

**DECISION SUPPORT SYSTEM FOR BUILDING CONSTRUCTION PRODUCT SELECTION  
USING LIFE-CYCLE MANAGEMENT (LCM)**

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**DECISION SUPPORT SYSTEM FOR BUILDING CONSTRUCTION PRODUCT SELECTION  
USING LIFE-CYCLE MANAGEMENT (LCM)**

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## SUMMARY

As the green movement begins to sweep through the construction industry, decision-makers are beginning to include a sustainable aspect to their purchase decisions. Selecting a product solely based on its sustainability, however, is not enough to drive product selection in the construction industry. Cost still dominates the selection of building products. The level of sustainability of a product and its cost are not interconnected as market prices do not reflect the cost of environmental impacts, such as the cost of global warming or fossil fuel depletion. Having two distinct aspects to consider adds complexity in the product selection process. Typically, it constrains decision-makers to perform a trade-off analysis that does not necessarily guarantee the most environmentally preferable purchase decision. This study proposes a life-cycle management (LCM) system that reinforces the choices made by decision-makers by providing a scientific justification for those decisions. The proposed system analyses the environmental and economic performance of building product through life-cycle analysis and purchase price analysis. It operates on tools publicly available in the market and state-of-the-art analysis, assessment, and interpretation methods. The LCM system combines two distinct product attributes into a single performance score that can be easily interpreted. It allows decision-makers to compare product scores and ultimately make the most environmentally responsible and financially viable selection. A comprehensive approach is used to refine and test the LCM system using case studies comprised of an environmental and economic performance evaluation of flooring products. The contribution of this research includes the consideration of a holistic approach to product selection based on environmental and cost performance. Pre-construction estimators and construction managers could improve their estimating and product selection practices using the proposed system. Material suppliers can also benefit from this approach, as they can use it to enhance their pricing strategies, marketing plans, and overall product competitiveness.

# CHAPTER 1

## INTRODUCTION

### 1.1 Overview

Building products in construction are typically judged and selected based on aesthetics, function, performance, and cost, all of which generally comply with the comprehensive scope of the project. With the increasing interest in green buildings, however, a new selection parameter has been added to include product sustainability (Castro-Lacouture et al. 2009). The growing credibility of green building rating systems in the building community has further increased the widespread demand for green products (Ding 2008). The popularity of green buildings and green products has also promoted the development of green building material rating systems (Spiegel and Meadows, 2010).

Evidence from adopting rating systems proves that implementing sustainable products in construction has the potential to not only reduce health and environmental effects, but to also bring savings from energy, maintenance, and operational costs (Ries et al.2009). Such benefits do not have to come at the expense of higher first costs, that is, the first cost of a sustainable product can be the same as, or lower than, that of a conventional product (USDOE 2010). The application of inexpensive green products is not only possible, but necessary in today's demanding economic market (USDOE 2010). As a result, creating a successfully integrated sustainable construction project requires the incorporation of products that are defined to be environmentally friendly and economically balanced.

Although there is no clearly adopted definition of sustainable products, several studies have characterized various qualities that describe them. Sustainable products have been defined as those with materials that promote good indoor air quality through low-emitting

contaminants (Mora 2007; Glavic and Lukman 2007; Florez 2010), incorporate pre- and post-consumer recycled content (Mora 2007), are made from natural or renewable resources that can be biodegraded (Glavic and Lukman 2007), are durable and have low maintenance requirements, and are easily salvaged or reused (Mora 2007). In addition, sustainable products are defined to have low embodied energy, or energy that is required to produce and transport products, during their entire life-cycle (Gumaste 2006, Bayer et al. 2010).

Identifying and defining financially-viable green products, just like selecting them, is an exercise in subjectivity. With so many variables to consider, the task of evaluating a green product's environmental life-cycle can be complex and discouraging. Adding the cost aspect further complicates the product selection process, as product cost variability is a significant issue in the construction market. To facilitate the selection process, it is critical for decision-makers to seek tools to perform a systematic analysis on building products.

## **1.2 Research Problem**

Buildings in the United States represent about 40% of primary energy use and 72% of national electricity consumption (EIA 2011), and account for 38% of all CO<sub>2</sub> emissions, the major contributor to green house gas emissions (EIA 2011). U.S. buildings also use 13.6% of all potable water totaling to 15 trillion gallons per year (USGC 2000). Buildings use 40% of raw materials globally, or 3 billion tons annually (Lenssen and Roodman 1995) which in turn generated an estimated 170 million tons of building-related construction and demolition debris in 2003 (US EPA 2009). The building construction community has become increasingly aware of the impact buildings have on the environment, and this is apparent considering the significant growth in the green construction market. The value of green building construction has increased by almost 50% from 2008 to 2010 from \$42 billion to \$71 billion, representing 25% of all new

construction in 2010 (McGraw-Hill 2010). Projections show that the green building market size will reach \$135 billion by 2015 (McGraw-Hill 2010).

As the market for green building continues to grow, the opportunity for green products will also expand. Currently, green labeling is the best source for determining the green value of products. Unfortunately, this has led to “greenwash” in the market, with manufacturers and suppliers promoting their products as green products without proper validation. The confusion is mostly prompted by the fact that many products are labeled green based on single attributes. For example, a product is labeled green because it contains recycled materials, or claimed not to be green because it emits volatile organic compounds (VOCs) (Lippiatt, 1999). These single-attribute claims ignore the possibility that other life-cycle stages or environmental impacts can yield offsetting impacts (Lippiatt, 1999). A recycled material product, for example, can contain high embodied energy that leads to ecological toxicity and fossil fuel depletion impacts during its manufacturing phase. Purchasing “greenwashed” products can possibly promote a shift of environmental problems from one life-cycle stage to another instead of an overall reduction of problems (Lippiatt, 1999).

In addition, the overwhelming amount of cost information further complicates the process of determining if green products are worth the investment. If the project scope requires a specific product to be both sustainable and within budget limits, a selector’s job becomes a trade-off game where costs are likely to be most highly considered unless otherwise specified (Trusty 2003, Castro-Lacouture et al. 2009, Florez et al. 2010, Florez 2010). A case study was performed to evaluate cost variability on bidding simulation scenario with similar project scope specifications. Results demonstrated large inconsistency in estimates, with over 60% variability between bids. This suggests significant variability in costs despite the narrow constraints on budget and green product qualifications. When decision-makers are challenged with product selection, it is difficult to determine if the product is the best purchase considering the significant

cost variability between products. This behavior results in unfair assessment of products that can lead to improper functionality within the project and overall dissatisfaction. Proper environmental and economic validation of building products cannot only facilitate the continuing growth of the green market, but is representative of true commitment to social, economic, and environmental responsibility. For this reason, decision-makers in building construction need well established metrics, tools, and data to support investment choices in sustainable materials.

### **1.3 Research Objective and Scope**

The objective of this study is to support decision-makers in selecting building products that are environmentally and economically balanced through a proposed conceptual system. A life-cycle management (LCM) approach was taken to create the system. It targets building construction stakeholders interested in evaluating a building product's environmental impacts using life-cycle assessment and its cost variability using cost statistics. The LCM system is designed to be practical, as it combines environmental and economic performance into a single performance value that is easily interpreted.

The LCM system is supported by environmental science, economics and decision science that validate the sustainability of building products and their financial worth based on scope parameters chosen by the decision-maker. Motivation for the system was created from case study results that proved the high variability in bidding estimates with and without the inclusion of green products. A case study was further developed to test the LCM system, reinforcing the significance in taking a multiattribute approach to assessing a building product's sustainable and financial performance. The case-study focuses on comparing two flooring products: generic vinyl composition tile and natural cork floating floor plank floor coverings.

Ultimately, the goal of this study is to provide decision-makers with the ability to evaluate products for their true environmental and economic sustainability with the help of tools readily available in the market. The proposed decision support system is a basis for developing a comprehensive building product assessment tool.

#### **1.4 Thesis Organization**

This study is divided into 5 chapters. Chapter 1 presents an overview of the research problem and introduces the objectives and scope of the study. Chapter 2 provides a literature review of the life-cycle assessment (LCA) resources, tools, and rating systems currently available to decision-makers to support product selection based on environmental qualities. Chapter 3 presents and describes the proposed life-cycle management (LCM) system by first defining the LCA process for which it is partly based. It also introduces and analyzes a case study performed to evaluate cost variability on a bidding simulation scenario. The objective and scope of the case study are explained, followed by an extensive results analysis. The case study justifies the rationale behind also assessing economic performance of products. The LCM system methodology is depicted in detail with several illustrations to demonstrate the environmental and economic performance evaluation. Chapter 4 tests the LCM system by providing a detailed description of methods used to execute the analysis and offers a comprehensive assessment of results. The LCM system is evaluated based on the total performance score it provides and also by clearly identifying the benefits and limitations of the process. Finally, Chapter 6 offers a comprehensive description of the proposed LCM system's implications and limitations. Recommendations for future research are also proposed.

## CHAPTER 2

### MATERIAL SELECTION LCA TOOLS AND RESOURCES

#### 2.1 Life-Cycle Assessment (LCA) Resources

The International Organization for Standardization (ISO) 14040 series describes four general steps to be performed in any Life-cycle assessment (LCA): goal and scope definition, inventory analysis, impact assessment and interpretation. The inventory analysis step requires the use of national or international databases or manufacturer-specific data that quantifies the inputs and outputs of systems. The U.S. Life-Cycle Inventory (LCI) Database is a commonly referred-to national database. The impact assessment step requires the application of assessment methodologies, such as the Environmental Protection Agency's (EPA) Tool for the Reduction and Assessment of Chemicals and other environmental Impacts (TRACI). An overview of commonly-used LCA resources is provided in the following sections.

##### 2.1.1 U.S. Life-Cycle Inventory (LCI) Database

In order for tools to provide results, information needs to be entered, and for LCA tools, the inputs are in the form of life-cycle inventories (LCI). The publicly available U.S. Life-Cycle Inventory (LCI) Database was developed by the National Renewable Energy Laboratory (NREL) and the ATHENA Institute as a resource to create extensive LCI's and LCAs (NREL 2004). The goal of the U.S. LCI database is to provide a central source of transparent and consistent information for the U.S. region (Bayer et al. 2010). Downloadable detailed spreadsheets provide calculated data from commonly used materials, products and processes (NREL 2004).

### **2.1.2 Tool for the Reduction and Assessment of Chemicals and other environmental Impacts (TRACI)**

The EPA's TRACI is the typical method by which most U.S. LCA tools assess the LCI data. It is an impact assessment tool that provides a consistent set of metrics in the form of impact categories including acidification, eco-toxicity, eutrophication, fossil fuel depletion, global warming, human health cancer, human health criteria, human health non-cancer, ozone depletion, global warming, land and water use, and smog formation (Bare 2010). TRACI quantifies the each potential contribution of a product's inventory flow data into one of the impact categories. Several of TRACI's impact categories were developed specifically for the U.S. using input parameters consistent with U.S. locations (Bare 2010). Other impact categories focus on regional and global impacts such as smog and global warming, respectively. All impact categories were selected based on their consistency with EPA research and other developing literature in the area (Bare 2010).

### **2.1.3 Environmental Product Declaration (EDP®)**

Purchasing "greenwashed" products can be avoided by selecting products that are certified based on their LCA evaluation approach. The standards of ISO 14020 series, specifically 14025 "Type III environmental declaration certified products", evaluate products using systems that represent the closest alignment to LCA metrics (BDC 2005). Programs like the Environmental Product Declaration® (EDP) are increasing the market value of products by providing quantitative and verified information about the environmental performance of products based on international standards for LCA such as ISO 14025 and 14040 (EPD 2011, Bayer et al 2010). The information is provided by suppliers and verified by third parties (BDC 2005). In addition, the certification of EDPs must declare data collection and assessment methods,

including value choices and subjectivity, the selected LCI analysis and LCIA impact categories, the quality of information in terms of relevance, accuracy and uncertainty, and the insurance of capability and comparability of product information (BDC 2005). This scientifically accepted program is one alternative to using LCA software tools to assess the environmental performance of products.

## **2.2 Life-Cycle Assessment (LCA) Tools**

Performing full LCA studies for each individual product, material, or process from scratch is not realistic, nor cost effective for building professionals. Building professionals interested in the environmental impacts of their projects do, however, have software tools developed by LCA experts at their disposal to facilitate the process. Such tools have product and process databases embedded in them, allowing decision-makers to quickly compare the environmental impacts of systems. This information can guide a simpler product procurement process. LCA tools are defined as environmental modeling software that develop LCI and perhaps provides life-cycle impact assessment (LCIA) information through standards provided by ISO 14000 series of environmental management standards and other LCA procedures (Trusty et al. 1998). The LCA tool uses information from the LCI data database available and converts materials of a product system into quantities of inputs and outputs in the form of resource and energy use (inputs) and emissions to air, water, and land (outputs). LCA tools can be classified based on the type of analysis they perform, such as product, assembly, or whole building analysis (Trusty 2003, Bayer et al. 2010). Tools are also classified as region-specific, are considered based on the life-cycle phases they cover, and on the required skill necessary to operate the tool (Bayer et al. 2010). Many tools have an established LCI database, while others can adapt to information from various LCI database sources.

### **2.2.1 The ATHENA® Impact Estimator**

The ATHENA® Impact Estimator, developed by the ATHENA® Institute, is capable of producing a whole building analysis, based on cradle-to-grave ATHENA® database and U.S. LCI Database (ATHENA Institute 2011). This LCA tool offers an LCIA method, provided by EPA's TRACI, that analyzes over 1,200 building material and assembly combinations (Bayer et al. 2010). This tool is widely used due to the region-specific databases it uses, the ability to allow the user to custom design assemblies from available products and the detailed results it provides (Bayer et al. 2010). Major drawbacks to this tool are the cost and required skills to use it, the limited options of designing high-performance assemblies, and the overall incomplete assessment of whole buildings environmental impacts (Bayer et al. 2010).

### **2.2.2 The ATHENA® EcoCalculator**

The ATHENA® EcoCalculator was also developed by the ATHENA® Institute as a free LCA tool that assesses more than 400 building material and assembly combinations in the U.S and Canada (ATHENA Institute 2011). It analyzes cradle-to-grave information from the U.S. LCI Database and Athena's own datasets using the EPA's TRACI LCI method (Bayer et al 2010). The tool is free of cost and requires no particular skill to use it. A limitation of the tool is that it only allows the evaluation of assembly options given that also come with fixed dimensions (Bayer et al. 2010).

### **2.2.3 BEES® 4.0**

The Building for Environmental and Economic Sustainability (BEES®) 4.0, the latest version developed by the National Institute Standards and Technology (NIST), provides a

cradle-to-grave product-to-product comparison of over 230 building products based on manufacturer and supply company information and U.S. LCI database information (Lippiatt 2007). The assessment method adopted by BEES® is the EPA's TRACI, which is used to form the impact categories, with the exception of Indoor Air Quality. This tool is used in the impact assessment step in the LCA process along with the Environmental Problems approach, where product inventory flows are classified and characterized into quantifiable environmental impact categories. The impact categories in BEES® include global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, ecological toxicity, human health cancer and non-cancer, and ozone depletion potential. The impact categories were selected based on their consistency with EPA regulations and policies, the level of commonality with the current literature and state of development and their perceived societal value (Bare 2002). The impact categories are further weighed, normalized, and merged into a final environmental performance score using multi-attribute decision analysis (MADA). The BEES system follows the ASTM standard practice for conducting MADA evaluations of investments related to buildings and building systems (Lippiatt 1999, 2007). MADA generates a single measure of desirability for project alternatives by combining qualitative and quantitative data, that is, apples and oranges. The system is not capable of providing data for a full LCA of a complete building, as it only produces data for a limited amount of building products (Lippiatt 2007, Bayer et al. 2010). From those products, BEES® only considers materials in product systems that are significant in either weight, energy, or cost (Lippiatt 2007, Bayer et al. 2010). At its current stage, BEES® quantifies data representative of U.S averages, which limits the accuracy of building product information in terms of local or regional impacts. Furthermore, EPA's TRACI categorizes a minimal set of impact categories and does not currently include impacts that are considered minimal, or those that are local such as odor, noise, radiation, heat waste, and accidents (Bare, 2002). This

method does not place clear environmental importance on the impacts, which negatively alters the subsequent weighing process (Lippiatt, 2007).

#### **2.2.4 The Economic Input Output LCA (EIO-LCA)**

The Economic Input Output LCA, or (EIO-LCA) was developed by the Green Institute at Carnegie Mellon University and estimates the materials and energy resources required for, and the emissions resulting from, products, materials, services, or industries from material extraction phase, to manufacturing, and transportation phase (CMU 2011). Unlike the ATHENA® or BEES® tools which are building assembly and product LCA tools, the EIO-LCA is an embodied energy tool (Bayer et al. 2010). It does not feed from a database or assess inventory information, but only provides estimates on environmental impacts. EIO-LCA systems can aggregate information from several industry types for one sector, which misinterprets actual information (CMU 2011). Table 2.2 summarizes the aforementioned LCA tools.

Table 2.2: Life-Cycle Assessment (LCA) Tool Overview

LCA Tool	Tool Type	Tool Developer	Collection	LCI Database	LCIA Method	Users	Limitations
ATHENA® Impact Estimator	Whole Building Analysis Tool	ATHENA® Institute	1,200+ building material and assembly combinations	ATHENA® Database, U.S. LCI Database	EPA TRACI	Architects, Engineers, Designers, Environmental Consultants	\$750 Software Cost
	Building Assembly Analysis Tool						Moderate Required User Skill
ATHENA® EcoCalculator	Building Assembly Analysis Tool	ATHENA® Institute	400+ building material and assembly combinations	ATHENA® Database, U.S. LCI Database	EPA TRACI	Architects, Engineers, Designers, Environmental Consultants	Limited assembly options Fixed assembly dimensions
BEES® 4.0	Building Product Life-Cycle Assessment (LCA) Tool	NIST	230+ building products	Manufacturer-specific data, U.S. LCI Database	EPA TRACI, Environmental Problems	Designers, Specifiers, Builders, Product Manufacturers, Purchasers, Researchers, and Policy Makers	Limited product options
	Building Product Life-Cycle Costing (LCC) Tool						Limited use for local/regional impact analysis Devaluating weighing process
EIO-LCA	Embodied Energy Tool	Carnegie Mellon University	N/A	N/A	N/A	Environmental Professionals, Tool/data developers	Aggregation of information

### **2.3 Green Building Rating Systems**

Integrating LCA into green building rating systems in the U.S. brings a significant shift from a prescriptive, or checklist, methodology, to a performance based approach to the selection of building products. Currently, Green Globes is the only green building rating system that assigns a high percentage of resource use credits based on LCA studies conducted using product LCA tools, such as BEES, or assembly LCA tools, such as ATHENA Environmental Impact Estimator (Trusty 2003, Bayer et al 2010, GBI 2011). The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED®) has established a pilot system that is not currently operational, but is allowing project teams to perform LCA of building assemblies and materials, replacing of a few existing "materials and resources" credits (USGBC 2010). The system uses the ATHENA EcoCalculator to provide LCA results that are then inputted into the USGBC LEED Credit Calculator which interprets the environmental impacts as LEED credit points. Incorporating LCA into LEED, the most widely accepted green building rating system in the U.S., would not only popularize LCA as a methodology, but would transform it into a standard way of accessing products, assemblies, and building systems (Trusty 2009).

## **CHAPTER 3**

### **LIFE CYCLE MANAGEMENT SYSTEM**

#### **3.1 Life-Cycle Assessment (LCA) Introduction and Terminology**

Life-cycle assessment, or LCA, is a methodology that evaluates the sustainability of products by identifying and quantifying energy and materials used and wastes released over its entire life-cycle (Trusty 2003). In building construction, an LCA is generally conducted over the full building life-cycle, including materials manufacturing, construction, operation, and decommissioning. LCA is generally accepted as a functional tool that quantifies environmental impacts and performance of systems (Trusty 2003, Mora 2005, Ljungberg 2007, Abeysundara et al 2009, Bayer et al. 2010, and Florez 2010). Although LCA is relatively new to the building sector, it has been used extensively since its conception in the 1960s.

The International Organization for Standardization (ISO) 14040 series describes four general steps to be performed in any LCA: goal and scope definition, inventory analysis, impact assessment and interpretation. The goal and scope definition phase defines the process or product to be assessed, and identifies the level of detail of the analysis to be performed, and the impact categories to be evaluated (Bayer et al. 2010, BDC 2005). The inventory analysis step quantifies and categorizes the inputs and outputs of a system, that is, energy and materials used and the emissions to air, water, and land. This phase is also known as the life-cycle inventory (LCI) phase (Bayer et al. 2010, BDC 2005). The impact assessment portion of the LCA process translates LCI information into specific environmental indicators or impact categories, such as global warming, eutrophication, and smog formation. Impact assessments differ from one LCA tool to another since it is based on the judgment and value of impacts. The

final phase of LCA is the interpretation of results, where benefits and limitations are outlined in order to make effective environmentally friendly decisions (Bayer et al. 2010).

LCA is highly advocated because it is transparent and multi-dimensional in demonstrating the tradeoffs required to properly select product, components, systems, and assemblies of a project (BDC 2005). At its current stage of development, however, there are not enough economic incentives for the building community to accept it as a selection support system, as it generally consumes more time and resources than it saves for building projects (Bayer et al. 2010). Furthermore, databases can be inaccurate, incomplete or too generalized, requiring the decision-maker to use multiple sources while drawing more assumptions to the analysis (Bayer et al. 2010). Finally, the lack of benchmarks limits data available, resulting in unnecessary repetition of complex work (Bayer et al. 2010). It should be noted that these limitations are only temporary, and will be resolved as more research and development is conducted (Bayer et al. 2010).

In addition, many LCA experts debate the impact assessment methods and the practice of weighing them. Since the methods used to translate and quantify inventories into impacts vary by the complexity of the impact category, information can be interpreted with inconsistency. The results from the impact assessment are further reduced into a single score, adding more assumptions and generalizations to an already existing inconsistency (Bayer et al. 2010).

### **3.2 Cost Variability Case Study**

In construction, economic analysis is conducted to find the most optimal use of resources available at the lowest cost compared to resources that perform the same task (Ashworth 2004). Although this is the ideal approach to selecting products in building

construction, it is not realistic due to the large price variability of products. Since cost variability reflects the level of inefficiency in the market, it is worthwhile to investigate the causes (Jayasena 2005). The implications of construction economics were evaluated by analyzing a simulation of economic choices taken by ten groups competitively bidding on a construction project. The objective of this case study was to analyze the cost variability between a conventional estimate and an estimate including green products, both of which included narrow constraints on budget and product type. A secondary objective was to analyze the perception and opinions of the groups performing the task.

### **3.2.1 Case Study Scope**

The case study was conducted on a construction estimating class in the School of Building Construction at the Georgia Institute of Technology. The class was divided into ten groups, each representing individual construction firms. They were provided with drawings specifications of a residential project on campus and were challenged to perform a complete quantity take-off for division eight of the CSI Master Format, which includes doors and windows. Their task was to estimate the cost of work based on two qualifications. The first was a conventional estimate where students were required to estimate the most economic way to meet the drawing specifications. The second was an alternative estimate, where groups were required to estimate the most economic way to meet the drawing specifications with three modifications: 10% to 40% of the total division costs must consist of recycled content materials, 10% to 40% must be local materials, and 2.5% to 7% of materials must consist of rapidly renewable materials. All groups were directed to price conventional items using RSMeans' CostWorks® 2011. The alternative estimate items were priced using CostWorks® and any other source of cost estimation, including the world wide web. The students were not immediately made aware that the

alternative modifications were based on the LEED® Materials and Resources category credits 4, 5, and 6. The goal was to avoid a biased perception of conventional versus green product costs in order to assess their knowledge before and after completing the task. Perceptions and opinions were examined using a comprehensive survey.

### 3.2.2 Measures of Bid Price Variability

Several common statistical methods were employed for the analysis of case study results. Standard variation and variance is appropriate because it uses all price information in the sample based on the same project parameters. Standard deviation is given by

$$\frac{\sum_{i=1}^n (P_i - \bar{P})^2}{n} \quad (1)$$

where  $n$  is the number of bids,  $P_i$  is the  $i^{\text{th}}$  bid and  $\bar{P}$  is the mean bid (Walpole 2007). The larger the value indicates bid estimates that are more variable or less uniform about the average bid estimate, as illustrated in the right graph of Figure 3.1 (Walpole 2007). Small variance or standard deviation demonstrates that most of the bid estimates are grouped around the mean, as illustrated in the left graph of Figure 3.1.

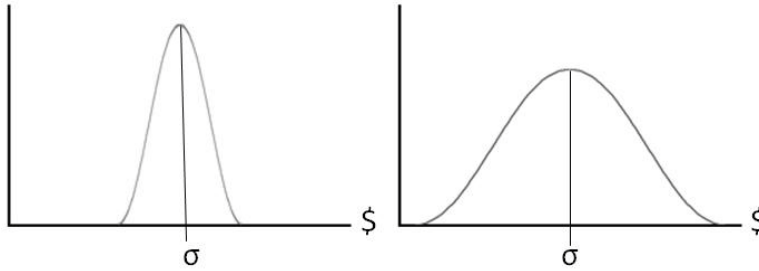


Figure 3.1: Variability of Bid Estimates About the Mean

The samples in this analysis are the conventional and alternate bids for the residential project. In order to account for wide bid price distributions, however, it is necessary to compute the coefficient of variation (CV). The coefficient of variation is a useful statistic comparing the degree of variation from one data series to another, even if the means are drastically different from each other. It is given by

$$CV = \frac{\sigma}{\bar{P}} \quad (2)$$

where  $CV$  is the coefficient of variation,  $\sigma$  is the standard deviation of the bid prices of the project and  $\bar{P}$  is the average bid of the project. The coefficient of variation is an appropriate measure of the variability of bid prices since it takes into account the dispersion of values (Walpole 2007). A relatively small value of  $CV$  indicates less variation, and is thus most accurate.

The third and final measure of bid price variability is the winning margin ( $\lambda$ ). It is the difference between the lowest and second lowest bids and is given by

$$\lambda = P_1 - P_0 \quad (3)$$

where  $P_0$  is the lowest bid and  $P_1$  is the second lowest bid. The percentage winning margin denoted by  $\gamma$  is the ratio of the winning margin ( $\lambda$ ) to the lowest bid. It is given by

Since contracts were awarded to the lowest bidder, the winning margin is a useful measure of the level of competition between groups and can be representative of the actual behavior in the construction industry.

### 3.2.3 Results

Results demonstrate that the average bid for both alternative and conventional bid estimates were similar, with only a 5% difference between the two. Relative to their average bid prices, the standard variations for conventional and alternative bids were found to be very high. This indicates a large variation or dispersion from the average. The coefficients of variation also illustrate the same large variability between bids. Since a competitive bid approach was taken to determine the most responsive bidder, it was found effective to analyze the winning margin between bids. The two lowest alternative bids had a 4% difference, compared to a 55% difference between the lowest and second lowest conventional bids. Table 3.1 summarizes the results for the case study.

Table 3.1 Case Study Results

Statistical Measures	Alternative Bid	Conventional Bid	Percent Difference
Average Bid Price	\$44,395.21	\$42,104.88	5%
Standard Deviation ( )	\$28,500.51	\$27,781.35	3%
Coefficient of Variation (CV)	64%	66%	2%
Winning Margin ( $\lambda$ )	\$ (532.98)	\$(5,736.64)	91%
% Winning Margin ( $\gamma$ )	-4%	-55%	-52%

An additional observation made from the results was that four of the ten groups had higher alternative bids compared to conventional bids, while three of the four had the opposite result. The other three groups had the same estimates for both alternative and conventional bids. Such results denote that 60% of the groups were able to include green products that cost the same or less than conventional products. Overall, supplementing students with alternative bids demonstrates the significant variability in costs despite the narrow constraints on budget and the green product qualifications. Furthermore, it suggests the complexity added to this challenge when also considering the variability from products' environmental features. This implication is demonstrative of the potential scenarios decision-makers are challenged with when they are responsible for selecting products that are constrained to the project scope.

A secondary objective was to analyze the perception and opinions of the groups performing the task. Each student was provided with a survey before and after completing bid estimates. The first observation made was that close to 40% of the students perceived that projects incur an additional cost of 5-10% from adding green doors and windows. The next highest perception included 24% of students believing green products add an additional 10-25% to the overall estimate. After arriving at their final estimates, their perception changed to 26% believing an initial investment of 0-5%, another 26% recognizing a 5-10% cost increase, and 29% identifying a 10-25% increased cost investment. The values indicate that prior to conducting the work, most students were confident that green products add a 5-25% initial investment. After completing the bid estimates, the range expanded to include the broad range from 0-25%. This is representative of their actual work, since, as previously stated, 60% of the groups were able to include green products that cost the same or less than conventional products. Before performing the work, half of the students thought that there would be no significant estimate variability when adding more environmentally friendly door and window

products to their conventional bids. This changed drastically when surveyed afterwards, with about 75% of the students believing in a significant variability. Furthermore, they recognized moderate to high bid estimate variability between groups before and after completing the work. The groups' acknowledgement of variability correlates to the significant dispersion of results.

### **3.2.4 Limitations and Implications**

A major limitation identified in this study is the potential error in the conventional and alternative cost estimates. More than 75% of students identified lacking experience in bid estimating. This can heavily influence the reliability of results as the learning curve for the majority of the students is at its origin. Additionally, three of the ten groups made the assumption that both bid estimates must be equal by only modifying the unit costs of certain products by performing a tradeoff analysis. Although this does not change statistical measures, the sample data that contributes to the analysis is minimized.

Supplementing the students with alternative bids demonstrates the significant variability in costs despite the narrow constraints on budget and the green product qualifications. When surveyed before and after performing their estimates, about half of the students recognized the principal reason why decision-makers chose not to implement green products if there are no specifications to do so is due to their high costs. This indicates that there is still a high perception of a high initial investment when using green products although 60% of the groups were able to demonstrate that a bid with green products costs the same or less than a bid using conventional products.

### 3.3 Life-Cycle Management (LCM) System Methodology

A proposed solution to the product selection problem is a life-cycle management (LCM) system. Generally, life-cycle management (LCM) is the integration of life-cycle perspective and economic, social, and environmental considerations into the overall strategy, planning and decision making processes of goods and services in order to promote more sustainable production and consumption (Saur 2003). LCM methodology takes a multidimensional approach in considering environmental and economic impacts over a building product's life. This system couples life-cycle assessment (LCA) information and first cost data into a system decision-makers can be supplemented with in order to make an informed investment. This system is representative of a comprehensive product selection process, as it considers multiple impacts and life stages of a product. The proposed LCM system is illustrated in Figure 3.2.

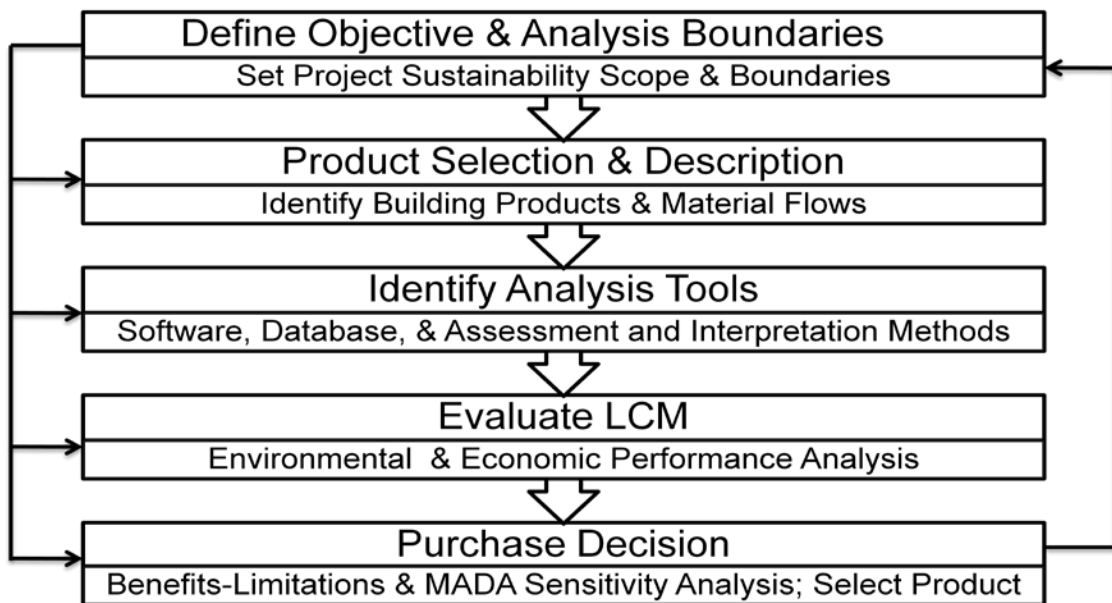


Figure 3.2: Life-Cycle Management (LCM) System

The system is designed to make a final product selection through a set of steps to guide the decision-maker. It begins with defining the objectives of the project and setting analysis boundaries. After defining the scope of the study, a set of products are selected and described. The chosen products must be consistent with the project objectives and boundaries defined in the first step. The following phase requires the identification of analysis tools to be used in the study. That includes software, database, and assessment and interpretation methods as defined in chapter 2. The tools must also conform to the project scope. Next, the selected products will be evaluated based on their environmental and economic performance, using LCA and cost analysis, as illustrated in Figure 3.3. In the last phase of the system, the best product is chosen based on the concluding total performance score. The total performance score is derived after a clear identification of benefits and limitations and a Multi-attribute Decision Analysis (MADA) sensitivity analysis. The product should clearly reflect the project objective defined in the first phase. If the final performance scores of the compared products are almost equivalent, or there is doubt about any step in the process, the purchase decision should be re-assessed and other alternative products should be considered. The following chapter is intended to describe the LCM system phases in detail with the aid of a case study.

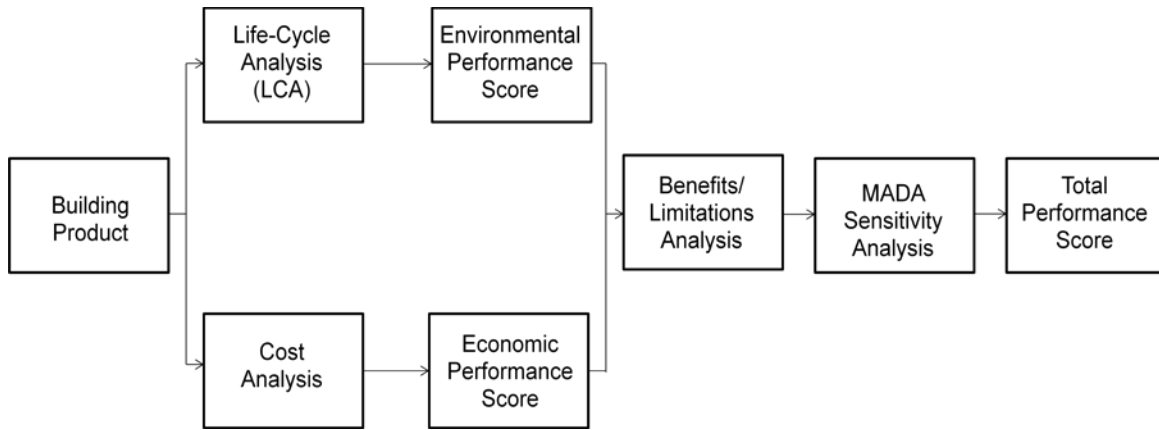


Figure 3.3: Deriving Environmental and Economic Performance Scores

The LCM system is able to cover all life-cycle stages of a product and its context of a building's life-cycle. It includes raw materials acquisition, manufacturing, design and construction, operation and maintenance, and decommission and waste management. Figure 3.4 illustrates the LCM system analysis phases.

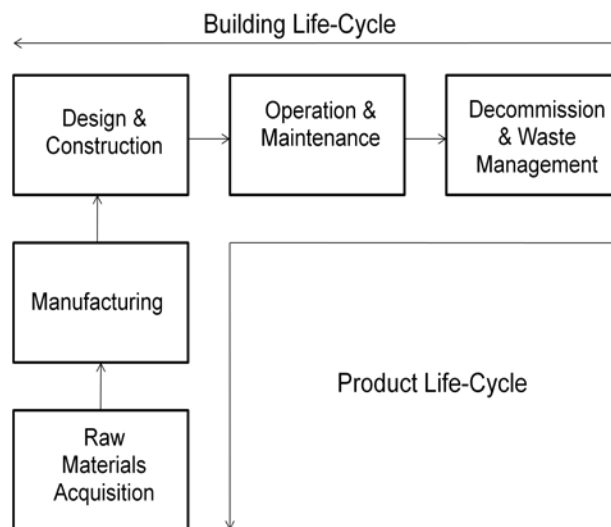


Figure 3.4: Life-Cycle Management (LCM) System Analysis Phases

**CHAPTER 4**  
**TESTING LIFE-CYCLE MANAGEMENT (LCM) SYSTEM: FLOORING PRODUCTS CASE**  
**STUDY**

**4.1 Define Objective and Analysis Boundaries**

The goal of this study is to test the proposed life-cycle management (LCM) system by evaluating and comparing the life-cycle environmental impacts and the product material cost of flooring systems. Ultimately, the objective is to choose the flooring product with the lowest total performance score, as it reflects the most environmentally preferable purchase decision.

BEES® 4.0 is used to measure the environmental performance of building products using the cradle-to-grave systems approach. This includes every life-cycle stage of a product, including raw materials acquisition, manufacture, transportation, installation, use, and recycling and waste management (Lippiatt, 1999). The system boundaries analyzed for the flooring products cover all of these life-cycle stages. The impact categories evaluated during each stage were those considered by BEES® 4.0, which include global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, ecological toxicity, human health cancer and non-cancer, and ozone depletion potential. The functional unit for flooring products is 0.99 m<sup>2</sup>, or 1 ft<sup>2</sup>, for 50 years. In other words, the environmental effects of 0.99 m<sup>2</sup> of a flooring product are quantified and compared to 0.99 m<sup>2</sup> of another flooring product, both of which are assumed to have a service life of 50 years.

The costs evaluated include only the material price, or the initial investment cost, of each product on a per square foot basis. The cost analysis only includes costs of products once on

the shelf, or the purchasing price and not a life-cycle cost analysis. The cost analysis covers U.S. geography and retrieved data represents U.S. average data.

## **4.2 Product Selection and Description**

Two floor covering alternatives were chosen in order to test the proposed LCM system. Generic vinyl composition tile and natural cork floating floor plank were selected for to examine the system. In this case study, the vinyl flooring is perceived as the conventional product, and the cork flooring as the alternative sustainable product. Flooring systems were preferred over other building products because of the extensive information available for a more comprehensive environmental and economic analysis. Both products are also readily available in BEES® 4.0.

Vinyl composition tile is known for its durability. BEES® 4.0 specifically analyzes a 30cm x 30cm x 0.3cm (12in x 12in x 1/8 in) product weighing about 1.35 lb mostly composed of limestone as inorganic filler (Lippiatt 2007). Figure 4.1 illustrates an example image of the product. The flow diagram adapted from BEES, illustrated in Figure 4.2, represents the major elements of the production of vinyl flooring, including every material and energy included from the raw materials to recycling and waste management.



Figure 4.1: Generic Vinyl Composition Tile

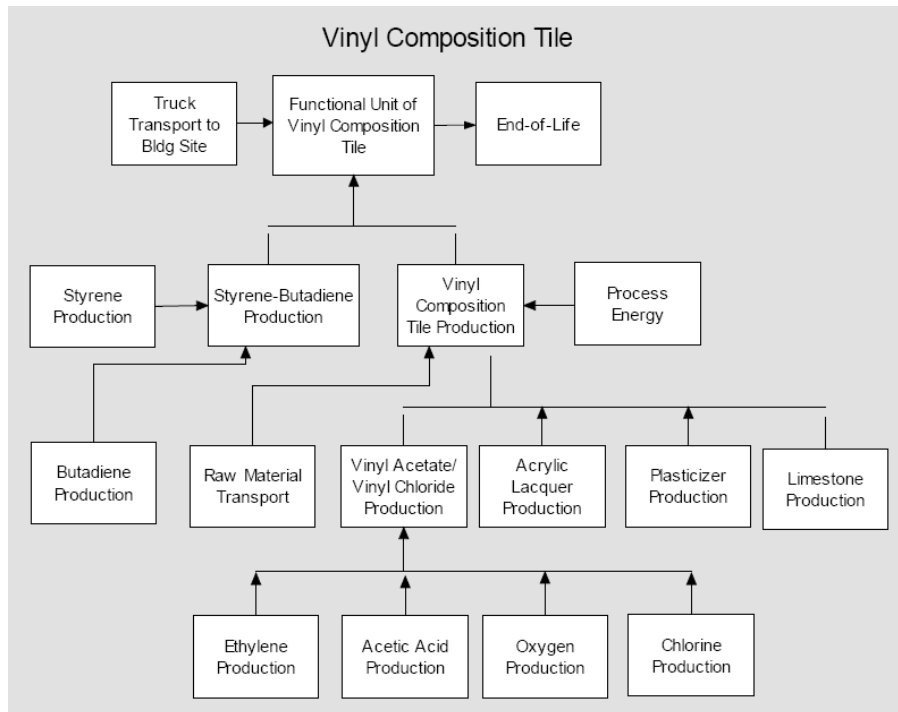


Figure 4.2: Flow Diagram of Generic Vinyl Composition Tile System Boundaries, adopted from

BEES® 4.0

Natural cork flooring, in specific, natural cork floating floor plank, is known for its composition of renewable materials. Cork is a modern flooring material and is generally perceived as a greener alternative, compared to generic vinyl composition tile. Figure 4.3 illustrates an example image of the product. The flow diagram adapted from BEES, illustrated in Figure 4.4, represents the major elements of the production of natural cork flooring, including every material and energy included from the raw materials to recycling and waste management.



Figure 4.3: Natural Cork Floating Floor Plank

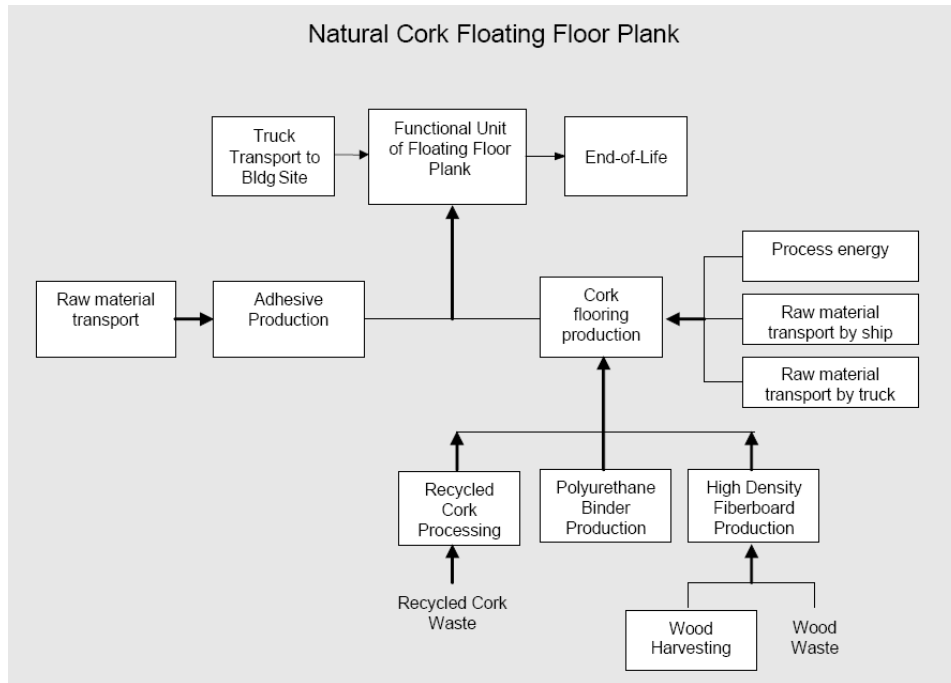


Figure 4.4: Flow Diagram of Natural Cork Floating Floor Plank System Boundaries, adopted from BEES® 4.0

### 4.3 Identify Analysis Tools

The software used to conduct the life-cycle analysis (LCA) on the products was the BEES® 4.0 software. The life-cycle inventory (LCI) data used in BEES® 4.0 is from the US LCI database. The method used to perform a life-cycle inventory analysis (LCIA) is the EPA's TRACI which developed the impact categories and the Environmental Problems approach developed by SETAC, which classifies and characterize inventory flows into impact categories as it is used in BEES® 4.0. Finally, the technique used to interpret environmental data was the multiattribute decision analysis (MADA), also used in BEES® 4.0, which follows the ASTM standard for conducting MADA evaluations of investments related to building (Lippiatt, 1999). The decision-maker uses the MADA technique to cater to the specific needs of the scope that was established in the first phase by setting their own set of importance weights ultimately resulting in normalized environmental scores that can easily be interpreted.

The software used to analyze national flooring prices was Microsoft Office Excel 2007. Price data was retrieved from 40 national supplier websites for a total of 1,636 flooring products. The methods used to analyze price data included statistical measurements such as standard deviation and coefficient of variation, as described in chapter 3.2. A life-cycle cost (LLC) analysis was not studied because of the large variability in the various types of applications of these flooring systems. Although BEES® 4.0 has the capability to produce a first cost for products, they are collected from R.S. Means 2007 publications, which is outdated for the purposes of this study. It is also not part of the proposed LCM system. The technique used to interpret economic data is a relative percentage calculation. This calculation is computed by dividing the average purchase price of one product by the highest average purchase price between the compared products. This value is multiplied by 100 to get a percentage value. Table 4.1 provides a tabulated summary of the analysis tools used in this case study.

Table 4.1: Summary of Analysis Tools

Performance Analysis	Environmental	Economic
Analysis Tools	LCA	First Cost
Software	BEES® 4.0	MS Excel 2007
Analysis Database	US LCI Database , Manufacturer-specific Data	National Websites
Assessment Method	TRACI, Environmental Problems	Statistical Methods
Interpretation Method	Multiattribute Decision Analysis (MADA)	Relative Percentage

## 4.4 Evaluate LCM

### 4.4.1 Environmental Performance Interpretation

A step-by-step analysis of the LCA portion of the LCM system is outlined beginning with life-cycle inventory analysis and impact assessment, and finally results interpretation, as standardized by ISO 14040. The BEES® system combines the first two steps, inventory analysis and impact assessment, into one step. The inventory analysis step requires the quantifying of inventory flows for a building product, including inputs of water, energy, and raw materials, and releases to air, land, and water (Lippiatt, 1999). It should be noted that BEES® system computes the effects of 500 miles of transportation distance from manufacture to user. The impact assessment step quantifies the potential contribution of a building product's inventory to a range of environmental impacts by classifying and characterizing each flow (Lippiatt, 1999). Classification categorizes each inventory flow into specific environmental impacts, while characterization weights each classified inventory flow by its relative contribution to the impact resulting in impact sums or potentials. A summary of the impact sum or potentials derived from the inventory flow and impact assessment values provided by BEES® 4.0 for generic vinyl composition tile and natural cork floating floor plank are provided in Table 4.2.

Table 4.2: Summary of BEES® 4.0 Impact Potentials

Impact Assessment Results			
Impact Category	Equivalent Units	Vinyl	Cork
Global Warming	(g CO <sub>2</sub> /unit)	1059.9062	917.3196
Acidification	(mg H <sup>+</sup> /unit)	569.4998	855.4843
Eutrophication	(g N/unit)	0.1873	0.8674
Fossil Fuel Depletion	(MJ/unit)	2.6726	1.0726
Indoor Air Quality	(g TVOCs/unit)	0.107	0
Habitat Alteration	(T&E species/unit)	0	0
Water Intake	(liters/unit)	2.52	1.207
Criteria Air Pollutants	(MicroDALYs/unit)	0.1547	0.1741
Ecological Toxicity	(g 2,4-D/unit)	3.0392	2.8225
Human Health Cancer	(g C <sub>6</sub> H <sub>6</sub> /unit)	6.4231	1.2172
Human Health Non-Cancer	(g C <sub>7</sub> H <sub>8</sub> /unit)	8017.0361	1599.6961
Ozone Depletion	(g CFG-11/unit)	0	0
Smog	(g Nox/unit)	4.5341	20.0737

The final step of the LCA analysis is to interpret the impact potentials by synthesizing them into a single score using MADA. Although one product can outperform the other in more one impact category, MADA combines all of the impact categories into one meaningful performance score. This is accomplished by weighing each impact category by its relative importance to environmental performance. BEES® allows the user to define the set of importance weights and provides two weight sets as guidance: the U.S. EPA's Scientific Advisory Board (SAB) and BEES Stakeholder Panel judgments (Lippiatt, 2007). It also allows the user to use equal weights. In this case study, BEES Stakeholder Panel importance weights were chosen because they integrate the expertise of building product manufacturers, green building designers, and LCA experts resulting in less assumptions and more comprehensive approach (Lippiatt 2007). The environmental performance scores are outlined in Table 4.3, where equal weights were defined.

Table 4.3: BEES Environmental Performance Scores for Generic Vinyl Composition Tile and Natural Cork Floating Floor Plank Based on BEES Stakeholder Panel Importance Weights

Environmental Performance Interpretation					
Impact Category	Relative Importance Weights, BEES Stakeholder Panel (%)	Vinyl		Cork	
		Normalized Impact Assessment Score	Normalized, Weighted Impact Assessment Score	Normalized Impact Assessment Score	Normalized, Weighted Impact Assessment Score
Global Warming	29	1.00	29	0.87	25
Acidification	3	0.67	2	1.00	3
Eutrophication	6	0.22	1	1.00	6
Fossil Fuel Depletion	10	1.00	10	0.40	4
Indoor Air Quality	3	1.00	3	0.00	0
Habitat Alteration	6	0.00	0	0.00	0
Water Intake	8	1.00	8	0.48	4
Criteria Air Pollutants	9	0.89	8	1.00	9
Ecological Toxicity	7	1.00	7	0.93	7
Human Health Cancer	9	1.00	9	0.19	2
Human Health Non-Cancer	4	1.00	4	0.20	1
Ozone Depletion	2	0.00	0	0.00	0
Smog	4	0.23	1	1.00	4
Performance Score	100		82		64

As shown, generic vinyl composition tile has lower scores and therefore performs better than the natural cork floating floor plank on acidification, eutrophication, criteria air pollutants, and smog. On the other hand, vinyl flooring also perform worse than cork flooring on global warming, fossil fuel depletion, indoor air quality, water intake, human health cancer and non-cancer. Both products perform the same on habitat alteration, ecological toxicity, and ozone depletion. Based on the overall score, it is evident that the cork floating floor plank performs better environmentally when compared to generic vinyl composition tile, since in the BEES® system, a lower the score represents a lower impact on the environment. BEES® 4.0 further relates the total amount of each impact's contribution to the total amount of greenhouse gases released every year, per person, in the United States, according to the stakeholder panel importance weights. Generic vinyl composite tile scores a total score of 0.0127 points per unit, while cork floating floor plank scores 0.0043. This means that over its life-cycle, the cork flooring does less damage to the environment compared to vinyl flooring. That is, cork flooring is more sustainable because it contributes, on average, 0.0043% of annual per capita U.S. environmental impacts compared to vinyl flooring which contributes more, 0.0127%.

A sensitivity analysis was performed in order to test the effects of the environmental performance scores when introducing alternative importance weights. As seen in Table 4.3, using the BEES Stakeholder Panel judgments as importance weights resulted in a lower score and therefore better environmental performance for cork flooring, with 64 points. Conversely, with a higher score of 82, vinyl flooring performed worse. When using the EPA's SAB importance weights, the vinyl flooring still performs worse than the cork flooring, with final environmental performance scores of 68 and 52, respectively. If equal weights are used as importance weights, the result correlates with the other two relative importance weights, at 67 for vinyl flooring and 58 for cork flooring, as seen in Table 4.3. The relative importance weights

available in BEES 4.0 and their respective scores for this case study on vinyl and cork flooring products are summarized in Table 4.4.

Table 4.4: The Relative Importance Weights Available in BEES 4.0 and Environmental Performance Scores for Each Product.

Impact Category	Equal Weights	EPA SAB	BEES Stakeholders Panel
Global Warming	9	16	29
Acidification	9	5	3
Eutrophication	9	5	6
Fossil Fuel Depletion	9	5	10
Indoor Air Quality	8	11	3
Habitat Alteration	8	16	6
Water Intake	8	3	8
Criteria Air Pollutants	8	6	9
Ecological Toxicity	8	11	7
Human Health Cancer	5	7	9
Human Health Non-Cancer	3	4	4
Ozone Depletion	8	5	2
Smog	8	6	4
Total	100	100	100
Vinyl Score	67	68	82
Cork Score	58	52	64

Overall, the generic vinyl composition tile performed worse environmentally compared to natural cork floating plank flooring. It should be noted that the difference in scores is not relatively large. This suggests that a reassessment of products be considered before making a final selection.

#### 4.4.2 Economic Performance Interpretation

The economic performance of generic vinyl composition tile and natural cork floating floor planks was measured using statistical methods including standard deviation and coefficient of variance to measure the variability in costs. Only the material cost, or purchase price, was considered in this study, and not labor and equipment costs to install them. A total of 40 websites were researched for both prices on a dollar per square foot basis. A total of 1,636 different products were found with 191 differing prices. The average price for 1,261 different vinyl flooring products was \$3.47. The average price for 375 cork flooring products was \$5.16. This resulted in a 33% difference in costs between the two products. Both flooring products had a relatively small standard deviation resulting in small variance as represented by each coefficient of variance. It should be acknowledged, however, that cork flooring had a less uniformity and more variance or distribution in cost prices compared to vinyl. Table 4.5 summarizes the statistical analysis used to determine the economic performance of generic composite vinyl tile and natural cork floating floor plank.

Table 4.5: Statistical Analysis Summary

Statistical Measures	Vinyl	Cork
Sample Size	1,261	375
Average Price (P), \$/sq. ft	3.47	5.16
Standard Deviation ( ), \$/sq. ft	0.57	1.06
Coefficient of Variance (CV)	16%	21%

The final step of the cost analysis is to interpret the average price, or what is considered the average purchase price, by computing their economic performance. The economic performance value is calculated by dividing purchase prices by the highest purchase price between the two products and multiplying by 100. This essentially interprets the percent cost difference between the two products. The lower percentage represents the cheaper alternative. Table 4.6 illustrates the economic performance scores.

Table 4.6: Economic Performance Scores for Generic Vinyl Composition Tile and Natural Cork Floating Floor Plank Based on BEES Stakeholder Panel Importance Weights

Economic Performance Interpretation		
	Vinyl	Cork
Purchase Cost (\$/sq. ft)	3.47	5.16
Performance Score	67	100

#### 4.5 Purchase Decision

Based on the environmental and economic performance analysis, it can be concluded that natural cork floating floor plank is the most environmentally friendly product, but is also the more expensive compared to generic vinyl composition tile. Prior to selecting a building product using a MADA conversion, it is necessary to identify the benefits and limitations implicated in the particular analysis tools, including the specific software, databases, and assessment and interpretation methods for the economic and environmental performance of generic vinyl composition tile and cork floating floor plank.

#### **4.5.1 Environmental Performance Benefits and Limitations**

The major benefit from using BEES® 4.0 as a tool is that it facilitates the comparison of products by having a single final performance score that accounts for the entire life-cycle of building products. It uses life-cycle concepts based on consensus standards, such as LCA from ISO 14040 and MADA from ASTM E1765 (Lippiatt, 1999). It also allows users to customize the relative importance weighting for different environmental impacts (Lippiatt, 1999). The tool is also transparent in documenting and providing data and computational algorithms (Bayer et al., 2010). Finally, the tool is free of cost and does not require extensive training to use.

BEES® 4.0 also includes many assumptions that limit its reliability. Building products in a generic product group, such as generic vinyl composition tile are not created in the same manner resulting in a misrepresentation of the environmental performance results of an individual product (Lippiatt 2007). BEES also excludes inventory flows which are currently neither scientifically validated nor quantified (Lippiatt 2007). If a decision-maker recognizes a missing inventory flow, a separate effort must be made to have a comprehensive analysis. During the interpretation step of the LCA analysis, the weighing and normalization calculations incorporate many assumptions and are subjective, increasing the level of uncertainty of results (Lippiatt 2007). More uncertainty is added when there is no reference to the whole building design and the incorporation of building elements within (Lippiatt 2007). During the operation and maintenance phase of a flooring product, for example, its environmental impact may be influenced by other elements such as subflooring (Lippiatt 2007). Having no reference to the whole building design forces decision-makers to make more assumptions resulting in less reliability of results.

#### 4.5.2 Economic Performance Benefits and Limitations

The software used to analyze national flooring prices was Microsoft Office Excel 2007. The methods used to analyze price data included standard deviation and coefficient of variance measures. A benefit to using these measures is their simplicity in using them and in interpreting them. They are also easily calculated using Excel, providing a quick analysis of a sample of any size. The method used to interpret the economic performance of products is also a simple calculation that is easily understandable. Like the environmental performance scores, the economic scores provides decision-makers with the ability to easily evaluate a single score.

A major drawback to the cost analysis approach is the inconsistency between the characteristics analyzed in the environmental performance to that of the economic performance. For example, BEES systems a vinyl tile size of 30cm x 30cm x 0.3 cm (12in x 12in x 1/8in) weighing 0.613 kg (1.35 lb) based on specific mass of constituents including limestone, vinyl resins, and plasticizer (Lippiatt 2007). Vinyl products analyzed for the economic performance ranged both in size and weight. Some supplier websites only provided a brief description of the product but did not include weights or type of materials constituting the product. For this case study, generic vinyl products were defined as products that are common and standard, creating many assumptions. The LCA for natural cork flooring specified constituents largely made from recycled waste. Such information was not available in many supplier web sites. Another significant limitation is the extensive amount of time needed to search for building product prices. More data results in more accurate average prices at the expense of time and perhaps money. Price data was retrieved from 40 supplier websites for over 1,600 products. This required expertise in navigating through the internet in order to be efficient. It should be noted that many suppliers websites do not provide a building product price unless a quota is requested, which can take days.

### 4.5.3 Results

After clearly identifying the opportunities and limitations provided by the methodologies used to analyze the two flooring products, decision-makers are more knowledgeable in selecting weights that reflect their personal reliability on each analysis. In this case study, a MADA sensitivity analysis was performed by modifying the weights used to evaluate the total performance of both building products. This is done to test the effects on the scores when changing the set of importance weights. Using equal weights to evaluate the total environmental and economic performance, Table 4.7 shows how the performance scores from Table 4.3 and Table 4.6 are weighed and normalized to derive comprehensive performance scores for vinyl and cork flooring products.

The results demonstrate that based on equal importance weights, vinyl composite tile performs better than natural cork flooring. To a more extensive indication of the performance of these products, a sensitivity analysis was conducted using 40/60%, 60/40%, 25/75%, and 75/25% weights for the environmental/economic performance, respectively.

Table 4.7: Total Scores for Flooring Products Based on Equal Importance Weights for Environmental and Economic Performance

Flooring Product	Weighed Scores			Weighted, Normalized Scores		
	Environmental (50% weight)	Economic (50% weight)	Total	Environmental	Economic	Total
Generic Vinyl Composition Tile	41	34	75	26	22	48
Natural Cork Floating Floor Plank	32	50	82	20	32	52
Sum			157			

Table 4.8: Sensitivity Analysis on Total Environmental and Economic Scores

Flooring Product	Total Weighted, Normalized Scores				
	50/50% weights	40/60% weights	60/40% weights	25/75% weights	75/25% weights
Generic Vinyl Composition Tile	48	46	49	44	52
Natural Cork Floating Floor Plank	52	54	51	56	48

Based on the sensitivity results, as shown in Table 4.8, vinyl had a better overall performance score in all of the differing weight specifications, except when weighed on a 75/25% environmental to economic performance. It should be recognized that the performance scores are relatively similar for both products. This suggests that the scope and objective of this analysis be revisited to justify a selection. Furthermore, it acknowledges that importance weights play a significant role in the final LCM performance score. The goal of this study was to select the product with the lowest total performance score based on results from the sensitivity analysis. As a result, generic vinyl composite flooring should be selected for having a superior LCM score.

## **CHAPTER 5**

### **CONCLUSIONS AND RECOMMENDATIONS**

#### **5.1 Life-Cycle Management (LCM) System Summary and Conclusion**

The objective of this study is to support decision-makers in selecting building products that are environmentally and economically balanced through a proposed LCM conceptual system. Motivation for the system originated from case study results that proved the high variability in bidding estimates with and without the inclusion of green products. A distinct case study was developed to test the LCM system. The results disprove conventional perceptions, including the intuition that natural cork flooring is a more environmentally preferable purchase choice compared to generic vinyl composition tile. Such results further reinforce the significance in taking a multiattribute approach to assessing a building product's sustainable and financial performance. The case study exposes the way in which LCM system transparently demonstrates the implications of each analysis. It also proved the practicality of using the system, as it combines environmental and economic performance into a single performance value that is easily interpreted. Ultimately, the LCM system exposes the true environmental and economic sustainability of building products with the help of tools readily available in the market. The proposed decision support system is a basis for developing a comprehensive building product assessment tool with a potential for use in cost estimating and bidding practices.

#### **5.2 Limitations of the Study**

At the current stage of development of LCA tools and resources, there are not enough economic incentives for the building community in the United States to accept it as a selection

support system, as it generally consumes more time and resources than it saves for building projects (Bayer et al. 2010). Furthermore, databases can be inaccurate, incomplete or too generalized, requiring the decision-maker to use multiple sources while drawing more assumptions to the analysis (Bayer et al. 2010). In addition, many LCA experts debate the impact assessment methods and the practice of weighing them. Since the methods used to translate and quantify inventories into impacts vary by the complexity of the impact category, information can be interpreted with inconsistency. The results from the impact assessment are further reduced into a single score, adding more assumptions and generalizations to an already existing inconsistency (Bayer et al. 2010, Bare 2000). Since LCA is still developing, the proposed LCM system only provides a temporary remedy to the complexity of selecting environmentally friendly building products. Many experts believe, however, that a better integration of LCA techniques and LCA-based decision support tools such as the LCM system can aid in the product selection problem (Trusty 2003).

This study does not recognize or consider the ramifications of selecting a specific product. For example, the maintenance and operation consequences of selecting vinyl composition tile, such as the use of water, detergent, polish, and wax and their respective impacts on the environment are not accounted for. The impacts from maintenance have proved to be significant compared to the impacts from the floor, as results are heavily dependent on the chosen cleaning method (Paulsen 2003). It is also important to recognize that the most significant environmental and economic impact incurred by energy consumption is during the operations and maintenance phase of a building. While considerable emphasis should be placed on the selection of green products and their embodied energies, it is not the most important aspect of sustainability when considering the operating energy of a building (Bayer et al. 2010). Evidence shows that operating energy is significantly greater over the life of a building to a point where concerns over embodied energy are irrelevant (Trusty 2003). This suggests

that the environmental payback is quick for buildings that usually have a life-span of up to 100 years. However, embodied energy must be taken into account because of the emissions related to energy consumption (Trusty 2003). Other embodied effects such as toxic releases to water to effects during the resource extraction and manufacturing stages greatly overshadow releases related to building operations (Bayer et al 2010).

### **5.3 Recommendations and Further Research**

Advances in research and development are perceived to promote a more reliable and popularized use of LCA. In the meantime, it is recommended that projects begin incorporating the pilot program established by LEED to incorporate LCA in order to begin setting benchmarks for the industry. This would transform the way the industry performs environmental assessment on whole-building assemblies and products and perhaps promote research in more simplified tools and methods to conduct LCA.

Another recommended follow-up to this study is to perform a comprehensive cost study on common building elements. By investigating the cost variability within those elements, other factors that account variation can be accounted for. The cost variability problem can also be investigated by studying the role of economical databases in construction, such as RSMeans CostWorks®. Finally, in order to focus on a more integrated approach, it is necessary to account for the operational and maintenance costs of selecting specific products.

This study provides a framework as a base for further development. It is necessary to investigate the environmental and economic effects and variability of several building products and ultimately complete a prototype study on an entire building to validate the LCM system. Such comprehensive study can result in more accurate conclusions on the environmental and financial consequences of selecting a product. Furthermore, an integrated study can identify the

opportunities and challenges of using LCA methodology and costing analysis when evaluating the performance of an entire building. Lastly, since Building Information Modeling (BIM) is becoming one of the most commonly used state-of-the-art design tools, research should be invested in studying the incorporation of LCA and cost information into the tool.

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