil	BioTrans Transformer Oil	12	G4010A	G4010,A0
Transformer Oil	Generic Mineral Oil Based Transformer Oil	12	G4010B	G4010,B0
Transformer Oil	Generic Silicone Based Transformer Oil	12	G4010C	G4010,C0

5. Future Directions

Development of the BEES tool does not end with the release of version 3.0. Plans to expand and refine BEES include releasing updates every 18 months to 24 months with model and software enhancements as well as expanded product coverage. Listed below are a number of directions for future research that have been proposed in response to obvious needs, feedback from BEES 2.0 users, and peer review comments:[123]

Proposed Model Enhancements

- Combine building products to permit comparative analyses of entire building components, assemblies, and ultimately entire buildings
- Conduct and apply research leading to the refinement of indoor air assessment and to the expansion of habitat alteration assessment to include all life cycle stages
- Characterize uncertainty in the underlying environmental and cost data, and reflect this uncertainty in BEES performance scores
- Update the BEES LCA methodology in line with future advances in the evolving LCA field

Proposed Data Enhancements

- Continue to solicit cooperation from industry to include more manufacturer-specific building products in future versions of BEES (this effort is known as the *BEES Please* program)
- 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 more accurate assessment 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 5 years, revisit products included in previous BEES releases for updates to their environmental and cost data
- Evaluate biobased products using BEES to assist the Federal procurement community in carrying out the biobased purchasing mandate of the *2002 Farm Security and Rural Investment Act* (Public Law 107-171)

Proposed Software Enhancements

- Make streamlined BEES results available on a web-based platform
- Add feature soliciting product quantities from the BEES user to automate the process of comparing BEES scores across building elements
- Add feature permitting import and export of life cycle inventories
- 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

[123] P. Hofstetter et al., *User Preferences for Life-Cycle Decision Support Tools: Evaluation of a Survey of BEES Users*, NISTIR 6874, National Institute of Standards and Technology, Washington, DC, July 2002; and M.A. Curran et al., *BEES 2.0, Building for Environmental and Economic Sustainability: Peer Review Report*, NISTIR 6865, National Institute of Standards and Technology, Washington, DC, 2002.

Appendix A. BEES Computational Algorithms

A.1 Environmental Performance

BEES environmental performance scores are derived as follows.

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

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

$$IAScore_{jk} = \frac{IA_{jk} * IVwt_k}{Norm_k} * 100, \text{ where}$$

$IVwt_k$ = impact category importance weight for impact k;
$Norm_k$ = normalization value for impact k (see section 2.1.3.3);
IA_{jk} = characterized score for alternative j with respect to impact k:

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

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 BEES environmental performance data file (See section 4.4.);
$IAfactor_i$ = impact assessment characterization 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:

$$LCScore_{sj} = \sum_{i=1}^{n} IAScore_{jk} * IPercent_{ij} * LCPercent_{sij}, \text{ where}$$

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

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

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

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

A.2 Economic Performance

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

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

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

A.3 Overall Performance

The overall performance scores are derived as follows:

$$Score_j = \left[(EnvWt * \frac{EnvScore_j}{\sum_{j=1}^{n} EnvScore_j}) + (EconWt * \frac{LCC_j}{\sum_{j=1}^{n} LCC_j}) \right] * 100, \text{ where}$$

$Score_j$ = 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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