A Methodology to Select Environmentally-Friendly Construction Materials

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An essential component of the green building construction process is the selection of building materials in order to minimize natural resource consumption and the resulting impact on the ecological systems. Despite this clear objective, selection of building materials for sustainable construction is one of the most difficult challenges facing the green movement. Available criteria that rate environmentally-friendly materials are numerous and often contradict one another. Although some materials are green and may be ideal from an environmental point of view, the entire life cycle must be considered to fully assess the ecological performance of the product. In addition, it can be debatable on whether the selection of building materials depends primarily on the material being renewable and sustainable or on the overall environmental impact of the resulting building. To address this issue, rather than focusing on a single issue, this paper describes a methodology that can be used to analyze different construction materials throughout their entire supply chain. The presented methodology focuses on important issues such as embodied energy, saved energy, emissions, waste, and options of recycling and reuse at the end of the service life. For demonstration purpose, this methodology is used in the selection of a sustainable flooring system.

Keywords: emissions, environmental issues, energy consumption, construction materials, recycling,

Introduction

Choosing the best material for green buildings is one of the most difficult tasks facing the sustainable movement. The criteria available to rate materials as environmentally preferable are numerous and often contradict one another. For instance, one school of thought rates green building materials by their chemical emissions and their impacts on the indoor air quality. Other schools of thought define green materials as those that are rapidly renewable such as wood originating from sustainable harvested forests. The Environmental Building News has suggested five major categories of what can be classified as an environmentally-friendly material (Environmental Building News 2000):

- Products made from environmentally-friendly materials
- Products that are considered green
- Products that reduce the environmental impact of construction operations
- Products that reduce the environmental impact of building operations
- Products that contribute to healthy indoor environment

Rather than focusing on a single factor, this paper describes a methodology that can be used to analyze different construction materials through their entire supply chain. This methodology considers important issues such as embodied energy, saved energy, emissions, waste, and options of recycling and reuse at the end of the service life.

Background

Embodied Energy, Operational Energy, and Saved Energy

Embodied energy is a measurement of the needed inputs to extract a given material. It is defined as the total energy consumed by all the processes associated with the material. These processes include the acquisition of raw materials, manufacturing, transportation, and installation of the material (Kibert 2005). To include the energy inputs in the material life cycle, embodied energy can also include all of the inputs of the material over the life span by including renovation and maintenance (Milne and Readon 2004). Typically, the greater the embodied energy the greater the potential negative impact on the environment due to all of the emissions due to the energy consumption. The durability of the product can be measured if the embodied energy is divided by its service life. A lower embodied energy per time in use is preferable due to its high durability (Ehlen 1997).

Embodied energy within a material is a difficult quantity to assess and many may believe that high embodied energy materials are justified when the material contributes to lower operating energy such as thermal mass materials (e.g., concrete). However, unlike operational energy, which is dependent on the occupant's consumption over time, embodied energy is constant and is built into the materials during the construction of the building. It only increases by maintenance and renovation operations. The longer the service life of the material, the less the embodied energy due to the increase in distribution of the energy throughout the life span, as described by the durability. Figure 1 shows that the savings in operational energy can be far greater than the savings seen in embodied energy. This fact will be utilized in setting the material selection criteria later in this paper.

There are two measurements of embodied energy, the Gross Energy Requirement (GER) and the Process Energy Requirement (PER) (Grefen 2005). Gross Energy Requirement is the idealistic true measurement of the embodied energy of a material. This includes all measurements, such as the transportation energy, the construction energy, and the manufacturing energy. Ideally the transportation energy includes both the energy to transport the materials as well as the energy of the urban infrastructure used to transport the material. The manufacturing energy ideally should include all of the energy to make the material such as the factory lighting, machine energy, etc. This measurement is fairly idealistic and impractical to measure. The Process Energy Requirement is a simpler method and is more commonly used. This includes all of the energy directly related to the manufacture process of the material. The PER is comprised of the energy to transport the raw materials, and the manufacturing energy. This method is still yet impractical to define an exact number and should only be used to assist in comparing materials (Milne and Readon 2004).

Both values the PER, and GER vary by product, process, manufacturer and application and by how it has been quantified. Hence, the values obtained should only be used as a relative guideline. Because of this variability, it is important to insure that when using the values of embodied energy that all of them are obtained by the same method (Mumma 1995). Therefore, embodied energy requires significant cooperation with suppliers and manufacturers due to its dependency on the extraction process. Suppliers should agree to monitor and measure the energy use and provide it to the designers. Embodied energy is often reduced if the energy efficiency of the manufacturing process is improved. To encourage this process, there must be a need for low embodied energy within the industry (Grefen 2005).

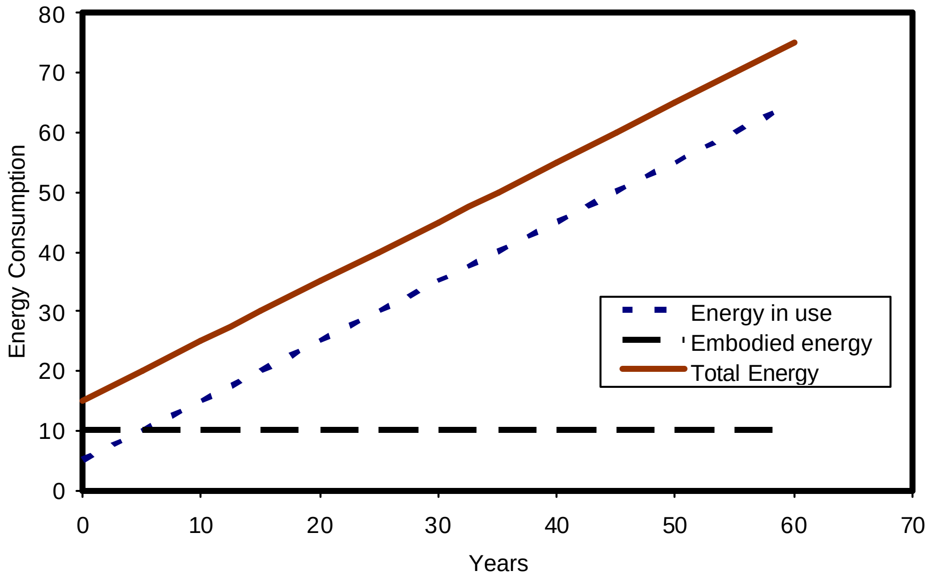

Figure 1. Comparing operational energy to embodied energy (Crane 1999)

The embodied energy also differs depending on whether the material is processed from its raw components, reused, or recycled. These values vary by materials and may be used to determine if reusing or recycling the material is worthwhile. If the embodied energy is reduced then there is saved energy. For example, recycling aluminum saves 95% of the required energy while recycling glass saves only 20% (Mumma 1995).

The energy saved in a building is highly influenced by the operating energy of the building. Some materials can reduce the operating energy consumption. For example, materials with high thermal mass reduce the size of the HVAC, and therefore, consume less energy. As shown in Figure 2, a material that requires more energy to make can be compensated by the savings in energy use and thus the outcome of total energy use is still lower. This fact suggests that the total energy serves as better selection criteria.

Emissions

Emission percentage varies with the material, the environment surrounding the material, and the condition of the material. Emissions are given off throughout the lifecycle of a material during manufacturing, use, and disposal. During the use of the product, there is a general correlation between new materials or materials placed in conditions of high humidity and temperature and the increase in emissions. The amount, effect, frequency and rate of emissions resulting vary based on the material used. Some materials only emit while in use, while others emit continuously. Emissions at high concentrations can remain for long periods of time in the air. It can be absorbed by other materials and re-emitted. High concentrations of emissions can result from materials that emit a large amount as well as materials that emit a small amount but that are present in large quantities. The target is how much a single source will emit and how hazardous the emissions are. This measurement is often affected by the age and upkeep of the material. Materials inside the home are more likely to affect the health of people when compared to the exterior materials (Milne and Readon 2004). A typical example of harmful emissions is volatile organic compounds (VOCs) which are a wide range of chemicals that become airborne at room temperature. Another example is the production and disposal of products emitting carbon monoxide, nitrogen oxide and methane as they are pollutants to the environment at high concentration (Stuart and Sommerville 1998).

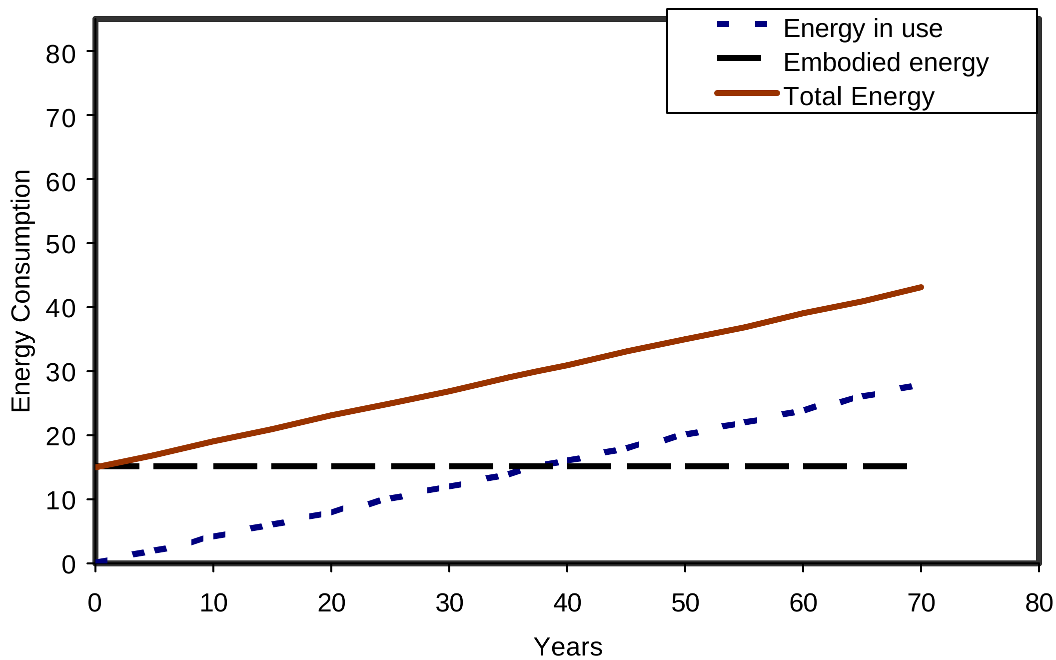

Figure 2. Energy consumption in a low energy house (Crane 1999)

Waste

Construction and deconstruction contributes 13% to 29% to landfills in the United States, Australia, Finland, Germany, and the Netherlands (Matson 2004). In addition to emissions due to energy use and materials off gassing, waste landfills are the largest source of methane - a greenhouse gas emission (EPA 2006). Since a building may not be demolished for many years after construction, accurate depiction of this stage would require forecasting technologies and markets for recycling and waste management far into the future (Forintek and Trusty 1997).

Reuse & Recycling

Although reuse and recycling offer many benefits, it is faced with many challenges. Asphalt concrete, steel, aluminum, and wood are the only materials that have been significantly recycled and has shown a positive market value. Recycling reduces the embodied energy, material cost and keeps the material out of the landfills longer (Matson 2004). Since it is difficult to measure which products are better candidates for recycling, the embodied energy will be expanded to include the estimated life span including the recycling of the material.

Current Material Selection Methodologies

There are a number of different tools available for comparing products from an environmental perspective. These tools include ATHENA Environmental Impact Estimator (EIE) and Building for Environmental and Economic Sustainability (BEES). Most of these tools are based on the life cycle assessment (LCA) methodology which assesses the environmental percussions of materials over their whole life cycle measured by a wide range of potential effects. ATHENA's Environmental Impact Estimator, is the only North American software for the life cycle assessment of buildings. It covers 90 to 95% of the structural and envelope systems typically used in both residential and non-residential buildings. Moreover, it has databases for energy use and related air emissions for on-site construction of a building's assemblies; for maintenance, repair and replacement effects through the operating life; and for demolition and disposal (Jincheng, Weichang, Xinli, and Tianmin 2001).

BEES, Building for Environmental and Economic Sustainability, measures the environmental performance of building products by using the life-cycle assessment approach specified in the ISO 14040 series of standards. All stages in the life of a product are analyzed as shown in Figure 3: raw material acquisition, manufacture, transportation, installation, use, and recycling and waste management. Economic performance is measured using the ASTM standard life-cycle cost method, which covers the costs of initial investment, replacement, operation, maintenance and repair, and disposal. Environmental and economic performances are combined into an overall performance measure using the ASTM standard for Multi-Attribute Decision Analysis. For the entire BEES analysis, building products are defined and classified according to the ASTM standard classification for building elements known as UNIFORMAT II (Gerfen 2005).

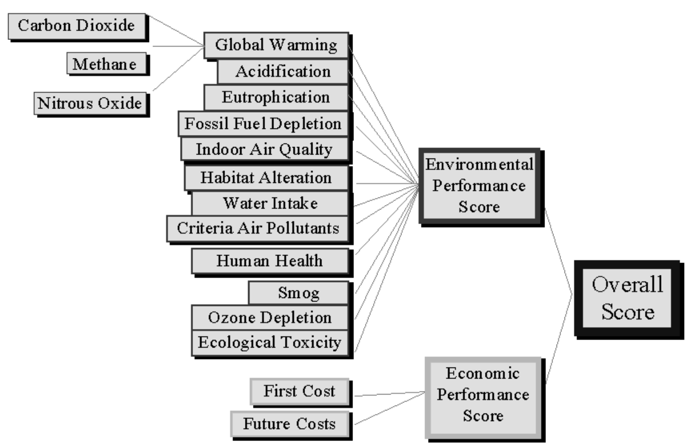

Figure 3. BEES framework analysis (After BEES 2002)

Proposed Methodology

Although the aforementioned tools provide a milestone for establishing a general design tool for green material selection, we are still lacking a systematic flexible procedure that helps the designer to choose green materials and optimize the design at the same time. This paper is proposing a methodology that will bridge this gap. A summary of the proposed methodology is presented in Figure 4. It has to be noted that this methodology prefers the utilization of sustainable materials wherever possible but it may allow utilization of sustainable products if it is the only solution to minimize the environmental impact of the building. In addition, it takes into account the environmental impacts of the selected green materials throughout their entire supply chain.

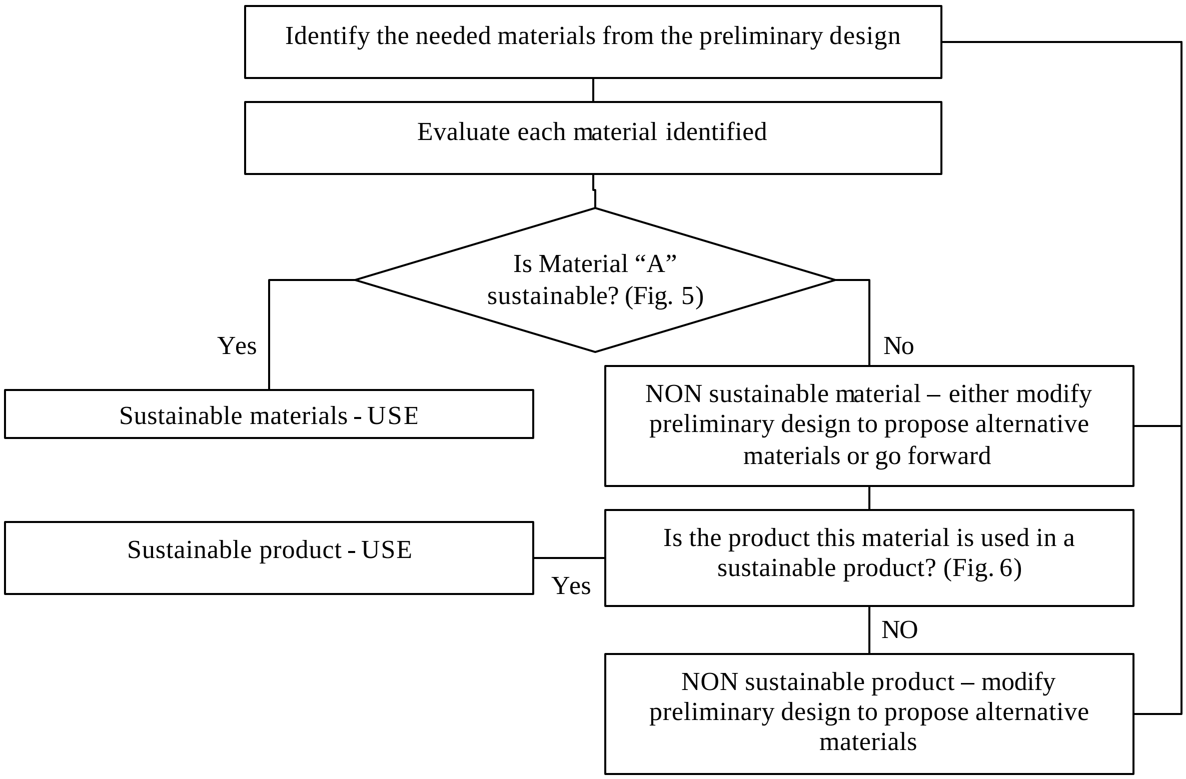

Figure 4. Summary of the proposed methodology

The first phase of any construction projects is the preliminary design phase. The proposed framework recommends extracting all the possible needed materials from the project's preliminary design. Once the design team compiles a list of all the materials that will be employed in the project, it must evaluate each material to determine whether it is sustainable or not as shown in Figure 5. This determination will be made in several steps. The first step consists of answering the following questions by yes or no:

- Is the material under consideration non toxic?
- Can the material under consideration be recycled, reused, or decompose without generating waste at the end of its service life?
- Is the material under consideration originating from reused or recycled products or is it from a renewable source, or abundant in nature?

where reused means remanufactured in the same form in a sustainable way i.e., re-milled lumber; recycled means the product is 100% recyclable in a closed-loop in a sustainable way; and renewable means able to regenerate at a normal way in a rate greater than the consumption rate and abundant means usage is much smaller than the natural existence of the material.

An answer of no to any of the three questions means that the material is not sustainable. If the answer to all questions is yes, the following need to be determined:

- Determine the material emissions
- Determine the material waste

- Determine the ecological rucksack of the material
- Determine the Material Intensity per unit service (MIPS)
- Determine the material embodied energy

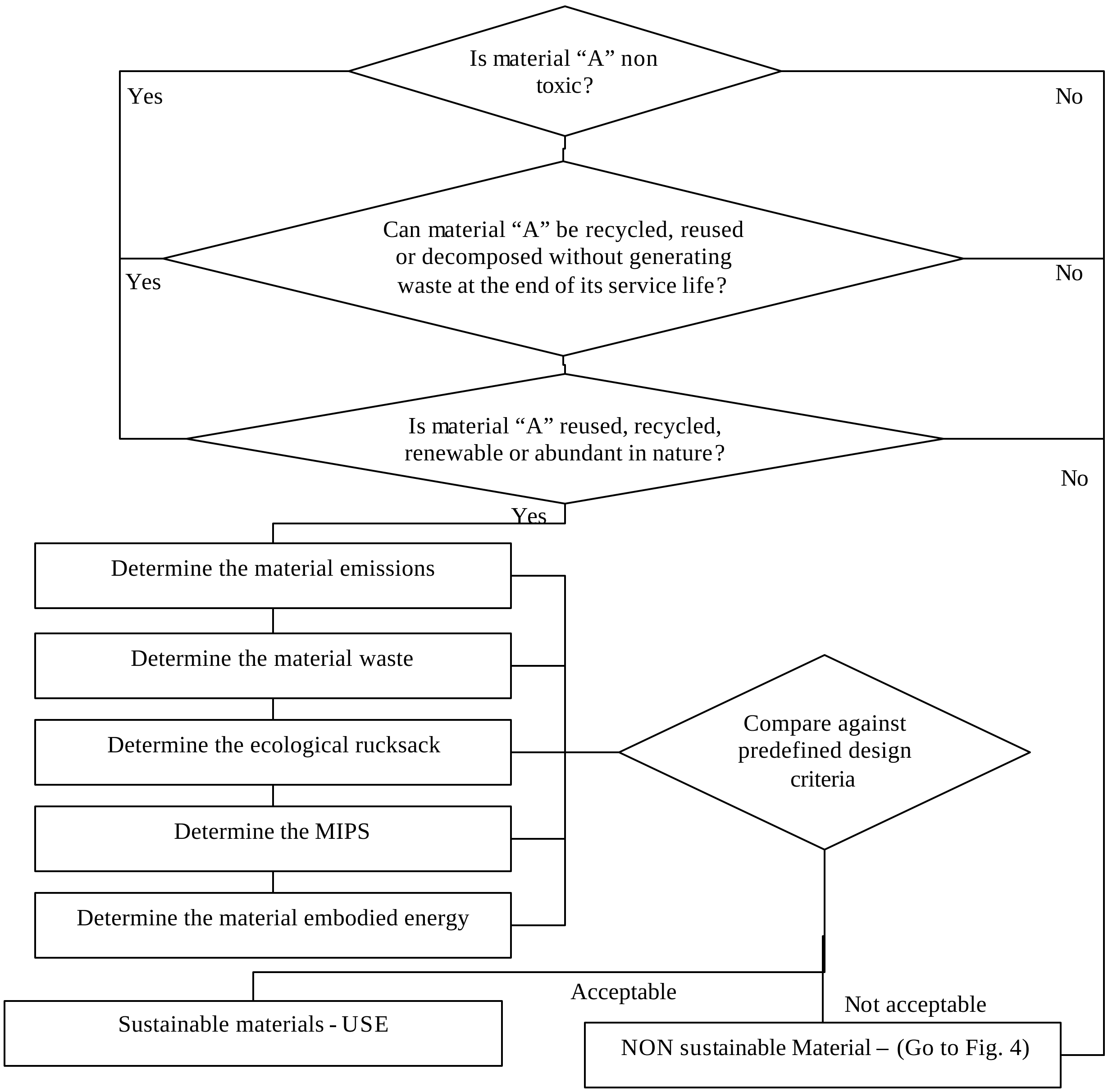

Figure 5. Defining sustainable materials

Where the ecological rucksack is defined as the amount of material that needs to be moved in order to extract a specific resource; MIPS is defined as the amount of service a given product delivers; the greater the service the lower the MIPS; and embodied energy is defined as the total energy consumed in the acquisition, and processing of raw materials manufacturing transportation and final installation. Low values of the variables indicate a sustainable material. High values indicate non-sustainable materials. The values determined from the aforementioned materials need to be compared against a predefined criterion selected by a charrette consisting of the different project stakeholders including owners, occupants and the city/town council. If the values are acceptable then the material is considered sustainable.

If the materials under consideration prove to be non sustainable, the design team should evaluate the product this material is used in to determine if it is a sustainable product. This evaluation is done in two steps: 1) an initial screening composed of answering a set of questions, and 2) calculating the environmental impact of the product using one the available tools i.e., BEES or Athena (EIE). The questions used for the initial screening, shown in Figure 6, are:

- Does the product under evaluation favor deconstruction, reuse, and durability?
- Does using this product reduce/eliminate the structure's use of non renewable resources, i.e. fossil fuels?
- Does using this product reduce emissions and waste?

If the answer to all of the questions is yes, then this product will help create a sustainable building and this may be a justifiable reason for using a non-sustainable material. For example, a desiccant de-humidifier may not be composed of 100% sustainable materials but it reduces the building's energy consumption thus reduces the building's environmental impact.

If the answer to some of the questions is yes and some is no, then the generated alternatives need to be evaluated using a more detailed analysis tool like ATHENA EIE or BEES. If the alternative materials/products selected do not prove to be sustainable materials or products, using the detailed analysis tools or the answer to all the questions is no, then the design team should propose alternative materials/and or products and the evaluation methodology will be repeated as shown in Figure 4.

Methodology Demonstration

To demonstrate the use of the proposed framework, this paper utilizes the methodology to evaluate a flooring system for a commercial building. The design team decided to utilize Linoleum as a flooring system. They set the material selection criteria as:

- Total emissions per hour of m^2 flooring: < 0.5 $mg/hr/m^2$
- Total waste per month of m^2 flooring: < 5 $g/month/m^2$
- Hazardous waste per month of m^2 flooring: < 1.0 $g/month/m^2$
- Ecological rucksack: < 3 Kg/Kg
- Embodied energy: < 63 MJ/m^2

Step 1 of the framework requires answering the following questions:

- Is Linoleum non toxic? Yes (Jonsson, Tillman, and Svensson 1997).
- Can Linoleum be recycled, reused, or decompose without generating waste at the end of its service life? Yes, it is biodegradable.
- Is Linoleum reused, recycled, renewable, or abundant in nature? Yes, Linoleum is a natural material that has readily renewable ingredients and is recyclable.

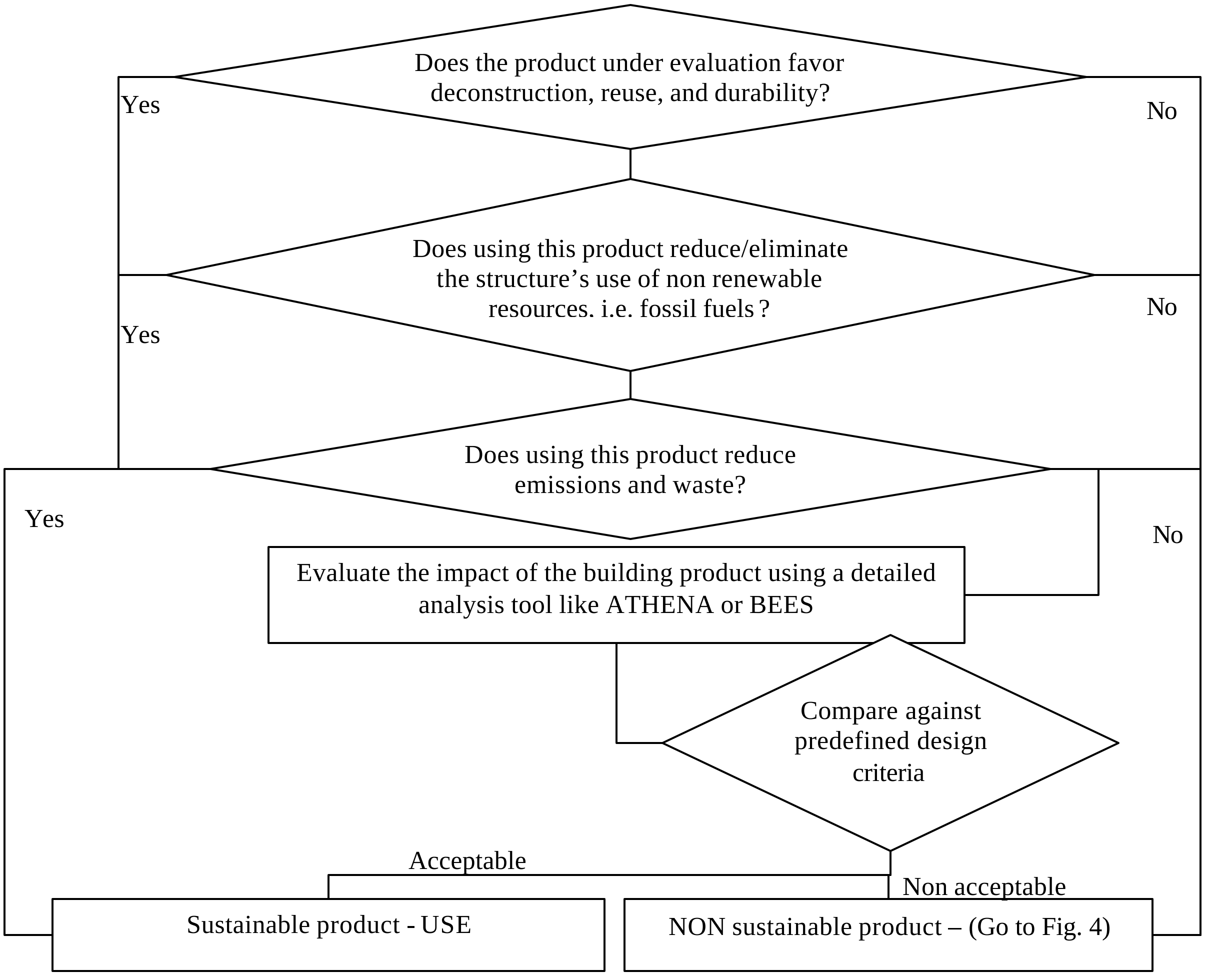

Figure 6. Defining sustainable products

Answering the aforementioned questions with yes moves us to the next step:

- Determine Linoleum emissions (Jonsson, Tillman, and Svensson 1997).

Air Emissions per hour per m^2 flooring

SO_2 (mg)	No_x (mg)	Dust (mg)	VOC (mg)	Total (mg)
0.018	0.057	0	0.046	0.121

- Determine Linoleum waste (Jonsson, Tillman, and Svensson 1997).

Waste for one year of m^2 flooring

Ash (g)	Hazardous Waste (g)	Total Waste (g)
1.9	0.83	2.73

- Determine the ecological rucksack of Linoleum: 2Kg/Kg
- Determine Linoleum Intensity per unit service (MIPS) – In this case, MIPS is not needed since Linoleum is a basic construction materials, not a product.
- Determine Linoleum embodied energy - 57.7 MJ/m^2

Comparing the five values against the aforementioned material selection criteria shows that Linoleum is an acceptable sustainable material and can be used in the flooring system.

Conclusions

Selecting the right materials to build sustainable buildings is a challenging task. Some materials are renewable but they produce hazardous waste, others are non renewable but utilizing them in a building product may reduce the overall environmental impact of the building. This raises the question of which materials can be classified as sustainable materials and which materials can be used in an environmentally-friendly construction project. Therefore, this paper attempts to present a flexible solution to this dilemma by presenting a methodology for selecting sustainable materials and sustainable products for building green construction projects. This methodology takes into consideration the life cycle of the materials throughout their entire supply chain. The methodology focuses on important issues such as embodied energy, emissions, waste, and options of recycling and reuse to select green design materials. For demonstration purpose, this methodology is used in the selection of a sustainable flooring system. Utilization of this methodology in sustainable design and construction processes will simplify and standardize the material selection decision making process. It will also highlight the research needs that will provide the industry with more environmentally friendly materials.

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