MEASURING THE LIFE-CYCLE ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF CONCRETE: THE BEES APPROACH

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Abstract

Society is increasingly concerned about the implications of manufactured products for the environment, public health, and future costs. How does a product affect global warming, smog, fossil fuel depletion, and human toxicity? How about its costs over time? Building for Environmental and Economic Sustainability (BEES) addresses these questions by measuring the life-cycle environmental and economic performance of construction products. Used by thousands of designers worldwide, BEES measures environmental performance using the life-cycle assessment approach specified in the ISO 14040 series of standards. All stages in the life of a product are analyzed: raw material acquisition, manufacture, transportation, installation, use, and recycling and waste management. Twelve environmental impacts are assessed: global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, smog, ozone depletion, ecological toxicity, human health, criteria air pollutants, and water intake. Economic performance is measured using the American Society for Testing and Materials, International (ASTM) standard life-cycle cost method, which covers the costs of initial investment, replacement, operation, maintenance and repair, and disposal. Environmental performance and economic performance are combined into an overall performance measure using the ASTM standard for Multiattribute Decision Analysis. The paper will explain the BEES approach and illustrate its application to alternative concrete products with and without supplementary cementitious materials.

1. Introduction

Worldwide, about one ton of concrete is produced each year for every human being in the world (some 6 billion tons per year), making concrete one of the world's most popular construction materials. The construction market in Asia is the leading market in the world, with an estimated value of about 1.2 trillion U.S. dollars (USD). Japan and China continue to lead the region's construction industry. Europe's construction market is estimated at 1.1 trillion USD. The United States, with the world's healthiest market, and Canada, with a hot market of its own, put North America at about 1 trillion USD. Latin America, led by Brazil and Mexico, places South America next with a market of about 300 billion USD. The construction market in the Middle East is about 150 billion USD, followed by Africa with a market of about 60 billion USD. The world construction market is estimated to be about 4 trillion USD.

The amount of world trade dealing with concrete is estimated to be about 13 to 14 trillion USD. This includes various aspects dealing with the production and use of concrete. The magnitude of this number shows that the wave of economic globalization has an impact on the concrete industry, as concrete represents the basic building material for the development and maintenance of the civil infrastructure facilities that are an integral component of an economy. About 1% of the world population has jobs that directly relate to the concrete construction industry.

On the basis of the use of concrete per person per year, the world's biggest market for concrete is North America. In the United States, concrete is used in excess of 2.5 tons per person per year. Gross product of concrete and cement manufacturing revenue exceeds 35 billion USD annually. In addition to concrete and cement manufacturing, the industry includes aggregates and material suppliers, designers, contractors, and repair and maintenance companies. Over 2 million jobs relate to the U.S. concrete construction industry. It is estimated that the production and consumption of concrete will see a rise of about 1% per year for the next three to five years.

Sustainability is becoming an increasingly important issue for concrete construction. This paper presents an overview of the approach taken by the Building for Environmental and Economic Sustainability (BEES) program to address some of these concerns.

The U.S. National Institute of Standards and Technology (NIST) Healthy and Sustainable Buildings Program began the BEES project in 1994. The purpose of BEES is to develop and implement a systematic methodology for selecting construction 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 used by over 9500 people worldwide, and comes complete with actual environmental and economic performance data for a number of concrete construction products [1]. The objective is a cost-effective reduction in construction-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 $240 billion in products and services they purchase each year, including construction 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. BEES Methodology

The BEES methodology takes a multidimensional, life-cycle approach. That is, it considers multiple environmental and economic impacts over the entire life of the construction product. Considering multiple impacts and life-cycle stages is necessary because product selection decisions based on single impacts or stages could obscure other impacts or stages 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 construction 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 [2]. 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 (MADA) [3]. For the entire BEES analysis, products are defined and classified based on UNIFORMAT II, the ASTM standard classification for construction elements [4].

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 construction 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 releases toxic chemicals during its manufacture. 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. The *goal and scope definition* step defines the context for the study, including its purpose and units of comparison. The purpose of BEES is to assess the life-cycle environmental and economic performance of construction products sold in the United States. The basis for all units of comparison is known as the *functional unit*, defined so that the products compared are true substitutes for one another. In the BEES model, the functional unit for concrete slabs, walls, and paving is 0.09 m^2 (1 ft^2) of product service for 50 years, while the functional unit for concrete beams and columns is 0.76 cubic meters (1 cubic yard) of product service for 50 years. The functional unit provides the critical reference point to which all quantities are scaled. All product alternatives are assumed to meet minimum technical performance requirements (e.g., hydration and strength development).

The *inventory analysis* step identifies and quantifies the environmental inputs and outputs associated with a product over its entire life cycle. As shown in Fig. 1, environmental inputs for any production process include water, energy, and other raw materials; outputs include releases to air, land, and water. In the LCA inventory analysis step, production processes for any given product are identified, as illustrated in Fig. 2, and the environmental inputs and outputs for each are summed. However, inventory analysis is only an intermediate step because it is not these summed 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*. The BEES impact assessment model uses state-of-the-art, peer-reviewed impact assessment methods recently developed by the U.S. EPA Office of Research and Development and known as TRACI [5]. Twelve environmental impacts are assessed: global warming potential, acidification potential, eutrophication potential, fossil fuel depletion, indoor air quality, habitat alteration, criteria air pollutants, human health, smog, ozone depletion, ecological toxicity, and water intake.

Once impacts have been assessed, the resulting impact category performance measures are expressed in non-commensurate units. Global warming is expressed in carbon dioxide equivalents, acidification in hydrogen ion equivalents, eutrophication in nitrogen equivalents, and so on. In order to assist in the next LCA step (interpretation), performance measures are often placed on the same scale through normalization. BEES normalizes based on data EPA developed for use with its TRACI impact assessment methods [6]. For each impact, the data estimate its performance at the U.S. level, yielding a yardstick against which to evaluate the *significance* of product-specific impacts. These normalization data are commonly referred to as “footprint” data. By expressing each product-specific impact measure in terms of its contribution to its respective U.S. footprint, all measures are all reduced to the same scale, allowing comparison across impacts.

Finally, at the *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 into a single score.

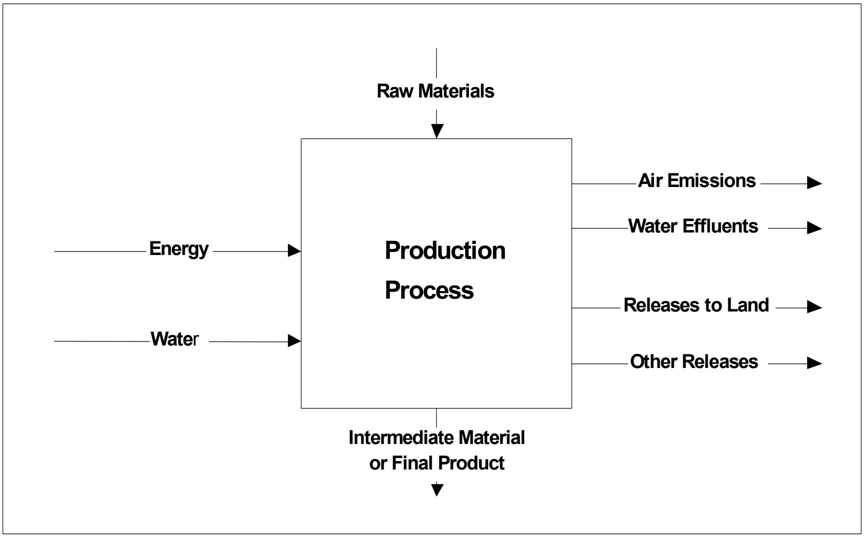


Fig. 1: BEES inventory data categories

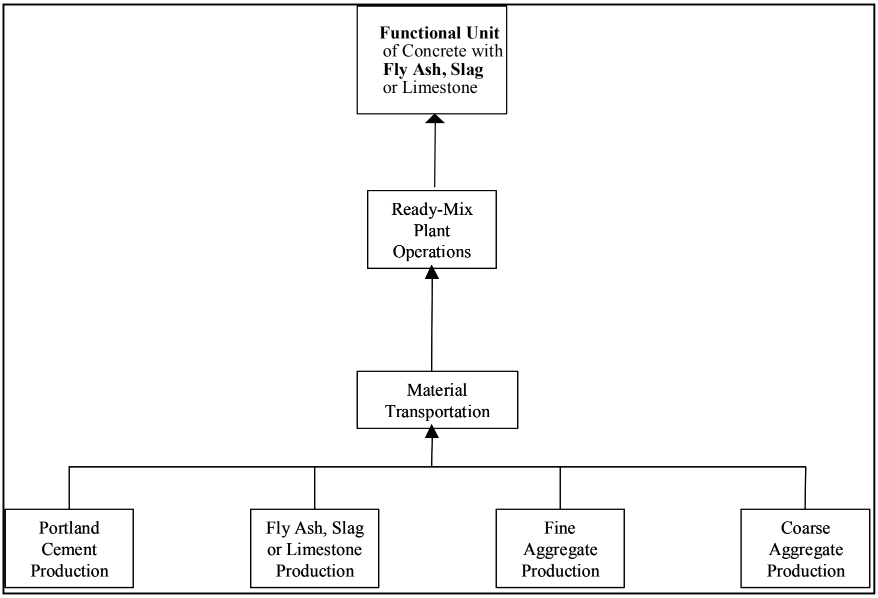


Fig. 2: Concrete production processes

Impact scores may be synthesized by weighting results for 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. Note that in BEES, synthesis of impact scores into a single score is optional.

2.2. Economic performance

Measuring the economic performance of construction products is more straightforward than measuring environmental performance. Published economic performance data are readily available, and there are well-established standard methods for conducting economic performance evaluations. The most appropriate method for measuring the economic performance of construction products is the life-cycle cost method. BEES follows the ASTM standard method for life-cycle costing of construction-related investments [7].

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 LCA, the time period begins with raw material acquisition and ends with product end-of-life. Economic performance, on the other hand, is evaluated over a fixed period (known as the study period) that begins with the purchase and installation of the product and ends at some point in the future that does not necessarily correspond with product end-of-life.

Economic performance is evaluated beginning at product purchase and installation because this is when out-of-pocket costs begin to be incurred and investment decisions are made based upon out-of-pocket costs. The study period ends at a fixed date in the future. For a private investor, its length is set at the period of product or facility ownership. For society as a whole, the study period length is often set at the useful life of the longest-lived product alternative. However, when 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. 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 parking lot paving, 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. Costs typically include purchase, installation, maintenance, repair, and replacement costs. 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.

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. 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. While the user may specify any reasonable discount rate, the BEES tool defaults to a real rate of 3.9%, the 2002 rate mandated by the U.S. Office of Management and Budget for most federal projects [8].

2.3. Overall performance

The BEES overall performance measure synthesizes the environmental and economic results into a single score, as illustrated in Fig. 3. 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 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 construction-related investments [3].

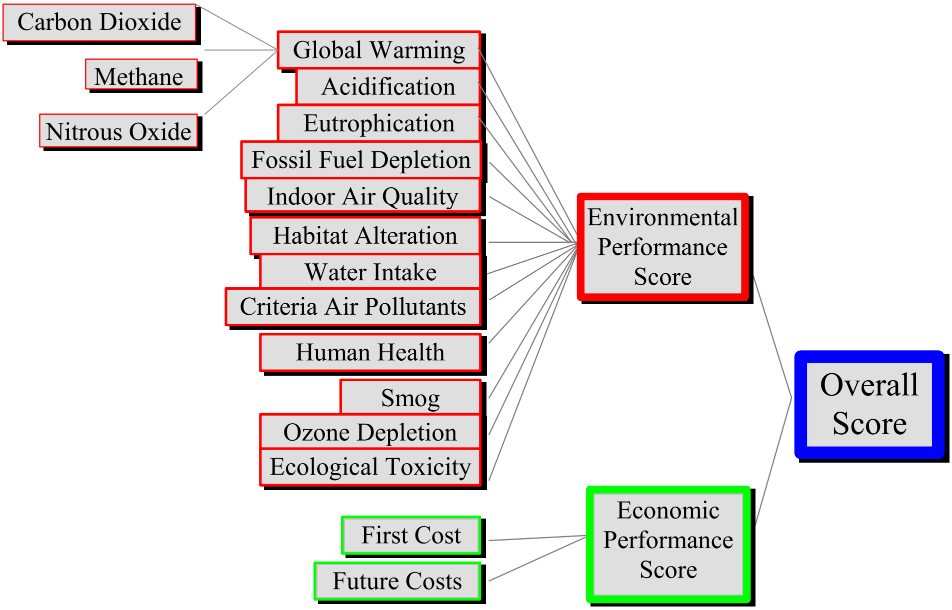


Fig. 3: Deriving the BEES overall performance score

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.

3. Case Example

How can the concrete industry use BEES to evaluate the life-cycle environmental and economic performance of its products? Over the years, cement producers have developed various blended cements to reduce the cost, heat generation, and presumably the environmental burden of concrete. For example, ground granulated blast furnace slag (referred to as GGBFS or “slag”), fly ash, and limestone have been 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 compressive strength development.

Let’s run through an example comparing concrete mixes with and without these supplementary materials. BEES includes life-cycle environmental and economic performance data for both generic (U.S. industry-average) concrete and manufacturer-specific concrete. These two data types allow for both comparison of “real” products against one another and against their hypothetical industry averages. Suppose we’re interested in the following concrete mixes for a residential concrete slab application, all with compressive strengths of 21 MPa and installed using plywood forms and steel reinforcing in quantities required for a 7.62-m (25-ft) span:

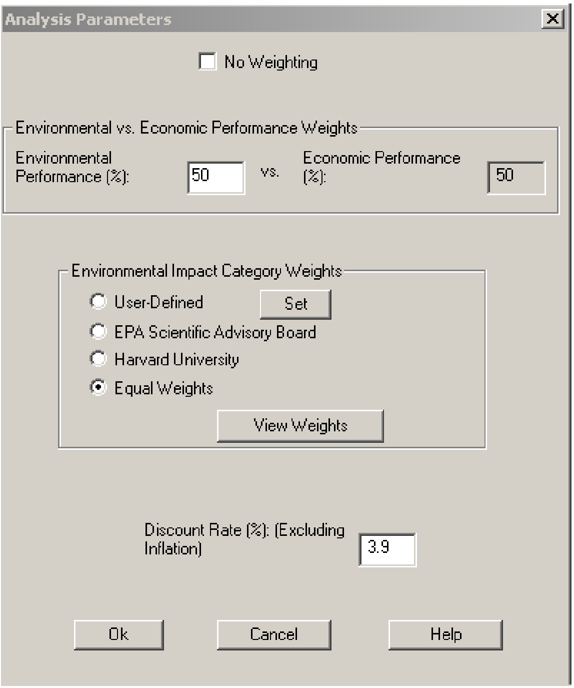
1. Generic concrete with cement consisting of 100% portland cement (referred to as 100% portland cement)
2. Generic blended cement concrete in which 20% of the portland cement, by mass fraction of cement, is replaced by limestone. Note that for this mix, more blended cement than usual is used in the concrete to achieve a strength equivalent to that for mixes with no limestone replacements (20% limestone cement)
3. Blended cement concrete manufactured by Lafarge North America, in which 10% of the portland cement, by mass fraction of cement, is replaced by silica fume (Lafarge silica fume) [9]
4. *NewCem* blended cement concrete manufactured by Lafarge North America, in which 50% of the portland cement, by mass fraction of cement, is replaced by ground granulated blast furnace slag (Lafarge NewCem (50%))
5. Generic blended cement concrete in which 35% of the portland cement, by mass fraction of cement, is replaced by fly ash (35% fly ash cement)

The first step is to set our analysis parameters using the BEES window shown in Fig. 4. If we do not wish to combine environmental and economic performance measures into a single score, we can select the “No Weighting” option and still compute disaggregated BEES results. Otherwise, we need to set importance weights. In this example, environmental performance and economic performance are of equal importance so both are set to 50%. Next, we need to set relative importance weights for the 12 environmental impact categories included in the BEES environmental performance score. We select the “Equal Weights” set, assigning equal importance to all impacts. Our last parameter is the real discount rate used to convert future concrete product costs to their equivalent present value. Here, we accept the default rate of 3.9% in real terms.

Next, we need to set a final parameter for each of our concrete slab alternatives – the transportation distance from the ready-mix plant to the construction site at which the concrete will be poured. This parameter lets BEES compute an environmental performance score accounting for the significance of using locally produced products. As illustrated in Fig. 5, a transportation distance of 80 km has been selected for the concrete alternatives used in the example.

After this, BEES can compute and display the results. Fig. 6 shows the BEES Environmental Performance Results displaying the weighted environmental performance scores for our example in graphical form. Lower values are better, with each product alternative's score denominated in percentage points representing the weighted contribution to the U.S. environmental footprint of 0.09 m^2 (1 ft^2) of the product over a 50-year use period. In this example, the product results are grouped into two tiers, with the 100% portland cement, 20% limestone cement, and Lafarge silica fume cement yielding slightly higher, or worse, scores (on the order of 0.014 percentage points) than both Lafarge NewCem (50%) and 35% fly ash cement (0.012 percentage points). The figure breaks down the weighted environmental score for each product by its 12 contributing, weighted impact scores. As shown, the weighted impact scores are fairly uniform across concrete mixes, as can be expected for product alternatives with predominately similar constituents. After all, cement—the material being partially replaced with supplementary materials—comprises only 10% to 15%, by mass fraction, of concrete.

Some may be surprised to see no significant difference between the BEES environmental performance scores for 100% portland cement, the traditional concrete mix, and one of the so-called "environmentally friendly" alternatives, 20% limestone cement. Upon closer examination, however, the reasons become clear. With 20% limestone cement, more blended cement than usual is used in the concrete to achieve a strength equivalent to that for mixes with no limestone replacements. Thus, while the limestone blend performs slightly better on ecological toxicity, global warming, and human health due to the limestone content, it performs worse on criteria air pollutants, primarily due to particulates released during limestone mining.



☐ No Weighting

Environmental vs. Economic Performance Weights

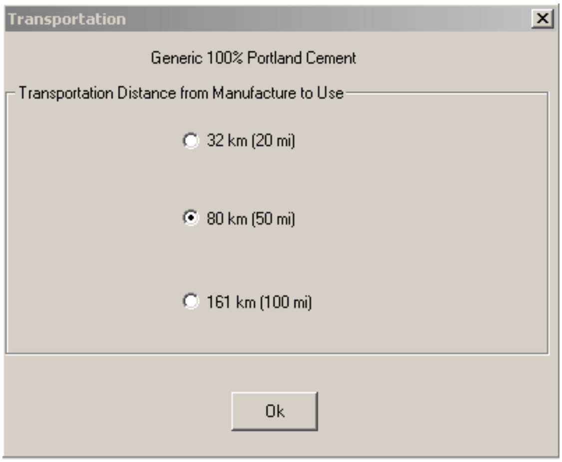
Environmental Performance (%): 50 vs. Economic Performance (%): 50

Environmental Impact Category Weights

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

Discount Rate (%): (Excluding Inflation) 3.9

Fig. 4: Setting BEES analysis parameters



Generic 100% Portland Cement

Transportation Distance from Manufacture to Use

○ 32 km (20 mi)
● 80 km (50 mi)
○ 161 km (100 mi)

Fig. 5: Setting product-specific parameters

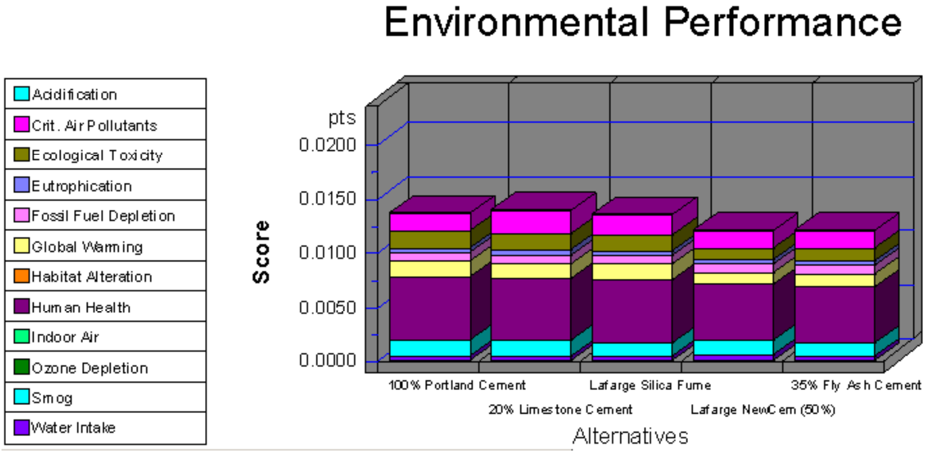


Fig. 6: Viewing BEES environmental performance results

Fig. 7 shows the BEES Economic Performance Results for our example, which plots first costs, discounted future costs, and their sum, the life-cycle cost expressed in present value dollars. Residential concrete slabs require no significant maintenance and repair costs over the BEES 50-year study period. Moreover, these products tend to last more than 50 years; BEES assumes a 75-year useful life for concrete slabs. In such cases where the product life exceeds the length of the study period, BEES *deducts* from the life-cycle cost a residual value representing the product value remaining at the end of the study period. That explains why you see a negative future cost in Fig. 7. Note that even though the residual value in year 50 is fully one-third of the first cost, once discounted to present value dollars it becomes very small.

The BEES overall performance score gives us a way to combine and balance the environmental and economic performance scores. Fig. 8 shows the BEES overall performance results based on our equal weighting of environmental and economic performance. It displays the overall performance score for each product alternative, which is the sum of its weighted environmental and economic performance scores. Since the environmental and economic performance results followed an identical pattern, with products essentially grouped into two tiers, the overall results follow the same pattern. Thus, based on the parameter values we set above, Lafarge NewCem (50%) and 35% fly ash cement are slightly preferable overall to 100% portland cement, 20% limestone cement, and Lafarge silica fume cement.

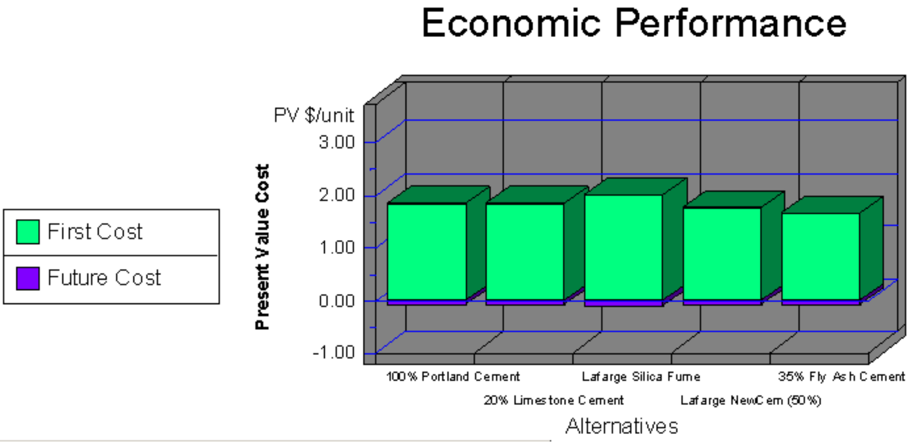


Fig. 7: Viewing BEES economic performance results

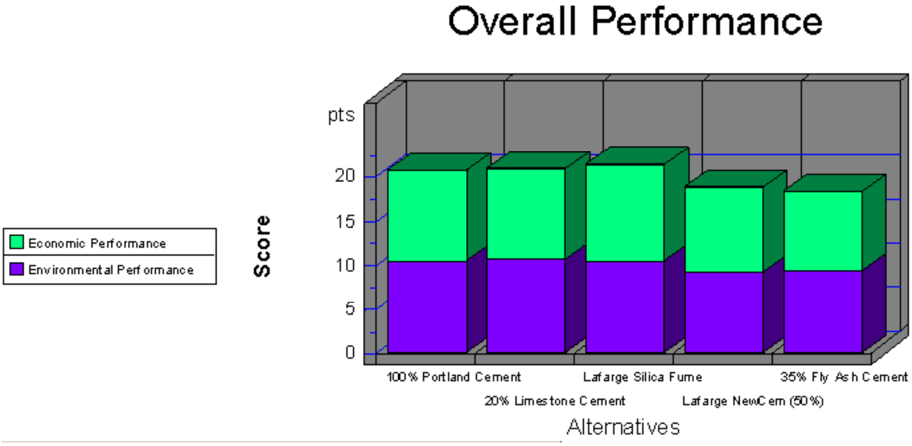


Fig. 8: Viewing BEES overall performance results

Some may be surprised to see no significant difference between the BEES environmental performance scores for 100% portland cement, the traditional concrete mix, and one of the so-called “environmentally friendly” alternatives, 20% limestone cement. Upon closer examination, however, the reasons become clear. With 20% limestone cement, more blended cement than usual is used in the concrete to achieve a strength equivalent to that for mixes with no limestone replacements. Thus, while the limestone blend performs slightly better on ecological toxicity, global warming, and human health due to the limestone content, it performs worse on criteria air pollutants, primarily due to particulates released during limestone mining.

In addition to the summary graphs described above, BEES offers detailed graphs for each environmental impact, broken down both by contributing flow and by contributing life-cycle stage. The detailed graphs help pinpoint the 'weak links' in products’ environmental life cycles. For example, Fig. 9 shows that for human health, the largest environmental impact for all products, cancer-causing dioxin air emissions—primarily caused by electricity production—constitute the largest contributing flow for all products from among the 215 flows tracked in BEES for their potential impact on human health. Similarly, Fig. 10 shows that for smog, the raw materials acquisition life-cycle stage contributes the most, by far, to all products’ smog impacts. This is primarily due to nitrogen oxide air emissions from fuel combustion necessary to power mining equipment.

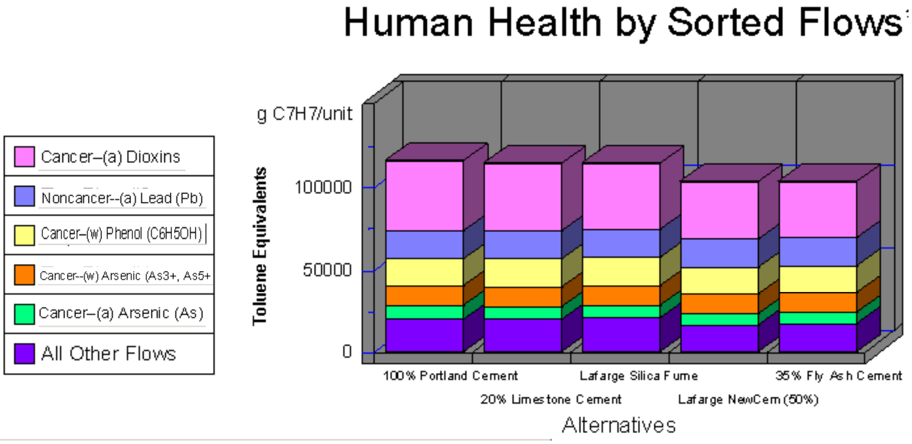


Fig. 9: Viewing BEES results by environmental flow

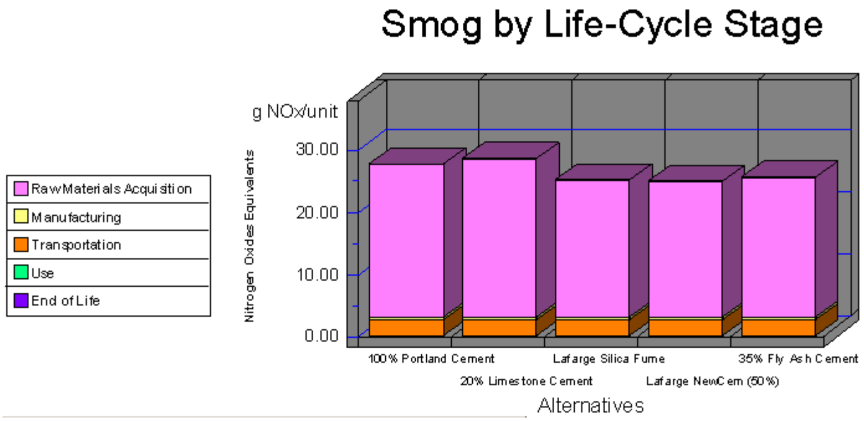


Fig. 10: Viewing BEES results by life-cycle stage

4. Summary

Over the last decade, the construction industry has become increasingly interested in the environmental performance of its products. Unfortunately, this has led to rampant “greenwash” in the market, with manufacturers promoting their products as environmentally friendly on the basis of weak science or popular wisdom. There are several reasons why these claims should be viewed with skepticism. First, they are often based on performance with respect to single impacts, and do not account for the fact that one impact may have been improved at the expense of others. Second, unless comparative claims are made on a *functional unit* basis, the products being compared may not be true substitutes for one another. One concrete mix may be environmentally superior to another on a kilogram-for-kilogram basis, but if more of that “superior” mix is required to fulfill the product function, the results may reverse. The results could also reverse if the mix that is environmentally superior on a kilogram-for-kilogram basis is less durable. Each time the product needs to be replaced, environmental impacts occur through its disposal and the production and installation of its replacement. Third, a product may contain a negative-impact constituent, like cement with its high embodied energy content, but if that constituent is a small portion of an otherwise relatively benign product, its significance decreases dramatically. Finally, a short-lived, low first-cost product is often not the cost-effective alternative. A higher first cost may be justified many times over for a durable, maintenance-free product. In sum, the answers lie in the tradeoffs.

5. Future Directions

To optimize concrete mix designs, environmental and economic performance criteria should be considered alongside other, more traditional, performance criteria. In other words, environmental and economic performance should be simultaneously balanced with desired levels of technical, or functional, performance. NIST is beginning to address this need for an integrated approach through its Virtual Cement and Concrete Testing Laboratory (VCCTL). As shown in Fig. 11, the purpose of VCCTL is to develop a web-based virtual laboratory for evaluating and optimizing the performance of cement- and concrete-based materials. The core of the virtual lab is a computer model for the hydration and microstructure development of cement-based systems that is based on more than 10 years of research at NIST. Much of this research is described in an electronic monograph available at http://ciks.cbt.nist.gov/monograph/. An effort is now underway to integrate BEES into the VCCTL. The goal is to provide material engineers with the tools they need to simultaneously optimize the technical, environmental, and economic performance of concrete mix designs.

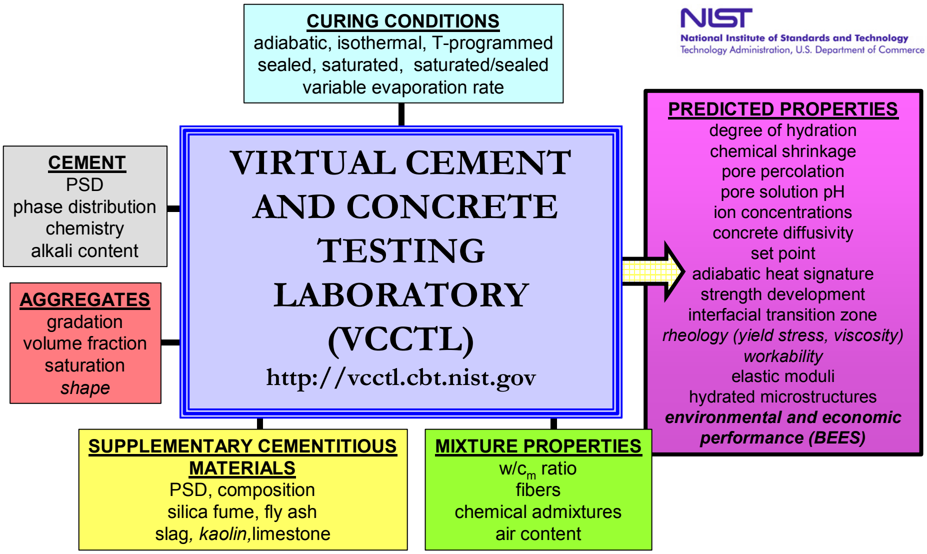


Figure 11. NIST Virtual Cement and Concrete Testing Laboratory: System Overview

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9. The mention of certain trade names and company products does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the product is the best available for the purpose.