

MATERIAL SELECTION OPTIMIZATION MODEL FOR GREEN BUILDINGS

by

Ömer Yakalı

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ABSTRACT

MATERIAL SELECTION OPTIMIZATION MODEL FOR GREEN BUILDINGS

Buildings deplete natural resources and pollute the environment. They are responsible for a large portion of harmful emissions and use notable amount of energy. Green building philosophy has evolved due to the immense impacts of conventional buildings. The green building movement intends to reduce these effects and form sustainable buildings. In this context, it is essential to assess environmental burdens of building materials in order to encourage decision-makers for selecting environmental-friendly materials. Recently, material selection process turns out to be an integral approach considering technical, environmental and economical aspects. Therefore, computer-based models are required to treat these multi-criteria problems. This study proposes a mathematical model in order to help decision-makers with the selection of proper materials in order to increase performance of green buildings. The integer programming optimization model tries to minimize the environmental impact of a building in a life cycle perspective based on candidate materials along with economic and additional environmental considerations. Economic factors are based on market prices. Moreover, environmental parameters cover recycled content ratio and availability of regional materials. The mathematical model is applied to a single storey building in order to analyze its effectiveness. Sensitivity analysis is performed in order to observe possible variations in decision-makers preferences. This thesis is distinctive from the previous studies. It determines a realistic approach between materials' cost and environmental features and enhances forming an entire environmental-friendly building. This study does not cover the environmental impacts result from occupancy phase of buildings.

ÖZET

YEŞİL BİNALARDA MALZEME SEÇİMİ İÇİN ENİYİLEME MODELİ

Binalar doğal kaynakları tüketir ve çevreyi kirletir. Binalar zararlı atıkların ve kullanılan enerjinin büyük bir bölümünden sorumludur. Yeşil bina felsefesi, geleneksel binaların bu önemli çevresel etkilerinden dolayı gelişmiştir. Yeşil bina hareketi bu etkilerin azaltılmasını ve sürdürülebilir binaların oluşturulmasını amaçlar. Bu bağlamda, karar vericilerin çevre dostu malzemeler seçebilmeleri için inşaat malzemelerinin çevresel yüklerinin ölçümlenmesi gerekmektedir. Günümüzde malzeme seçim süreci mekanik, çevresel, ekonomik etkiler gibi çeşitli faktörlerle ilgilenen çok boyutlu bir çalışmadır. Bu çoklu karar verme problemlerinin çözümü için bilgisayarla bütünleşik modellere gereksinim vardır. Bu çalışma, yeşil binaların performansını yükseltmek için karar vericiye uygun malzeme seçimi konusunda bir matematiksel model önerir. Bu tam sayılı programlama modeli bir binanın çevresel etkisini alternatif malzemeleri temel alarak; aynı zamanda ekonomik ve ek çevresel faktörleri hesaba katarak yaşam çevrimi perspektifi içerisinde en aza indirmeye çalışır. Ekonomik faktörler malzemelerin pazar fiyatına göre temellendirilmiştir. Ayrıca, çevresel parametreler geri dönüştürülebilir içerik oranı ve bölgesel malzemenin mevcudiyetini içerir. Model, geçerliliğinin analizi için tek katlı bir binaya uygulanmıştır. Karar vericilerin tercihlerindeki olası değişiklikler için duyarlılık analizi uygulanmıştır. Bu tez geçmiş çalışmalardan farklılık göstermektedir. Bu çalışma, malzemelerin maliyetleri ve çevresel özellikleri konusunda gerçekçi bir yaklaşıma sahiptir ve çevre dostu bir binanın kurulmasına yardımcı olur. Bu çalışma, binaların kullanımı süresince doğan çevresel etkileri içermez.

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LIST OF SYMBOLS

a_{ij}	Required amount for building material ij
ACP_f	Millimoles of hydrogen ions with the same potential acidifying effect as one gram of inventory flow f
B	Allocated budget for building materials
c	Index for environmental criteria
c_{ij}	Cost of material ij per unit
CO	Carbon Monoxide
CO_2	Carbon Dioxide
e_{ijk}	Characterized value for material ij with respect to category k per functional unit
EP_f	Grams of nitrogen with the same potential effect as one gram of inventory flow f
ES	Environmental impact score for the entire building
f	Index for inventory flow
GWP_f	Grams of carbon dioxide with the same heat trapping potential as one gram of inventory flow f
H	Hydrogen
i	Index for candidate materials
j	Index for building materials
k	Index for environmental impact categories
L	Building environmental loadings
m_f	Mass of inventory flow f
N	Nitrogen
N_k	Normalization value with respect to impact category k
NO_x	Oxides of Nitrogen
Q	Building environmental quality and performance
R	Desired recycled content fraction by cost
r_{ij}	Recycled content percentage of material ij
RM	Desired recycled regional material fraction by cost

rm_{ij}	1 if material ij is a regional material, 0 otherwise
s	Index for sub criteria
TS	Total Score
V_c	Gained value for criteria c
V_s	Gained value for sub criteria s
W_c	Relative weighting for criteria c
w_k	Relative importance weight for impact category k
y_{ij}	1 if material i is used for element j , 0 otherwise

LIST OF ACCRONYMS /ABBREVIATIONS

ACP	Acidification Potential
AI	Acidification Index
BEE	Building Environmental Efficiency
BEES	Building for Environment and Economic Sustainability
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
DfE	Design for Environment
EI	Eutrophication Index
EP	Eutrophication Potential
EPA	Environmental Protection Agency
GBC	Green Building Challenge
GHG	Greenhouse Gases
GWI	Global Warming Index
GWP	Global Warming Potential
IEQ	Indoor Environmental Quality
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LEED	Leadership in Energy and Environmental Design
NIST	National Institute of Standards and Technology
SBTool	Sustainable Building Tool
USGBC	United State Green Building Council

1. INTRODUCTION

Green building philosophy has emerged due to significant and continuously increasing negative impact of buildings on environment. Buildings deplete natural resources and pollute the environment. Buildings use nearly 40 % of natural resources extracted in the industrialized countries (Pulselli *et al.*, 2007). In addition, the construction sector consumes globally about 70 % of electricity, and 12 % of water (Wang *et al.* 2005). Besides, buildings have notable impacts on pollution. They are directly responsible for 30 % of greenhouse gases due to construction operations, and they cause 18 % of greenhouse gases indirectly by material extraction and transportation (Venkatamara and Jagadish, 2003).

Building materials account for a significant portion in such environmental burdens caused by buildings. Building materials are responsible for 10-15 % of energy consumed by buildings throughout their life cycle (Cole, 1996). Processes related to building materials such as production, transportation to construction site, and on-site construction consume 2.2 % of energy use during building's life span (Scheuer, 2003). Therefore, buildings' environmental impact is directly influenced by the environmental properties of the materials used; thereby material selection process has a strategic importance. It is worthwhile to note that assessment of environmental effects related with candidate building materials is essential in order to erect an environmental-friendly building.

Construction sector requires reliable methods in order to perform environmental impact quantification of building materials effectively. The most appropriate method for a holistic assessment of products, processes, and services is life-cycle assessment (LCA) (Junnala *et al.*, 2006). It quantifies the energy and material inputs and various emissions and waste outputs from an entire life cycle, starting with raw material acquisition, materials production, use, maintenance, and end of life. Thus, both the elements and stages which cause significant emissions and energy use could be identified and treated for improvement with LCA.

Designing for the environment (DfE) emerges as a critical concept in the construction sector. It is essential to assess the overall environmental effect of both production and processing of a single material or a combination of materials in this process. It is a natural expectation that the creation and use of any engineering product carries with it an environmental burden. There is a growing recognition that the minimization of this burden must become a primary design objective (Sirisale *et al.*, 2004). The inclusion of realistically complex environmental criteria in the design process necessitates the development of methodologies and tools to assist designers.

In addition, green building rating systems play an essential role in implementing the sustainability principles into the construction industry. They are defined as tools that analyze the performance of an entire building and give an overall assessment score that allows comparison against other buildings (Cole, 1999). Developing such rating systems are becoming significant due to considerable environmental, social, and economical problems; especially in developing countries with poor resources and inefficient use (Gibberd, 2005).

The proper material selection is not only a simple consideration of cost and material properties, but also an integral process that includes many factors such as environmental impacts and environmental characteristics. Thus, it can be formulated as a multi-criteria decision problem. Material selection process and life cycle of a product should be evaluated together (Chan and Tong, 2007). A study is essential considering both material environmental characteristics and life cycle assessment for a green building.

The intention of this study is to construct cost-effective and environmentally preferable buildings. The proposed model allows decision-makers to minimize specified environmental impacts of buildings in a life cycle perspective based on candidate materials used for building components while satisfying additional environmental and economic considerations in the selection of materials. There are many techniques for material selection in building construction. However, this study considers alternative materials along with realistic cost approach and supportive environmental considerations. It will help decision-makers to select suitable materials in order to develop green buildings.

The aim of this study is to provide a mathematical model in order to reduce the environmental effects of buildings caused by alternative materials. The model attempts to identify the best environmental-friendly materials for a comprehensive building envelope as well as considering economic and environmental characteristic issues. The proposed model is applicable to all building types. It broadens the scope for material selection process by incorporating environmental properties of materials and their market prices.

This study does not cover the environmental impacts resulting from occupancy phase of buildings. The inclusion of occupancy stage into LCA of buildings requires great efforts and considerable time. The proposed mathematical model enhances the material selection process at purchase stage. It offers decision-makers selecting environmentally benign materials regarding their specified environmental labels.

After this brief overview related to the green buildings, the remaining parts of the thesis is organized as follows. Chapter 2 presents literature review on holistic description of life cycle assessment and green building rating systems. Also, it performs an overview for related studies in the literature regarding material selection which underlines their weaknesses. The framework is drawn in order to establish the LCA approach. This chapter also describes the four mainstream rating systems and discusses their shortages.

Chapter 3 explains the proposed methodology for the material selection problem and the solution framework. It determines environmental impact score which offers a single indicator for comprehensive evaluation. Moreover, this chapter proposes the mathematical model and explains the inputs of the model in detail.

Chapter 4 applies a numerical illustration to a single storey building. It examines the outcomes of the model for the entire building. The recommended candidate materials for each building element are investigated. Besides, the total environmental impacts of the desired building are calculated, and the results are interpreted. Chapter 5 presents sensitivity analysis and observes the results based on outcomes of the studies. It covers significant findings involving environmental and economic issues. Chapter 6 points out the importance of the study along with recommendations for future studies.

2. LITERATURE REVIEW

The scope of the study is considerably broad which requires comprehensive information from various disciplines. The literature survey can be classified into three main groups. First, life cycle assessment framework is reviewed pointing out relevant studies. Then, the concept of green building rating systems is explained along with the most common systems used internationally. Finally, material selection process is discussed as well as notable studies related with it. The details are shown in the following sections respectively.

2.1. Life Cycle Assessment

Life cycle assessment is defined as the comprehensive evaluation of a product or process over its life-span (ISO, 1997). Hence, the assessment of a product encompasses stages such as raw material acquisition, manufacturing process, use and maintenance, and disposal or recycling as well as the transportation processes between these stages. LCA covers environmental evaluation of a product or a process spanning from raw material extraction to disposal (Fava *et al.*, 1993). Mostly the products are assessed in cradle-to-grave or cradle-to-gate perspective. In cradle to grave viewpoint, all stages are analyzed from the raw material extraction to disposal of the product. The latter perspective -cradle to gate- considers the stages until the product is sold to the consumer.

The main idea beneath the LCA is to track all inputs and outputs of products' life cycle stages and to provide a blueprint for environmental burden due to the product. LCA tool quantifies all inputs and outputs associated with the scope of the study. The inputs for product life cycle cover raw materials from virgin or recycled materials, water, and energy. Waste outputs include emissions released to air and water effluents, and solid wastes. The main purpose of LCA is to quantify the energy consumption and environmental emissions of each life-cycle phase in detail (Abeyundara *et al.*, 2009).

In industrial engineering perspective, the fundamental objective is to minimize environmental impacts resulting from life cycle stages of products. It could be achieved

with proper material selection and focusing on the life cycle stages which significantly contribute to environmental damage due to a product. LCA possess opportunities in order to develop environmental performance (ISO, 1997). For instance, use of recycled material will significantly reduce the need for energy and resources during manufacturing process which leads environmental impact reduction. Eventually, LCA is a useful method in determining environmental deficits of products during their life time and taking corrective action in order to minimize such burdens.

2.1.1. Methodology Framework for LCA

Evaluation of products' impacts on human and environment is a challenging and a complex task. There are numerous inputs and outputs throughout products' life cycle. The inventories taken from such inputs and outputs are called life cycle inventory (LCI). Considerable amount of inventory data is required in order to conduct holistic assessment. Data collection is costly and challenging (Sun, 2003). Therefore, expertise is needed for handling LCI and converting them into environmental impacts. As it is clearly observed from the definitions, a framework is essential in order to employ LCA properly. According to International Organization for Standardization (ISO) 14040, the LCA framework is comprised of four phases: Goal and scope definition, Inventory analysis, Impact assessment, Interpretation.

Goal and scope phase describes the objective of the LCA. The LCA scope is generally cradle-to-grave or cradle-to-gate depending on valid data. This is also the phase in which boundaries of the product system are established. There are three steps in order to generate system boundaries. There are numerous unit processes over life span of a product. Each unit process has various inventory flows in terms of inputs and outputs. Therefore, the first step defines the unit processes which will involve in the LCA. Selecting the necessary processes is significant for inventory tracking properly. Since quantifying all inventory flows is not practical, the tracked flows -inputs and outputs of selected unit processes- during life time of a product are determined in the second step. The flows are significant for a relevant calculation for environmental impacts in the third phase. Finally, the functional units for product comparison are assigned. It provides a fair comparison among product alternatives in terms of impact values.

Inventory analysis is the second phase of LCA framework. LCA is as valid as its data. This phase includes data collection within the system boundaries consistent with the goal and scope definition. As stated before, there are a number of unit processes during life cycle of a product. The union of specified unit processes forms the scope of the study. The Figure 2.1 illustrates a unit process with its input and outputs.

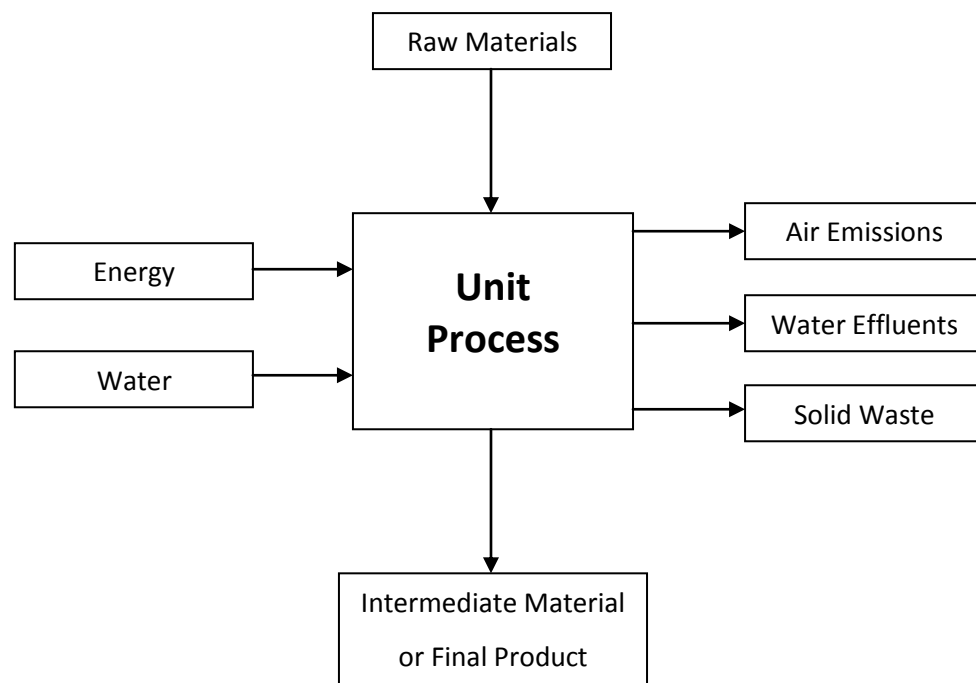


Figure 2.1. Unit process with inventory flows.

The data are gathered from particular environmental flows of all tracked unit processes. Such flows can be classified as inputs and outputs. Input flows can be stated as materials, water, and energy. Output flows are air emissions, water effluents, and solid wastes. The quantified values are elementary environmental values. Interpretation could also be made at this phase by observing and investigating these environmental flow values. The functional units for inventory flows should be suitable with the units defined at goal and scope phase. This provides a relevant comparison among alternative materials or products. The parameters for inventory data should be the same for each candidate material in order to conduct a fair comparison. Since the data collection process is very complex, decision makers may refer to LCI databases and LCA tools.

Impact assessment phase is basically an evaluation of the environmental impacts of the inputs and outputs determined in the inventory analysis phase. It comprises of four steps. Classification is the first step which allocates inventory parameters into categories of impacts such as global warming, eutrophication, and acidification. These impact categories will be further illustrated in Section 2.1.3. Then, impact potentials are characterized and calculated regarding LCI results. Large amount of data are summarized at this step. Impact categories have different units. For instance, global warming potential is expressed in carbon dioxide equivalents, acidification in hydrogen ion equivalents. In normalization step, normalization values are applied to the impact potentials in order to remove different units and synthesize different environmental impact potentials into same units. Finally, weighting step provides decision maker assigning relative importance weights in order to convert the life cycle impacts of a product into a single indicator.

Interpretation phase performs comprehensive analysis of the remaining three phases. In fact, it provides transition through life cycle framework. Decision makers can interpret both results from LCI and environmental impact evaluations. Moreover, they may ensure whether the goal and scope for the LCA is achieved. If there are problems in meeting the aim of the study, improvements could be made in each step. Figure 2.2 below depicts the framework for life cycle assessment methodology (ISO, 1997).

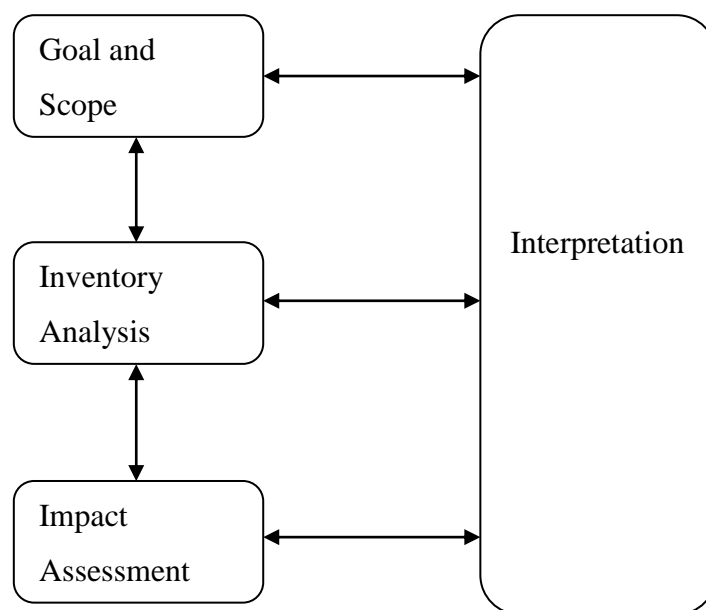


Figure 2.2. Life cycle assessment methodology.

Figure 2.2 clearly demonstrates the phases of a life cycle analysis. Every phase has direct interaction with the other phases. This indicates that conclusions drawn from one phase can influence other phases for a more improved assessment.

2.1.2. LCA of a Building

In order to construct green buildings, it is desired to know how each of the building components affects the environment through its life span. Figure 2.3 demonstrates the LCA framework of a building including all stages. This section describes all stages of a building associated with LCA. The stages can be classified in five groups: Raw material extraction, Manufacturing, On-site construction, Occupancy, and Demolition.

Resource Extraction is the starting phase of life cycle assessment of a building. Tracking inventory data begins at this stage. It also includes the environmental impact evaluation of raw materials transportation to the manufacturing plant. Transportation is the connection process between extraction and manufacturing.

Manufacturing stage is responsible for the largest proportion of embodied energy regarding the life cycle of a building (Thormark, 2006). It starts with the delivery of raw materials to the manufacturing plant. This stage ends with finished products ready for shipment.

The occupancy stage considers functions such as energy use regarding heating, cooling, and lightning as well as water use. Maintenance stage takes into account the fact that interior parts could be reconfigured or replaced. Main components may not be remodeled until demolition. Demolition is the termination stage of a building's life cycle. Building material is treated by landfill, incineration, reused or recycled.

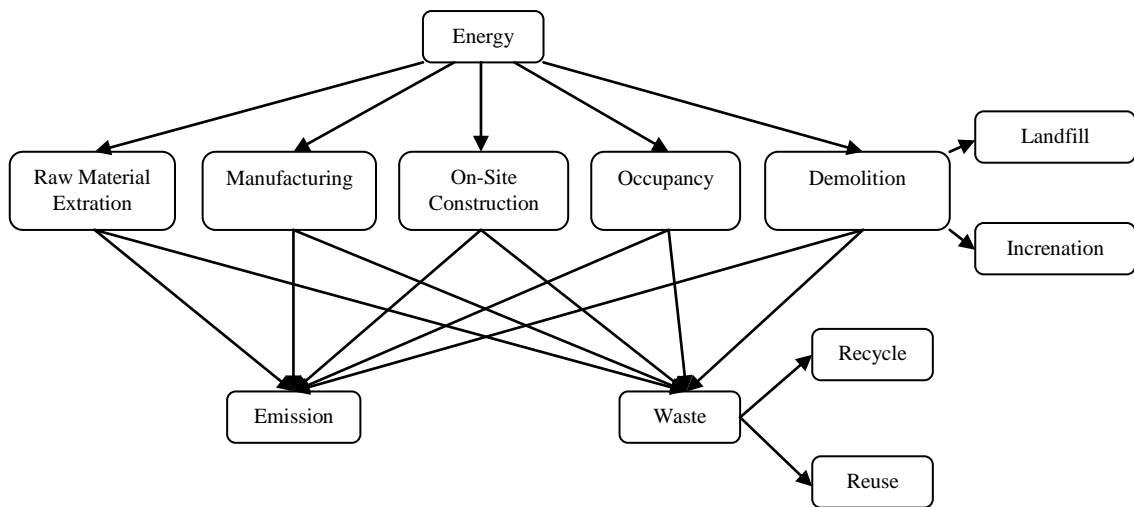


Figure 2.3. LCA framework of a building.

2.1.3. Life Cycle Impact Categories

Building materials deplete natural resources and pollute the environment with emissions and solid wastes. Impact categories quantify environmental burdens. This study describes three categories which are used in our study. These categories are global warming potential, eutrophication potential, and acidification potential.

Global warming is briefly defined as the increase in average temperature of the Earth's surface. It occurs with the absorption of heat, radiating back from the Earth, by greenhouse gases in the atmosphere. Greenhouse gases prevent heat loss reduction and provide warmer temperatures on Earth.

Global warming is a significant issue in global climate change which should be widely examined. Global climate change has the potential to damage the nature on planet with rising sea levels, melting of polar ice, loss of biodiversity, food supplies reduction, and many other aspects that directly affect humans.

Greenhouse gases (GHG) comprise of carbon dioxide (CO₂), methane, nitrous oxide, ozone, sulfur hexafluoride, hydro fluorocarbons, per fluorocarbons, and chlorofluorocarbons, and several gases that indirectly influence heat absorption such as carbon monoxide (CO), oxides of nitrogen (NO_x). GHG is beneficial for keeping

temperature on Earth in a suitable range. However, increased amount of GHG emissions could cause excessive warming of earth surface which seriously affect human life.

Since the Industrial revolution, global atmospheric concentration of CO₂ has risen around 35 %. Fossil fuel combustion is responsible for 94 % of CO₂ emissions. 75 % of greenhouse gas emissions produced by humans is generated from fossil fuel combustion (IPCC, 2007).

In the manufacturing process of building materials, the emissions result from the fossil fuel combustion in order to form the products. Hence, green house gas emissions are directly related to the embodied energy of construction materials. As an example, the manufacturing process for steel requires high amount of energy which is derived from coal combustion.

In order to characterize the green house effect due to emissions and absorptions affecting on humans, global warming potentials (GWP) have been developed. GWPs provide a single index, expressed in grams of carbon dioxide per functional unit of a product, which measures the quantity of CO₂ equivalent. The Global Warming Index is an aggregated measure including all emission as

$$GWI = \sum_f m_f GWP_f \quad (2.1)$$

GWIs is the Global Warming Index, m_f is mass (in grams) of inventory flow f , GWP_f denotes grams of carbon dioxide with the same heat trapping potential as one gram of inventory flow f . Eutrophication is the addition of nutrients to soil or water which causes excessive plant growth. Although eutrophication is a natural process, its intensity is increased by human activities. This increase results in ecological diversity reduction.

Eutrophication decreases the quality of waters. For instance, eutrophication causes excessive growth of algae which block sunlight and become responsible for elimination of underwater grasses. Loss of grasses reduces habitat and food for species, even causing their death. As an addition, the amount of oxygen in water is also exhausted. Such

environmental burdens directly affect human health. Majority of health problems affecting humans happen from drinking waters.

Eutrophication occurs from negative effects of pollutants such as nitrogen and phosphorus to surface waters from fertilizers, waste waters, and manufacturing wastewater. Nitrogen and phosphorus are major components of synthetic fertilizers used in landscape maintenance.

Characterization factors are developed with nitrogen as the reference substance. Equation 2.2 represents a single index computed for potential eutrophication in grams of nitrogen per functional unit of product. The Eutrophication Index is an aggregated measure including all emissions as

$$EI = \sum_f m_f EP_f \quad (2.2)$$

EI is the Eutrophication Index. Mass (in grams) of inventory flow f is expressed by m_f . EP_f denotes grams of nitrogen with the same potential effect as one gram of inventory flow f . Acidification occurs from acidifying gases, sulfur and nitrogen compounds primarily. They either dissolve in water or join to solid particles. These compounds reach ecosystems in the form of acid rain. The primary sources of acid rain are emissions of sulfur dioxide and nitrogen dioxide from fossil fuel combustion. Such emissions also occur from decaying of vegetation and volcanoes.

Acidification is also enhanced through building life cycle. During life-span of building, fossil fuels are burned to produce electricity and to power equipments used in raw material extraction, manufacture, transportation, construction, and maintenance. Winds carry such emissions from power and manufacturing plants over hundreds of miles. Hence, it is challenging to remove the acidification potential.

Acidification gives harm to fish and other water animals by lowering the pH of water. Soil is also negatively affected from acidification. Acids can carry toxins and damage nutrients and minerals. Sulfur dioxide prevents photosynthesis of vegetation which

slows the growth of forests. Impact nutrients and minerals due to acidification can also negatively contribute to vegetation. Nitrogen oxides affect animals and humans respiratory systems. Acid rain also accelerates weathering of building materials such as granite, limestone, concrete, and metals which can cause early removal or replacement for some building materials.

Characterization for acidification potential is developed with hydrogen ions as the reference substance. Acidification is measured in grams of hydrogen ions per functional unit of a product. Acidification index is an aggregated measure including all emissions as

$$AI = \sum_f m_f ACP_f \quad (2.3)$$

Acidification index is represented by AI. Mass (in grams) of inventory flow f is expressed by m_f . ACP_f denotes millimoles of hydrogen ions with the same potential acidifying effect as one gram of inventory flow f .

2.1.4. Life Cycle Assessment Tools

Gathering LCI and quantifying environmental impact for a product is a significant issue. LCI tracking for an individual product is costly and challenging. A holistic analysis for life cycle requires investigating a number of inventory flows. Moreover, in order to compare candidate products properly in terms of environmental impact, equivalent data for each product is needed. Finally, decision makers may be incompetent for treating LCI and interpreting data. LCA tools are quite beneficial as a decision in this process.

There are two publicly available LCA tools regarding construction materials: Building for Environment and Economic Sustainability (BEES), EcoCalculator. BEES is developed by National Institute of Standards and technology (NIST) and the latter is developed by Athena Institute. Each tool treats the LCI data and evaluates environmental impacts with relevant weightings which provide a fair and proper assessment for building assemblies and elements.

BEES measures environmental performance of a building product using the LCA approach specified in the ISO 14040 standards. The windows based tool includes environmental impact values and economic performance values of over 280 building materials. Figure 2.4 illustrates the BEES criteria and overall performance measure (Lippiat, 2007).

BEES covers twelve different environmental impact values, such as global warming, acidification, eutrophication, for each building material derived from LCI data. The environmental values should be synthesized in order to obtain environmental performance score. BEES recommends two additional weightings: U.S. EPA Science Advisory Board weightings and BEES stake-holder panel weightings. One can also assign weightings regarding self-preference.

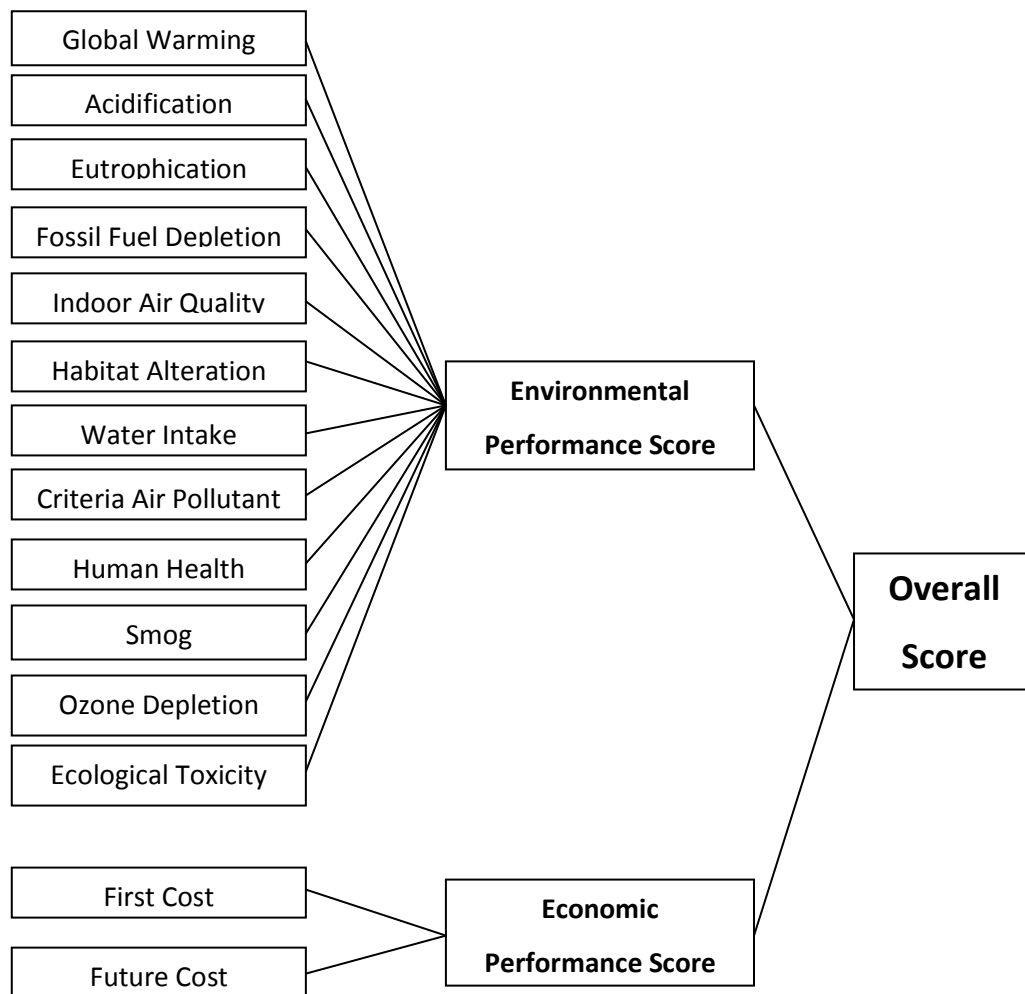


Figure 2.4. BEES criteria and performance measure.

BEES also includes purchase cost of building materials per their functional units and net present value of their future costs. The overall performance score is derived with assigning relative importance for both environmental performance score and economic performance score by decision-makers. Eventually, BEES implements a systematic technique for selecting environmental-friendly and cost effective building products (Lippiat, 2002).

The Athena Materials Institute aims providing vast building assembly database in order to achieve sustainable buildings (ATHENA, 2003). The non-profit organization uses LCA approach for evaluating impacts of building components. The institute offers two tools for environmentally-preferred buildings.

The tool user is allowed to assign building elements in order to form building assemblies and even a building design. Moreover, it provides observing environmental burden contribution of both building assemblies and LCA stages. Comparisons can be made up to five building assemblies and whole building designs.

The Athena EcoCalculator encompasses LCA information for more than 400 common building assemblies in terms of environmental impact values. The free tool splits a building into seven components: Foundation and footing, Columns and beams, Intermediate floors, Exterior walls, Windows, Interior walls, and Roofs. Each building component includes a set of assemblies containing combinations of different building elements. The decision maker assigns required areas as size for each preferred building assembly in order to calculate the environmental impacts of each preferred component and the total for the entire building. The environmental impacts' contribution for each assembly can be observed as percentage from EcoCalculator tool.

2.2. Green Building Rating Systems

Building rating system implements a comprehensive analysis of environmental characteristics of a building by setting criteria and targets for building owners and designers in order to enforce them achieve higher standards. It also contributes to the environmental awareness of building practices and provides the direction for building

industry to evolve towards environmental protection and achieve sustainability. It performs an objective assessment of building performance. Building evaluation methods are generally regarded with a single criterion such as energy use, indoor comfort in order to assess the overall performance of a building (Kohler, 1999). Therefore, as environmental issues become more urgent, holistic methods are required to evaluate building performance across a broader range of environmental considerations (Ding, 2008).

This section presents detailed description, and comparison of four mainstream green building rating systems: LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), SBTool (Sustainable Building Tool), and CASBEE (Comprehensive Assessment System for Building Environmental Efficiency). Comprehensive criticism about general issues of rating systems is also mentioned.

2.2.1. LEED

The LEED rating system was established by the United State Green Building Council (USGBC) to evaluate the environmental performance of buildings in 1998. It is a consensus based building rating system. There are LEED based projects in 91 countries. The number of registered and certified project for LEED certification is 19524 and 2476, respectively.

LEED provides a complete framework in order to assess building performance and meet sustainability goals. LEED is classified in six categories: Sustainable sites, Water efficiency, Energy and atmosphere, Materials and resources, Indoor environmental quality (IEQ), Innovation and design category.

Each category contains a specific number of credits and prerequisites. LEED is a performance-based tool where credits are earned for meeting credit performance criteria. A project is certified based on the overall points earned.

2.2.2. BREEAM

BREEAM was developed by BRE (Building Research Establishment) in 1990 in the United Kingdom. It is the first environmental assessment tool. It sets the standard for best practices in environmental design and management. It is widely accepted by the construction sector. BREEAM evaluates the performance of buildings in nine categories: Management, energy use, health and well-being, pollution, transport, land use, ecology, materials, and water. Points are awarded for each criterion and added for a total score. The overall building performance is awarded as pass, good, very good or excellent rating based on the score. BREEAM has various assessment standards for different types of buildings. They are BREEAM for offices, retail, industry units, courts, education, healthcare, prisons.

2.2.3. SBTool

SBTool was developed by the International Framework Committee for the Green Building Challenge (GBC). GBC is an international project which has study groups from more than 25 countries since 1996. The main idea of SBTool is to develop a building environmental assessment tool that addresses various building performance criteria. Hence, the participating countries can directly contribute to this project as well as modify their own tools in accordance with the proposed model.

The SBTool performance criteria are divided into six categories: Resource consumption, environmental loadings, indoor environmental quality, quality of service, economics, and pre-operations. SBTool is a rating framework which becomes an efficient assessment tool after defining scope for specified region and setting weights. SBTool is not very successful in penetrating into the construction market. Consequently, it has not been adopted by building projects teams as a design tool that can provide project teams and designers with strategies to improve the performance of building projects.

2.2.4. CASBEE

It is developed in Japan in 2001. It is used in evaluation of pre-design, new construction, existing building, and renovation. CASBEE splits environmental load from quality of building performance and evaluates them separately. Then, ratio of building environmental quality to environmental load gives the rank of the building. The most promising buildings are expected to have lowest environmental load and highest building quality. The Equation 2.4 presents the building environmental efficiency ratio which provides the rank of a specified building.

$$BEE = \frac{Q}{L} \quad (2.4)$$

BEE denotes the building environmental efficiency value. Building environmental quality and performance is expressed by Q. L represents building environmental loadings. Building environmental quality and performance is expressed in three dimensions: Indoor environment (Noise, Thermal Comfort, Lighting, Air Quality), Quality of services (Functionality and Usability, Durability, Flexibility), Outdoor Environment (Emissions, Waste, Sustainable sites). Building environmental load is composed of four categories: Energy, Resource and materials, Reuse and reusability, off-site environment.

2.2.5. Comparative Evaluation of Building Rating Systems

The features of green building rating systems differ from each other. Therefore, it is essential to compare mainstream rating systems. LEED and BREEAM have strong market penetration, while SBTool and CASBEE are not market oriented. Moreover, unlike CASBEE, the other three tools have high flexibility around the world. They could be applied to different countries. Each described rating systems have evaluation tools covering life cycle of a building. Table 2.1 illustrates the comparison table of the main stream building rating tools regarding market orientation, flexibility, and life cycle coverage.

Table 2.1. Comparison table of mainstream building rating tools.

Features	LEED	BREEAM	SBTool	CASBEE
Market Orientation	✓	✓	✗	✗
Flexibility	✓	✓	✓	✗
Life Cycle Coverage	✓	✓	✓	✓

The mainstream rating systems attempts to promote various building types. Some systems may cover buildings in a broad scope. However, some rating systems treat limited number of building types. For instance, BREEAM has environmental evaluation criteria for residence, office, retail, industry unit, court, education, healthcare, and prison. However, CASBEE only covers residential buildings. Table 2.2 depicts the building type coverage of building rating tools.

Table 2.2. The building type coverage of building rating tools.

Building Types	LEED	BREEAM	SBTool	CASBEE
Residence	✓	✓	✓	✓
Office	✓	✓	✓	✗
Retail	✓	✓	✓	✗
Industry Unit	✗	✓	✓	✗
Court	✗	✓	✓	✗
Education	✓	✓	✓	✗
Healthcare	✓	✓	✓	✗
Prison	✗	✓	✓	✗

In addition, the rating tools have different labeling systems. The score ranges and certifications are distinctive from each other. For instance, the highest achievable point is 69 in LEED. However, BREEAM is scored on percentage basis. Table 2.3 represents the score ranges for each system and the possible awards that candidate building could gain.

Table 2.3. Certification systems for rating tools.

Certification	LEED	BREEAM	SBTool	CASBEE
Total Score	69	100	5	5
Score Ranges	26-32 (Certified)	36-47 (Pass)	-1 (Deficient)	0-0.5 (Poor)
	33-38 (Silver)	48-57 (Good)	0 (Acceptable)	0.5-1.0 (Fair)
	39-51 (Gold)	58-69 (Very Good)	1-4 (Intermediate)	1.0-1.5 (Good)
	52+ (Platinum)	70+ (Excellent)	5 (Best Practice)	1.5-3.0 (Very Good)
	-	-	-	3+ (Excellent)

This part aims to criticize international building rating systems and examine the limitations of current environmental building assessment methods. First, a successful assessment tool should consider all phases of a building including pre-design, design, occupancy, and demolition. However, international rating systems have different versions that evaluate each building construction stage individually. The usefulness of the rating tools in this respect is controversial as renovation process in order to make the building proper with performance criteria may be too costly and time consuming (Lowton, 1997). Thus, it is essential to consider all stages of a building for an environmental rating system from scratch (Crawley and Aho, 1999). Green building rating systems should evaluate not only the design stage but also the other stages that a construction process passes through. Therefore, existing performance based rating systems should be integrated with various evaluation concepts.

Another limitation is the financial aspect of building assessment systems; many assessment tools do not include financial issues of a sustainable construction (Ding, 2008). For instance, LEED and BREAM do not contain financial criteria in the evaluation framework. This is a serious inadequacy for developing countries whereas financial and environmental issues should be taken into consideration simultaneously. A building owner wishes a good financial return. Moreover, occupants may be more comfortable with air quality, safety issues or cost benefit from energy bills. Thus, using a single method is not a suitable solution in order to satisfy all stakeholders. Therefore, a convenient solution must consider regional, financial and environmental issues all together. The primary role of an environmental building evaluation method is to provide a comprehensive assessment.

Previously, the international rating systems have been considered for local use. As an example, LEED is established for the USA, BREAM is developed for UK. Hence, they are inadequate for reflecting regional variations. Although some rating tools have weighting system for their categories, such adjustments can not define regional, social and cultural variations (Reijnders and Rockel, 1999). These variations include climatic conditions, income level, building materials (Kohler, 1999). All in all, regional issues are substantially important and should be incorporated into particular building rating systems.

It is essential to draw a general scoring equation in order to criticize the evaluation mechanism of the mainstream rating systems. Scoring is required to certificate the building and benchmark them with the other buildings. Also, scoring enhances multiple criteria evaluation. The total score of a building could be calculated as

$$TS = \sum_c V_c w_c \quad (2.5)$$

TS represents the total score. Index for environmental criteria is expressed by c . V_c denotes the gained value for criteria c . Relative weighting for criteria c is denoted by w_c . It is clearly seen from the Equation 2.5 that the total score of a candidate building is the weighted sum of achieved values from environmental criteria. Besides, green building rating systems maintain sub-criteria for each criteria. The computation of gained value for criteria could be formulated as the aggregation of achieved values from sub-criteria.

$$V_c = \sum_s V_s \quad (2.6)$$

Index for subcriteria is denoted by s . V_s expresses the gained value for subcriteria s . As it is formulated in the previous equations, weighting and scoring systems are two controversial issues about green building rating tools. There is not a consensus-based approach or a particular method in assigning weights to performance criteria.

SBTool allows the users to change weights based on regional differences. However, users could manipulate the results in order to come up with a biased score (Larsson, 1999). Score based systems such as LEED are also problematic. In such systems, total score is gained from just adding up all the points. Therefore, the weighting parameter should be assigned as 1 in Equation 2.5. Even if a factor such as material selection fails to achieve desired points, building can still gain a high score meeting other criteria (Curwell, 1996). Scoring and weighting system is an important issue. Assigning weights could be biased and easily manipulated.

The difficulty and complexity of weight determination prevents gaining proper outcomes. In some scoring systems, total point is obtained by score aggregation assigned to each criterion. As an example, in LEED every performance criteria has single point which is assumed that every criterion has equal importance. More in-depth analysis must be made about this issue. Every performance factor may be evaluated individually before a final indicator point and boundaries could be set for each performance factor. Scoring systems narrow the real value of a performance criterion. For example, recycled content is not awarded in LEED rating system if the percentage of recycled content exceeds 10 %. However, recycled content is essential for environmental impact reduction of a green building. This could be solved by range based evaluation instead of scoring. Also, LCA integrated with performance based systems could be useful.

2.3. Material Selection

Conventional material selection process considers mechanical properties, process properties, and cost. Environmental issues are getting more significant recently due to limited resources and environmental pollution (Zhou *et al.*, 2009). Thus, environmental properties should be taken into account along with traditional criteria. A number of criteria and requirements should be considered simultaneously in selection process (Chan and Tong, 2007). Therefore, material selection is regarded as multi-criteria decision problem recently and requires trade-offs amongst decisive factors. Any improvement in one criterion usually results with worsening of other criteria. One of the major concerns of material selection is minimizing cost while meeting engineering requirements and environmental considerations (Chen, 1994).

Best material choice is a compromise under multi-criteria decision. Material selection process is a complex task that various evaluation criteria are considered (Giudice *et al.*, 2005). Such evaluation criteria often conflict with one other which means in order to optimize one criterion through selection process, decision-maker should make trade-off between criteria (Asbhy, 2000). Since there are a number of materials and their properties, computational tools are essential for material selection.

Mechanical properties include strength, stiffness, toughness, hardness, density, creep resistance. They are the basic requirements of a product. Economic properties contain cost components related to procurement, manufacturing, transportation, and disposal processes. Environmental pollution, energy consumption during life cycle, and recyclability are major environmental properties of materials.

Likewise other products material selection in building construction is a critical issue. Building construction has immense effects on environment. Therefore, environmental properties of building materials should be integrated into material selection process in conjunction with mechanical and/or budget restrictions for green buildings.

2.3.1. Environmental Characterization of Construction Materials

A number of environmental properties should play a significant role in selecting construction materials. In order to perform a comparative and comprehensive evaluation of building components, four properties are significant: recyclability, reusability, rapid renewability, and using regional materials.

Recycling involves processing used materials, wastes, into new products. Recycled content is encouraged in order to reduce impacts resulting from extraction and processing of virgin materials. Every construction material has recyclability ratio that demonstrates the recycled fraction of the material in terms of weight.

Reusing material has the same purpose with recycling. It aims to prevent depletion of virgin materials and excessive environmental impact. It is possible to reuse building materials such as steel, wood, bamboo and stone, after the demolition.

Using rapidly renewable materials reduces the use and depletion of finite raw materials and long-cycle renewable materials by replacing them with rapidly renewable materials. Rapidly renewable materials are sustainable due to their rapid regeneration -less than ten years- and growth cycles. For instance, bamboo -a rapidly renewable material- matures up to twenty times faster than some of the tree species that are used in flooring. It is also as durable as other alternatives.

Regional building materials are extracted and manufactured within the region. Transportation during construction consumes energy, and generates wastes and emissions. Regional materials are encouraged in order to reduce environmental pollution caused by transportation. They also enhance regional economy by supporting the use of local resources.

2.3.2. Overview of Related Material Selection Studies

Material selection studies regarding environmental effects have been extensively treated in the literature. Relevant studies prove that material selection problem requires multi-criteria decision making approach. The investigated papers cover environmental-friendly material selection employing mathematical models. The overview also includes studies incorporating economic issues into environmental preferences.

A systematic methodology is proposed that incorporates environmental considerations into the conventional material selection process (Chen *et al.*, 1994). The environmental-burdens of materials are translated in terms of internal and external costs. The internal cost is determined as the environmental cost to the manufacturer and the external cost is the environmental cost to the society. The main idea of this study is to use cost as a common basis in order to integrate environmental and traditional material selection considerations. The aim is to select the material with minimal cost. However, reflecting environmental properties into cost is not a realistic approach.

It is pointed out that only particular studies consider material selection based on LCA of alternative materials (Giudice *et al.*, 2005). Hence, they performed an index based method satisfying conventional performance requirements as well as minimizing environmental impact over the material's life span. In this study, some candidate materials are eliminated due to the conventional requirements in order to constitute a potential solution set. Then, indicators for environmental impact and life cycle cost of each potential material are evaluated in order to choose the optimal material.

An artificial neural network model integrated with genetic algorithm approach is proposed in order to optimize the multi-objectives of material selection (Zhou *et al.*, 2009). In this study, the candidate materials are evaluated in three aspects: Mechanical properties, Economic properties, and Environmental properties. By assigning proper weights, neural network gives overall performance score for each material. The outputs from the model help decision makers select sustainable materials.

Weighted sum method is proposed which is a common technique applied to material selection problems (Sirisalee *et al.*, 2004). In this study, they defined utility function which includes different performance metrics for materials and converts such metrics into single units. Hence, the appropriate value of utility function performs multi-objective optimization of the material selection. Although the weighted sum method is simple, it requires consensus for relative importance. This method is also time consuming and subjective.

Even though material selection problem is widely investigated in the literature, the studies for building materials regarding environmental issues are very rare. A method is presented using building materials' environmental inventory to evaluate environmental impact based on LCA (Wu *et al.*, 2005). In this study, they described the term "green tax" which is the shadow prices of pollutants negatively affecting society. The environmental impacts are categorized and green tax is employed in determination for relative importance of categories. High green tax rate makes corresponding environmental impact of the material more significant than the others. However, transforming environmental damage into penalty cost is not credible and such evaluations depend mostly on local environmental issues.

A mixed integer optimization model is proposed in order to obtain maximum number of possible points from LEED credits based on candidate materials for the desired building (Lacouture *et al.*, 2009). In this study, they also incorporate design requirements and budget limitations to the model. The outputs of the optimization tool determine the extent of materials to be used and the number of LEED-based credits achieved under scarce budget. Besides, the model is also modified to demonstrate the additional money required to gain extra credits.

For further study, they also pointed out that a comprehensive optimization procedure can be generated covering broad environmental impacts such as LCA while considering design, budget, and environmental goals. The outlined model is the only study that considers a building as a whole instead of treating the construction materials in discrete sets. However, the building systems used in the article have shortages in fulfilling a comprehensive building. Also, the used data sources are not reliable. Hence, a more realistic study is essential considering both environmental characteristics and life cycle assessment for a comprehensive building.

Our proposed model performs a more realistic approach between cost and environmental features. Besides, it integrates LCA perspective into the material selection process as suggested in the previous article. The study also provides assistance to erect an environmental friendly and cost effective building based on candidate materials instead of treating material alternatives in discrete sets. The methodology and the mathematical model will be expressed in the following chapter.

3. PROPOSED MODEL AND METHODOLOGY

The optimization model considers that buildings are comprised of components such as foundation, columns and beams, roof, interior and exterior walls. Components include building elements. Each element is chosen from a specific set of materials classified in categories. Therefore, the foremost aim of the model is to select the appropriate materials in order to build each component. As an example, for roofing component, a single candidate material should be selected from a particular set to compose the roof for each flooring element. However, this decision must be made considering environmental performance criteria, budget limitation, and environmental impact assessment.

Figure 3.1 illustrates the methodology for the optimization model. In the data input module, the model requires alternative materials' environmental and financial features. It covers the market prices for financial aspect. Besides, the optimization tool also requires the environmental characteristic values such as recycled content ratio of materials and their regional availability as well as their environmental impact values.

The environmental requirements and limitations play a vital role in the selection process. Requirements include performance criteria such as desired recycled content ratio and regional material availability ratio for the entire building. Moreover, the limitation for the model could encompass budgeting.

In the optimization model, the tool attempts to minimize the environmental impact value of an entire building considering the data gathered from the previous module. This optimization process leads to the selection of proper materials for our model. Therefore, the decision module provides appropriate bill of materials. Bill of materials draws a detailed picture for both building components and the selected materials for each building element. The aggregation of proper materials erects the desired building.

Once all the data is entered, the optimization model minimizes the environmental impact of a building throughout the life cycle based on optimally selected materials. The output of the optimization model is the proper materials used in order to build up each

element. The union of properly selected materials for each building element forms the desired building. It is important to note that the candidate materials for each building element should be true substitutes for each other. Therefore, one candidate material can be easily changed with its alternative without preventing the construction process. Also, it is assumed that the candidate materials meet the required technical performances for the desired building.

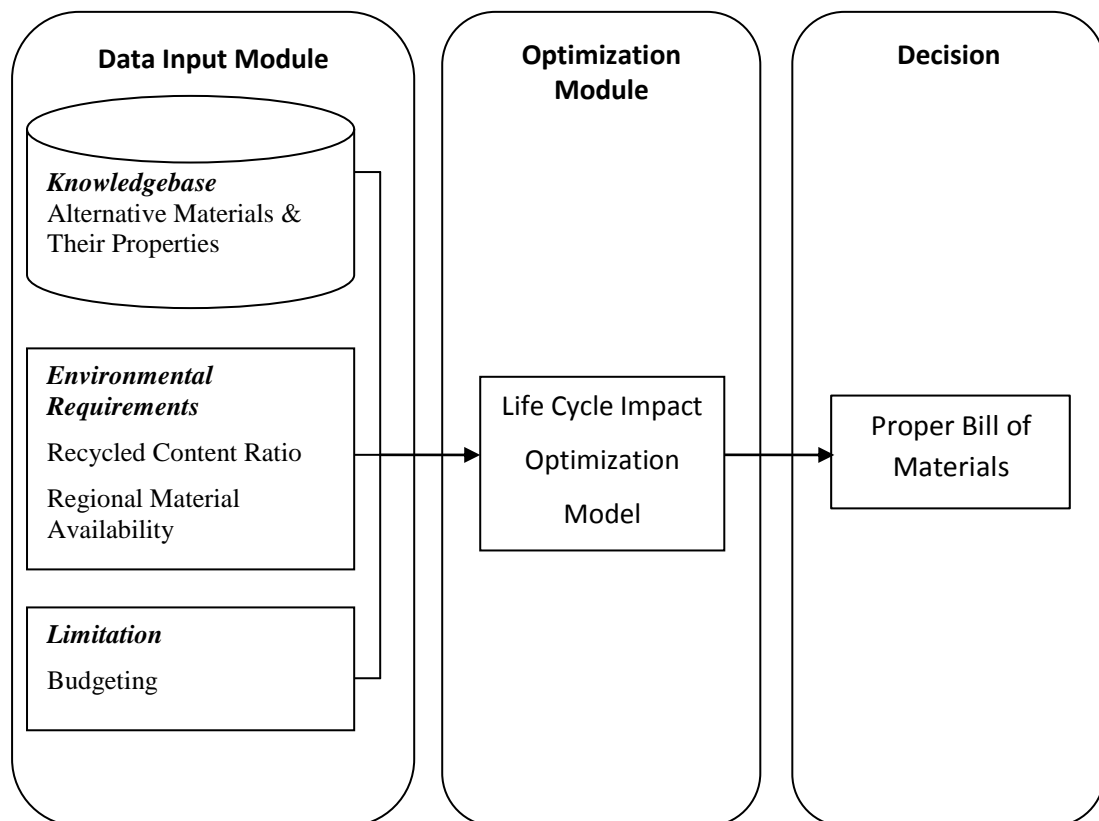


Figure 3.1. Methodology for the optimization model.

3.1. Determination of the Environmental Score Value

This study determines a new LCA evaluation method which calculates a single indicator for an entire building. The new index provides an overall score for environmental impact categories. Methods and models in the literature elect the building elements from discrete set of candidate materials. Then, they combine the discretely selected proper materials in order to form the building. The proposed mathematical model considers the building as a single product and evaluates the impacts of entire building at once rather than

taking into account candidate set of materials separately. The environmental impact indicator for an entire building is called as environmental impact score (ES).

The environmental impact score computation of an entire building can be described in three steps. First of all, the environmental impact values of selected materials for each category are summed up in order to calculate the total impact value of the desired building with respect to particular categories. Then, normalization factors are employed in order to remove different units of environmental impact categories and synthesis the impacts for a single indicator value. Finally, relative importance weights are assigned for comprehensive environmental impact evaluation of the entire house. This thesis investigates the following environmental impact categories: Global warming, Eutrophication, and Acidification. Formula 3.1 calculates the single indicator value of an entire building.

$$ES = \sum_k \sum_j \sum_i w_k \frac{e_{ijk} a_{ij}}{N_k} \quad (3.1)$$

$$\sum_k w_k = 1 \quad (3.2)$$

Index for candidate materials are denoted by i . Index for building elements are expressed by j . Index for environmental impact category is represented by k . ES denotes the environmental impact score for the entire building. Characterized value of material i per unit for building element j with respect to category k is expressed by e_{ijk} . Required amount of building material i for building element j is represented by a_{ij} . Relative importance weight for impact category k is denoted by w_k . N_k provides normalization value with respect to impact category k .

It should be pointed out that the environmental score is determined in order to combine various environmental impact categories. Therefore, environmental score contributes to perform a single objective function for impact minimization. It does not possess the intention to reflect an accurate indicator for evaluating buildings effectively. However, this aim will be performed by observing the total environmental impact values of buildings for each category. Table B.1 lists environmental impact categories and respective additional values per functional units for our candidate materials appropriate for the

building. The normalization values with respect to environmental impacts are listed in Table 4.2.

3.2. Mathematical Modeling

This section presents the optimization model for the material selection process. The proposed tool is an integer programming model. As shown in objective function (Equation 3.3), the model aims to minimize the environmental impact score of a comprehensive building based on optimally selected materials. The economic constraint (Equation 3.4) demonstrates that purchased materials for the building system must not exceed an assigned budget. Equation 3.5 presents that only a single material should be used for each building element. The regional material constraint (Equation 3.6) requires that the proportion of regional materials used for the building must exceed a desired percentage of the total used materials by cost. Recycled content constraint (Equation 3.7) encourages recycled material use for a minimum of desired percentage of the total materials cost used for the entire building. Equation 3.8 assigns binary values to the respective variables.

$$\min \sum_k \sum_j \sum_i w_k \frac{e_{ijk} a_{ij} y_{ij}}{N_k} \quad (3.3)$$

subject to

$$\sum_j \sum_i c_{ij} a_{ij} y_{ij} \leq B \quad (3.4)$$

$$\sum_i y_{ij} = 1; \quad \forall j \quad (3.5)$$

$$\frac{\sum_j \sum_i c_{ij} r_{m_{ij}} a_{ij} y_{ij}}{\sum_j \sum_i c_{ij} a_{ij} y_{ij}} \geq RM \quad (3.6)$$

$$\frac{\sum_j \sum_i c_{ij} r_{ij} a_{ij} y_{ij}}{\sum_j \sum_i c_{ij} a_{ij} y_{ij}} \geq R \quad (3.7)$$

$$y_{ij} \in \{0,1\} \quad (3.8)$$

Cost per unit of material i for building element j is denoted by c_{ij} . B represents allocated budget for building materials. y_{ij} takes the value of 1 if material i is used for building element j , it takes the value of 0, otherwise. Recycled content percentage of material i for building element j is expressed by r_{ij} . rm_{ij} takes the value of 1 if material i for building element j is a regional material, it takes the value of 0, otherwise. R represents the desired recycled content fraction by cost. RM denotes the desired regional material fraction by cost.

As previously stated, budgeting is a significant factor for material selection process. Unfortunately, most building project proposals terminate due to shortage of appropriate budget. Therefore, a sub-model should be integrated to the main model. This sub-model should calculate the minimum amount of money that meets the environmental characteristic requirements.

Since this numerical study considers the purchase cost of construction materials, a reasonable budget is required in order to calculate the results. The total cost of a building is computed with the required amounts for each element and their market prices per unit costs. The summation of total costs for each building element provides the total cost for an entire building.

Moreover, the mathematical model is modified in order to determine a budget for conducting a convenient study. The objective function (Equation 3.3) associated with environmental impact minimization is disregarded. Also, Equation 3.4 is removed from the mathematical model. Then, the previous objective function is substituted by a new objective function. Equation 3.9 formulates the specified objective function.

$$\min \sum_j \sum_i c_{ij} a_{ij} y_{ij} \quad (3.9)$$

The new modified model tries to minimize the required cost by disregarding environmental impact issues. It takes into account the required amount restrictions, recycled content ratio, and regional material availability ratio. It aims to determine the minimum cost that is required to fulfill the remaining constraints.

Figure 3.2 illustrates the integration of the sub-model to the main model. The sub-model calculates the minimum possible budget required for building construction. If the decision maker cannot afford that amount of money, then the construction project terminates. Conversely, the decision-maker initializes the allocated budget, when it exceeds the minimum required amount resulting from the sub-model. Eventually, the main model runs in order to determine the proper bill of materials.

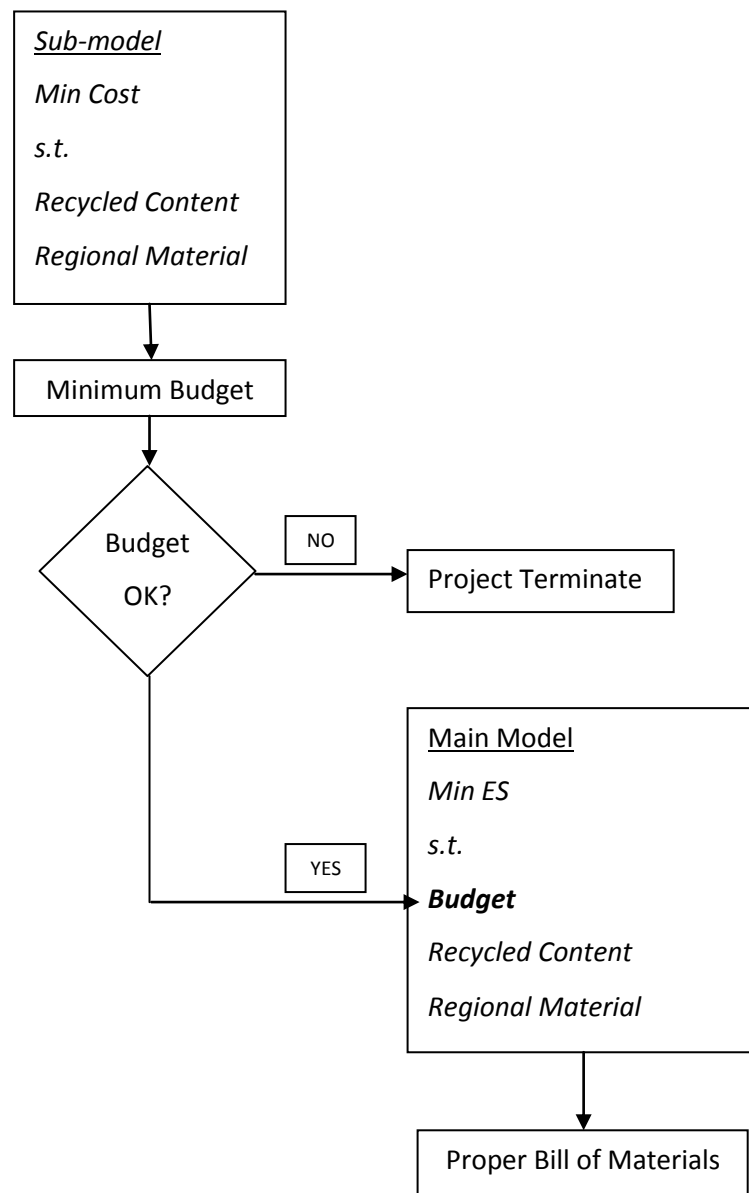


Figure 3.2. Integration of the sub-model to the main model.

4. NUMERICAL STUDY

This numerical study is based on the application of the model in a single-storey residential building. The building project has 133.8 m² usable area. Figure 4.1 illustrates the technical plan of the desired residential building with measurements in centimeters. It is worth noting that the mathematical model is also applicable to other building types.

The objective of the study is to minimize the environmental impact score of the desired building as well as considering economic issues and specified environmental characteristics of candidate materials. Therefore, the main purpose is to construct an environmental-friendly and a cost-effective building. As it is indicated in the life cycle framework, the scope is selected as cradle to grave assuming 50 years of life time for each candidate material.

The numerical example includes almost every part of a residential building's envelope systems covering twelve different building elements such as foundation, framing systems, windows and doors, roofing systems, interior and exterior walls. The complete list of these twelve building elements is displayed in Table 4.1. The materials for each building element are alternatives for the residential building.

The numerical study considers the most commonly used materials for each type of element. For instance, OSB and plywood for exterior and roof sheathings, steel and wood for structural framing, ceramic, parquet and floating plank for floor tile. It also analyses the environmental impacts throughout life cycle of these materials in order to assess the environmental performance criteria. Besides, purchase costs of materials are taken into account in order to observe economic limitations and affordability.

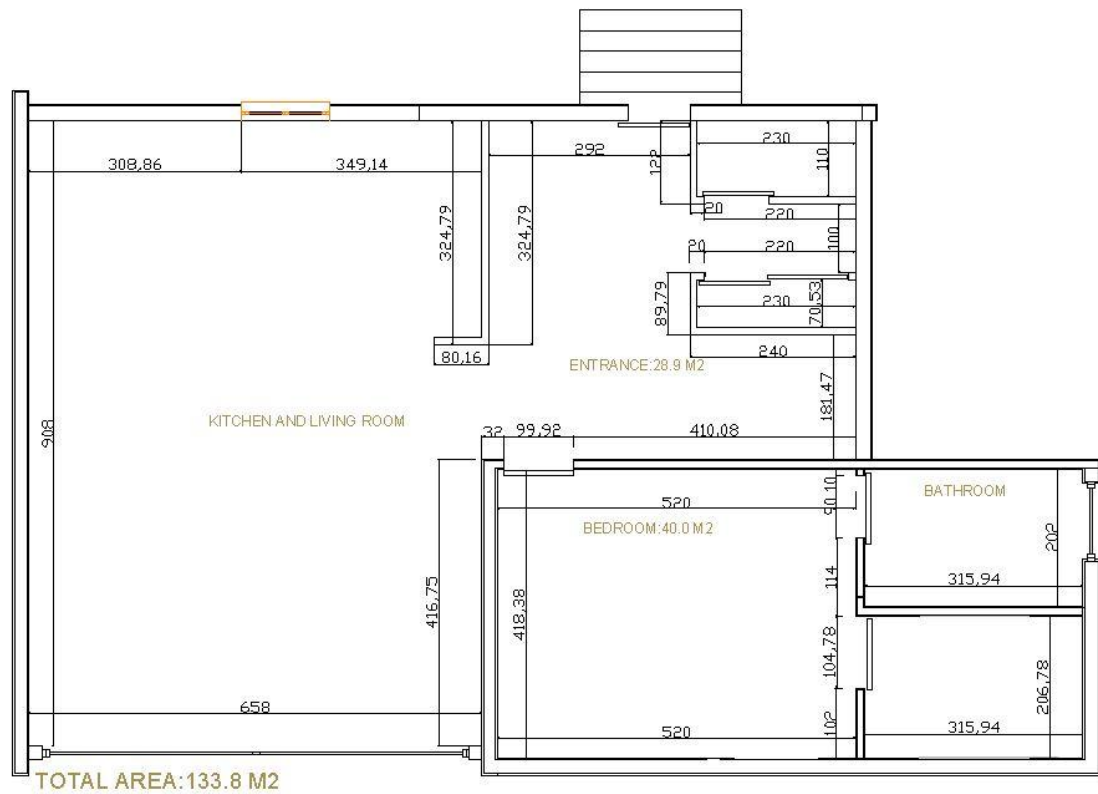


Figure 4.1. Technical plan of the residential building.

4.1. Data Sources

The environmental impact values of candidate materials for each category are validated from Eco-calculator and BEES material selection software. Appendix A provides screenshots for these two software. They maintain comprehensive life-cycle inventory databases for building elements and assemblies. The environmental impacts associated with these twelve elements are analyzed in terms of global warming, eutrophication, and acidification potentials. The environmental values in the databases are presented on per functional units of candidate materials for 50 years product life. Table B.1 in Appendix B lists the specified environmental impact categories and respective additional values per functional units for our candidate materials appropriate for the building. Table 4.1. lists the candidate materials for each building element. The suitability of the candidate materials for residential buildings is confirmed by architecture and construction firm named “iSTART”. The classification of elements and candidate materials are estimated from BEES software. It is assumed that the materials are chosen in a functional basis which means the candidate materials are substitutes for one another. It is worth noting that the functional units of

building materials used are per square-meters, except concrete for foundation which is cubic-meters.

Table 4.1. Alternative materials list in the optimization model.

Building element	Candidate material	Building element	Candidate material
Foundation	Poured Concrete	Partitions	Gypsum Board
Framing	Steel Framing	Roof Coverings	Asphalt Shingles
	Wood Framing- Treated		Clay Tile
	Wood Framing- Untreated		Fiber Cement Shingles
Floor Tile	Ceramic Tile	Roof Insulation	Blown Cellulose-R38
	Parquet Tile		Fiberglass-R38
	Floating Floor Plank		Mineral Wool-R38
Exterior Wall Finishes	Aluminum Siding	Paint	Consolidated Latex Paint
	Cedar Siding		Reprocessed Latex Paint
	Vinyl Siding		Virgin Latex paint
Exterior Wall Insulation	Blown Cellulose-R13	Windows & Doors	Aluminum
	Mineral Wool-R13		Vinyl Clad Wood
	Fiberglass Batt-R13		Vinyl
Exterior Wall Sheathing	OSB Sheathing	Roof Sheathing	OSB Sheathing
	Plywood Sheathing		Plywood Sheathing

The global warming potential is measured with kg of CO₂ equivalents, acidification is expressed in hydrogen ion equivalents, and eutrophication is measured with gram of N equivalents. Since environmental impacts are measured with different units, normalization values should be used in order to equalize units and develop a comprehensive indicator value. The normalization values maintain all U.S. activity contributing particular impacts per year per capita. The normalization values with respect to environmental impacts are listed in Table 4.2 which are developed for the U.S. Environmental Protection Agency (EPA) Office of Research and Development (Bare *et al.*, 2007).

The normalization values for each impact category are per year and per capita. These values place the effect of each category in a range removing the specified units. Normalization method is also relevant to indicate the contribution of the building to the specified impacts.

Table 4.2. Normalization values.

Impact	Normalization Value
Eutrophication	19 214 g N equivalents/year/capita
Global Warming	25 582 kg CO ₂ equivalents/year/capita
Acidification	7 800 200 moles H ⁺ equivalents/year/capita

The remaining data are gathered from various sources. The unit prices (US Dollars) of candidate materials and determination of regional materials are derived from BEES software. Recycled content values are gathered from online recycled content product directory called calrecycle. The desired recycled content ratio (R) and the desired regional material ratio (RM) are described in relation to the requirements of related LEED performance criteria. They are both taken as 20 % for each constraint.

The data are taken from various sources due to lack of available data in the environmental evaluation tools. However, those estimates give an overall picture about a building construction associated with our study. Therefore, this study gathers information from various sources and performs an integrated data set. The remaining required candidate material parameters are listed in Table B.2 in Appendix B.

In the optimization study, relative weights are assigned as 76 % for global warming, 16 % for eutrophication, and 8 % for acidification. The relative importance weights are based on BEES stakeholder panel judgments.

The sub-model is solved by General Algebraic Modeling System (GAMS distribution 22.2) with CPLEX solver. It is observed that the minimum amount of allocated budget should be USD 68727. The ES for this amount of budget is 2.02. If the decision maker has at least that amount of money for material purchase, then the current data allow

an alternative building for construction. Budgets under that limit will fail to build a desired building. Therefore, the allocated budget is defined as USD 70000 in our study.

In this study, foundation element does not include foundation wall. It covers foundation slab and footings. The given values for both foundation slab and footings include building rebar environmental values. 75 m³ of concrete and 8650 kg of rebar are used for foundation footings. 26 m³ of concrete and 3000 kg of rebar are used for foundation slab. The unit cost for foundation is estimated per cubic-meters.

The erected building is decided as structural framing building which means framing materials such as steel and wood will be used instead of using columns and beams. Structural framing materials cover the exterior walls, interior walls, and roofing. In order to cover the floor with floor covering alternatives, the usable floor area of the building is used which is 133.8 m². The functional unit for exterior enclosure elements -exterior wall finishes, exterior wall insulation, and exterior wall sheathing- is square-meters and the required amount for the external wall enclosures are taken as 143.10 m² which is the area of the exterior walls.

The required amount for roofing elements is estimated as 160 m². In order to paint the gypsum board, the area for inner side of the exterior walls, the area for inner side of the roof, and the area for the interior walls are chosen and they are totally measured as 582.40 m². The same area is also relevant for used gypsum board. The doors are estimated as sliding glass doors, and the given values for windows and doors include glass for glazing. As described in BEES and EcoCalculator on-line databases, each material lifetime is assumed as 50 years.

4.2. In-depth Analysis of Model Outputs

The mathematical model is solved through GAMS by CPLEX solver as a Mixed Integer Programming (MIP) model. Appendix C provides the GAMS codes for the mathematical model. Table 4.3 shows the results of the model. It represents the properly selected materials that minimize environmental score as well as the entire building's environmental impact values throughout life-span. The table also demonstrates the selected

materials' total global warming potential (GWP), eutrophication potential (EP), and acidification potential (ACP) respectively. Environmental impacts of each material with respect to categories are calculated by multiplying the required amount of an optimal material with the respective environmental impact values per functional unit. Table 4.3 is a proper way to display the contribution of selected materials to the related total building environmental impacts. Material costs are calculated using materials unit prices and the required amounts for building elements. The total cost required for materials is also displayed.

Table 4.3. Environmental impact and cost distribution for optimal materials.

Building Element	Optimal Material Choice	GWP	EP	ACP	Cost
Foundation	Poured Concrete	27642	7708	9436	14948
Framing	Wood Framing- Untreated	984	49	236	13184
Floor Tile	Parquet Tile	505	119	268	13915
Exterior Wall Finishes	Vinyl Siding	1765	302	1383	3689
Exterior Wall Insulation	Blown Cellulose-R13	127	32	65	811
Exterior Wall Sheathing	Plywood Sheathing	652	334	156	2147
Roof Sheathing	Plywood Sheathing	729	373	174	2400
Roof Coverings	Asphalt Shingles	2497	1145	1440	1901
Roof Insulation	Blown Cellulose-R38	338	89	173	2720
Paint	Reprocessed Latex Paint	518	129	287	4336
Partitions	Gypsum Board	12619	4271	5306	4659
Windows&Doors	Vinyl	14405	4319	12957	4706
ES= 2.02	Total	62781	18871	31881	69415

As a general framework, there are 12 types of building elements in order to construct the entire building. Table 4.3 lists the proper materials given as the outcome of the mathematical model with determined limitations. For instance, parquet tile material is the best choice in order to cover the floor under defined circumstances. Moreover, in order to paint the gypsum board, the optimization tool recommends reprocessed latex paint by considering budget limitation and other environmental characteristics requirements.

70000 US Dollar is allocated as a restricted budget for the total cost of materials. When the costs of all optimal materials are estimated, the total cost is USD 69415. The total eutrophication potential of the building based on the specified elements is 18871 kg N equal. The building has 62781 kg CO₂ Equation global warming potential and 31881 moles H⁺ Equation acidification potential through 50 years life time.

Table 4.4 demonstrates the impact of each building element in terms of a selected measure as percentage. This table allows us to track the effects of each element regarding the particular effect of the entire building.

Table 4.4. Environmental impact distribution of materials as percentage.

Building element	Proper Material	GWP	EP	ACP	Cost
Foundation	Poured Concrete	44.0	40.8	29.6	21.5
Framing	Wood Framing- Untreated	1.6	0.3	0.7	19.0
Floor Tile	Parquet Tile	0.8	0.6	0.8	20.0
Exterior Wall Finishes	Vinyl Siding	2.8	1.6	4.3	5.3
Exterior Wall Insulation	Blown Cellulose-R13	0.2	0.2	0.2	1.2
Exterior Wall Sheathing	Plywood Sheathing	1.0	1.8	0.5	3.1
Roof Sheathing	Plywood Sheathing	1.2	2.0	0.5	3.5
Roof Coverings	Asphalt Shingles	4.0	6.1	4.5	2.7
Roof Insulation	Blown Cellulose-R38	0.5	0.5	0.5	3.9
Paint	Reprocessed Latex Paint	0.8	0.7	0.9	6.2
Partitions	Gypsum Board	20.1	22.6	16.6	6.7
Windows & Doors	Vinyl	22.9	22.9	40.6	6.8

The relative required amount for footings and foundation is significant compared with other elements. Apart from the size requirement, the poured concrete includes building rebar. It is a known fact that metal elements provide excessive amount of emissions throughout their life cycle. Hence, the environmental impacts of poured concrete with rebar are notable with 44 % contribution for GWP, 41 % for EP, and 30 % for ACP. Concrete for slab and footing has the biggest cost contribution, by 21.5 %, to the total cost of the building.

Framing, usually called studs, is a technique used for building envelope. It supports floor, walls, and roof partitions. For instance, gypsum board, sheathings, and coverings for walls and roofs are attached to the framing system. The optimization tool recommends the untreated wood alternative for structural framing element. Untreated wood is the best alternative in terms of environmental impact. It has the lowest impact values throughout life span compared to the other alternatives. Like treated-wood material, it is more affordable than steel material. Although untreated wood for framing fails to meet the regional material criteria, the entire building achieves this goal. The cost contribution of the structural framing is significant by 19 %.

Since the represented building is a single storey building in our study, the floor tile only covers the foundation slab. The proper material for floor tile is selected as cork parquet. Cork parquet is an eco-friendly and completely a renewable resource. Although the parquet tile has the lowest values in terms of environmental impacts, it is also the cheapest material among the flooring alternatives. Compared to the ceramic tile, its global warming potential is roughly seven times better per functional unit. It is three times affordable than the floating floor plank. Flooring with parquet tile has significant contribution to total cost by 20 %. However, its environmental impact relative to other building elements is not dramatic.

Sidings for exterior wall finishes are outer coverings protecting a residential building from water and effects of weather. Sidings are made of wood, metal, plastic, masonry, or composite materials. In the numerical analysis, the vinyl siding material alternative is the proper material for exterior wall covering. Vinyl siding is widely used due to low maintenance and low cost. It is observed from the data that vinyl siding is the cheapest alternative among exterior wall finish candidates. Exterior wall finish element has 5.3 % cost contribution to the entire building. However, there are disadvantages related with the environmental aspects of vinyl siding. It is less recyclable compared to other candidates. In our study, the recycled content ratio is significantly low with 10 %. It is also hard to dispose, and it releases toxic gases during incineration process. Besides, vinyl siding is flammable. It has lower environmental impact value than aluminum siding in terms of global warming and is the best alternative in terms of eutrophication potential. The

environmental impact contributions of vinyl siding to the building are 2.8 % for GWP, 1.6 % for EP, and 4.3 % for ACP, respectively.

External wall insulation provides heat loss reduction and energy conservation. It also contributes to in-door environmental comfort and prevents sound transfer. As compared to other candidate materials, blown cellulose is the most affordable material. Cellulose has the highest recycled content rather than any insulation material available at the market. Therefore, it is clearly seen from the database that it has 85 % recycled content by weight. Blown cellulose is also a regional material made with locally available materials. It is also the best alternative in terms of environmental impact values which means it possesses the lowest impact values among exterior wall insulation materials. Both cost and environmental impact contribution to the entire building are not significant by 1.2 % for cost and by 0.2 for each environmental impact category.

Plywood and OSB are wood based materials used for sheathing floor, exterior wall, and roofing systems. Even though they have similar features, OSB is cheaper compared to plywood. However, it is observed that environmental impact values for plywood are significantly lower than OSB. The recycled content ratios are very small for both sheathing materials which are 5 % for OSB and 10 % for plywood. Plywood material is more favorable than OSB material for both exterior wall and roof sheathings under these circumstances. The optimization tool recommends plywood material for exterior wall sheathing and roof sheathing under the assigned environmental and budget restrictions. The selected candidate material for exterior sheathing contributes to the impact categories by 1 % for GWP, 1.8 % for EP, and 0.5 % for ACP. It also constitutes 3.1 % portion of the total cost. For roof sheathing, impact contribution as percentage is 1.2 for GWP, 2 for EP, and 0.5 for ACP. The cost for roof sheathing comprises 3.5 % of the total cost for entire building.

Roof coverings are waterproof materials that protect buildings from the effects of the weather. Many kinds of materials are used for roofing at present. Asphalt shingle is relatively inexpensive and one of the most widely used material for roof covering. Moreover, its recycled content rate is higher than the other candidate materials. None of the three alternative roofing materials outperforms in terms of environmental impact

values. For instance, asphalt shingle is the best choice for GWP. However, clay tile is better at EP and ACP. Fiber cement shingle is the worst material in terms of environmental impact values. The environmental impacts of asphalt shingle are significant with 4 % contribution for GWP, 6.1 % contribution for EP, and 4.5 % contribution for ACP. Moreover, it has cost contribution by 2.7 to the total cost of the building.

Roof insulation enhances thermal comfort to occupants. It also reduces heat loss and energy demand. Although the advised material for the roof insulation is the same material type, blown cellulose, as exterior wall insulation, the environmental features of the materials are different from the wall insulation materials. Blown cellulose R13 is the best material in terms of environmental impact categories among alternatives. However, blown cellulose R38 is worse at GWP than mineral wool R38. It is still the cheapest candidate material and has the highest recycled content ratio. The environmental impacts of the chosen material are not notable with 0.5 % contribution for each environmental impact category. However, it has 3.9 % contribution to the total cost of the building.

It is observed from the data that reprocessed latex paint and virgin latex paint are more affordable than consolidated latex paint. Moreover, reprocessed latex paint has considerably lower environmental impact values compared with other paint alternatives. However, the recycled content rate of consolidated latex paint has the highest ratio. The proper candidate material is reprocessed latex paint in this circumstance. The environmental impacts of the selected material are not significant with 0.8 % contribution for GWP, 0.7 % for EP, and 0.9 % for ACP. However, reprocessed latex paint usage constitutes considerable portion of the total cost by 6.2 %.

Gypsum board is comprised of gypsum plaster pressed between two sheets of paper. It is used in order to form interior walls and ceilings. In this study, it is a single material for covering inner side of the building. Gypsum board has low recycled content rate which is 4 % by weight. Gypsum board has notable contribution to the environmental impact by 20 % for global warming potential, 22.6 % for eutrophication potential, and 16.6 % for acidification potential. It has 6.7 % cost contribution to the total cost of the building.

There are three candidate materials for windows and doors. The vinyl based alternative is the cheapest material. On the other hand, vinyl clad wood is the best choice in terms of environmental impact. The optimization tool recommends vinyl based material which possesses the highest recycled content rate. Although vinyl based windows and doors covers 6.8 % of the total cost of the building, environmental impact values of windows and doors seem problematic with high contribution to the environmental score of the building as 23 %, 23 %, and 40.6 %, respectively. Such high contribution to the building's environmental impact results from the inclusion of glass.

5. SENSITIVITY ANALYSIS

The solution of the mathematical model satisfies the pre-specified economic, design, and environmental constraints. However, the environmental impact results may be insufficient to obtain a greener building compared with other alternative building designs. Besides, changes in decision-makers' preferences can affect the optimal solution. Thus, further analysis should be performed in order to enhance material selection process.

This section provides sensitivity analyses to observe how changes in construction material selection would affect the results of the study. First of all, allocated budget for construction materials is adjusted in order to observe the changes in the environmental impact scores as well as the substitutions in the building materials. Then, the best case which minimizes the environmental impact score is calculated by modifying the existing model and the variations from the existing study are analyzed. Finally, different relative importance weights for environmental impacts are determined and the results are obtained.

5.1. Budget Adjustment

There is a general perception that conventional buildings are more affordable than green buildings. It is believed that one of the critical factors is the allocated budget that prevents constructing greener buildings. The mathematical model may fail to select more proper materials due to restricted budget which leads to obtaining low environmental impact scores.

A sensitivity analysis is essential to observe the effects of the additional funding to the mathematical model. Therefore, the model is solved several times by varying the budget parameter. The compromise between assigned budgets and environmental impact scores are analyzed.

The model is run several times with increasing the budget parameter from the initial allocated budget to maximum budget available. The budget is increased by USD 5000 at each run. Then, the environmental scores are obtained. Figure 5.1 represents the compromise between the budget and environmental scores.

In the previous section, we have determined the minimum required amount for material purchase regarding our available data. Now, we will justify the most expensive building among candidate buildings. It is achieved by modifying the initial mathematical model. First, the budget constraint (Equation 3.4) is removed from the model similar to Section 3.2. Then, the objective function is replaced with the following objective function. However, this time the objective is specified as maximization function which is

$$\max \sum_j \sum_i c_{ij} a_{ij} y_{ij} \quad (5.1)$$

Equation 5.1 disregards the environmental impact minimization. It aims to determine the most expensive amount in order to build the desired building as well as meeting remaining constraints in the optimization model. The modified model is run and USD 116106 is obtained as the biggest possible allocated budget related with our data.

Once the costs of all cheapest materials for each element are calculated, the lowest possible value of a building alternative is USD 68726. Conversely, the most valuable building costs USD 116106. For instance, decision-maker should allocate USD 116106 in order to select the most expensive materials for each building element. The model is solved ten times varying the parameter B from USD 70000 to USD 115000.

Each point on Figure 5.1 demonstrates a different choice of materials that form alternative building designs with respective allocated budgets. For instance, under the environmental characteristic limitations and USD 75000 restricted budget, the environmental score for the erected building is 2.01.

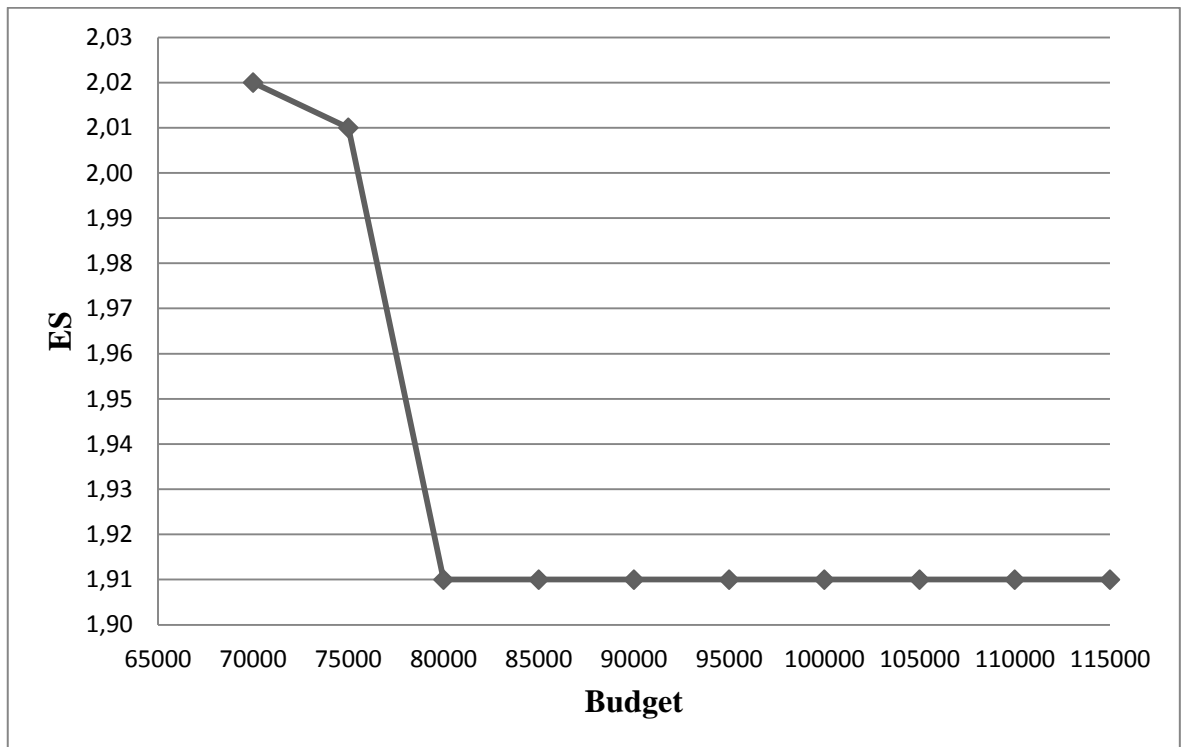


Figure 5.1. Compromise between budget and environmental score.

At first glance, it seems that increasing the budget for material purchase leads to more environmental friendly building. However, the best environmental score is achieved even before the maximum allocated amount of money. After we increase the budget above USD 80000, there seems no trade-off between budget and environmental impact score. A more careful analysis should be made to determine the minimum cost that also gains the smallest environmental score. This could be obtained with a slight modification to the existing model.

5.2. Model Modification

The mathematical model is modified in order to obtain the additional funding for the best possible environmental score of alternative buildings. The objective function tries to minimize the environmental score without considering budget limitation. The Appendix B.2 demonstrates the GAMS codes of the modified model.

The modified mathematical model disregards the budget limitations. It aims to determine the best material alternative in order to minimize the environmental burden of

the building. It is achieved by removing the budget constraint from the previous mathematical model. The new model is run and the variations are examined in order to perform more in-depth analysis. The outputs of both the previous and new model are compared with each other. Table 5.1 below lists the best materials and their environmental impact values. It also demonstrates total cost contribution of each building element to the entire building.

Table 5.1. Outputs for the modified model.

Building element	Optimal Material Choice	GWP	EP	ACP	Cost
Foundation	Poured Concrete	27642	7708	9436	14948
Framing	Wood Framing- Untreated	984	49	236	13184
Floor Tile	Parquet Tile	505	119	268	13915
Exterior Wall Finishes	Cedar Siding	1097	827	366	7409
Exterior Wall Insulation	Blown Cellulose-R13	127	32	65	811
Exterior Wall Sheathing	Plywood Sheathing	652	334	156	2147
Roof Sheathing	Plywood Sheathing	729	373	174	2400
Roof Coverings	Asphalt Shingles	2497	1145	1440	1901
Roof Insulation	Mineral Wool-R38	320	107	187	3893
Paint	Reprocessed Latex Paint	518	129	287	4336
Partitions	Gypsum Board	12619	4271	5306	4659
Windows & Doors	Vinyl Clad Wood	11369	3987	11628	7475
ES=1.91	Total	59059	19081	29548	77078

After running the model with no budget limitation, variations occur in the selected materials. Since poured concrete and gypsum board provide single choice for both partition and concrete elements, three out of the remaining ten selected materials are replaced with the new modified model. The comparison between the model outputs shows that vinyl siding for exterior wall finishes is substituted by cedar siding, which is the most costly alternative material. This is due to the fact that, cedar siding is the best choice in terms of environmental impact values. Moreover, blown cellulose-R38 for roof insulation is replaced by mineral wool-R38 which is again more expensive, but also more

environmental-friendly. Finally, the modified model recommends vinyl clad wood for windows and doors instead of vinyl based material.

The modified model shows that USD 77078 is required in order to minimize environmental score -which is 1.91- along with meeting environmental performance criteria. As it could be observed from Table 5.1, the new building has 59059 kg CO₂ Equation global warming potential. The total eutrophication potential of the building based on specified materials is 19081 kg N equal. Finally, the building has 29548 moles H+ Equation acidification potential through 50 years life time.

Table 5.2 provides the comparison between the two models in terms of cost and environmental impacts. When we compare the outputs for the two models, it is observed that the modified model performs better in environmental impact assessment. Apart from meeting performance criteria, there are recoveries for the impact categories considering entire buildings. Global warming potential is reduced by 6 % from 62781 to 59059 kg Equation CO₂. Acidification potential is declined by 7 % from 31881 to 29548 moles H+ Equation The eutrophication potential is increased by 1 %. However, the latter building overweighs in environmental impact score due to the assigned relative importance weights for each environmental impact categories.

Table 5.2. Comparison of the two models.

	GWP	EP	ACP	Cost
Initial Model	62781	18871	31881	69415
Modified Model	59059	19081	29548	77078
Variation	-%6	+%1	-%7	+%11

It is worthwhile to mention that in the modified case, the decision maker should pay USD 7662 price premium for material purchase which refers to 11 % budget increase to achieve the environmental score. This result reveals the existing trade-off between allocated budget and environmental score. It is also observed in Figure 5.1 that at some point material selection problem is a compromise between budget and environmental burden. However, increasing the allocated budget after USD 77078 fails to enhance

obtaining better environmental values. For instance, the best environmental score is achieved and remains the same for the budget interval USD 77078 and USD 115000. Consequently, this analysis reflects that decision-makers do not necessarily pay higher budgets at material purchase stage for better buildings in terms of environmental burden.

Table 5.3 demonstrates the proportions of the building elements in total environmental impacts and total cost for the modified model. It is important to note that disregarding budget limitation enhances considerable proportion reduction for substituted materials. The modified model recommends three different alternative materials for respective building elements. However, the proportion distribution of the building elements in total figures is similar. The specific building elements still have the notable contributions to the entire building compared with the initial model.

Table 5.3. Proportions of environmental impact and cost for the modified model.

Building element	Optimal Material Choice	GWP	EP	ACP	Cost
Foundation	Poured Concrete	46.8	40.4	31.9	19.4
Framing	Wood Framing- Untreated	1.7	0.3	0.8	17.1
Floor Tile	Parquet Tile	0.9	0.6	0.9	18.1
Exterior Wall Finishes	Cedar Siding	1.9	4.3	1.2	9.6
Exterior Wall Insulation	Blown Cellulose-R13	0.2	0.2	0.2	1.1
Exterior Wall Sheathing	Plywood Sheathing	1.1	1.7	0.5	2.8
Roof Sheathing	Plywood Sheathing	1.2	2.0	0.6	3.1
Roof Coverings	Asphalt Shingles	4.2	6.0	4.9	2.5
Roof Insulation	Mineral Wool-R38	0.5	0.6	0.6	5.1
Paint	Reprocessed Latex Paint	0.9	0.7	1.0	5.6
Partitions	Gypsum Board	21.4	22.4	18.0	6.0
Windows&Doors	Vinyl Clad Wood	19.2	20.9	39.4	9.7

Poured concrete still has the most significant proportion in environmental impact categories. It has approximately 20 % contribution to the total cost. Even though, vinyl clad wood is replaced with vinyl based material for windows and doors, it has still the third biggest contribution to the total environmental impact of the entire building with 19.2 %

for GWP, 20.9 % for EP, and 39.4 % for ACP. These figures reveal that specific building elements should be focused on in order to reduce the environmental burden. This could be achieved with developing manufacturing technologies and improving production processes which is out of the scope for our study.

5.3. Weighting Adjustment

Weighting adjustment is crucial for calculating a single environmental indicator for a set of impact categories. Besides, it is essential to assign proper relative importance weights in order to perform a convenient study. Our mathematical model provides the flexibility for the users to assign different weightings. However, decision makers may manipulate the results by adjusting weightings. In this part, two alternative relative importance weights are applied to the mathematical model. First weightings are the same as the initial weightings which are 76 % for GWP, 16 % for EP, 8 % for ACP. The latter weighting case forces equal weights to each impact category. Assigned budget is determined as USD 90000 for each model. Table 5.4 lists the assigned weightings for each case.

Table 5.4. Determined relative weightings for each case.

Weighting System	GWP	EP	ACP
Initial Weighting	0.76	0.18	0.08
Equal Weighting	0.33	0.33	0.33

Table 5.5 and Table 5.6 gather and summarize the results for the two different weighting alternatives. In Table 5.5 it is clearly seen that weighting adjustment has changed the optimal materials. It is worth noting that two of the optimal materials are substituted by equal relative importance alternative. In the latter alternative, cedar siding is replaced by vinyl siding and blown cellulose R38 is recommended instead of mineral wool R38. The important point is which of the determined weighting is better for environmental impact analysis. Therefore, the total contribution of the two buildings should be studied in detail.

Table 5.5. Best materials for alternative weightings.

Building element	Initial Weighting	Equal Weighting
Foundation	Poured Concrete	Poured Concrete
Framing	Wood Framing- Untreated	Wood Framing- Untreated
Floor Tile	Parquet Tile	Parquet Tile
Exterior Wall Finishes	Cedar Siding	Vinyl Siding
Exterior Wall Insulation	Blown Cellulose-R13	Blown Cellulose-R13
Exterior Wall Sheathing	Plywood Sheathing	Plywood Sheathing
Roof Sheathing	Plywood Sheathing	Plywood Sheathing
Roof Coverings	Asphalt Shingles	Asphalt Shingles
Roof Insulation	Mineral Wool-R38	Blown Cellulose-R38
Paint	Reprocessed Latex Paint	Reprocessed Latex Paint
Partitions	Gypsum Board	Gypsum Board
Windows&Doors	Vinyl Clad Wood	Vinyl Clad Wood

In order to conduct in-depth analysis, Table 5.6 represents total cost and total environmental impact values for each category. First of all, the two models reach the optimal solutions with significantly lower budgets. For equal weighting alternative, USD 72184 is enough for the construction of the optimal building which is USD 17816 cheaper than the allocated budget.

Table 5.6. Total cost and environmental burdens for alternative weightings.

Total	GWP	EP	ACP	Cost
Initial Weighting	59059	19081	29548	77078
Equal Weighting	59744	18538	30552	72184

The total required cost for equal weighting is more preferable than initial weighting. Since the decision maker can afford USD 90000 for construction materials, cost factor should not be taken into consideration for comparison. Second, the initial weighting system overweighs the equal relative importance assignment in GWP and ACP. All in all, weighting strictly affects the material selection process.

6. CONCLUSION

There is a strong relationship between buildings and environment. Relevant literature indicates that buildings have significant negative impacts on natural environment. Buildings demand natural resources such as raw materials, energy, and water. They transform resources into wastes in related processes. Construction activities release harmful emissions that are dangerous for both humans and environment. Therefore, improvements for reducing effects of buildings provide significant benefits for a sustainable future.

Green buildings have evolved due to the need for environmental protection. This philosophy aims to construct environmentally benign and sustainable buildings. Green buildings require the consideration of resource depletion and waste emissions. Despite green buildings have many benefits, they are perceived as costly investments. Thus, decision makers may feel discouraged about participating in green projects. Therefore, it is essential to carry out both environmental and economic issues.

Proper material selection is crucial in order to increase performance of green buildings. Conventional material selection techniques most often neglect environmental issues. They primarily focus on technical requirements and affordability. However, addition of environmental considerations is a must due to the immense effects caused by construction materials. Recent approaches indicate that material selection process should be part of the investigation process covering various factors simultaneously. Therefore, decision makers should assess environmental burdens of materials along with other decisive factors. As a result, construction material selection turns into a promising multi criteria decision problem.

As previously stated, there are numerous factors that influence material selection. This thesis treats the selection problem through a broad scope. The study covers environmental impact quantification of material through life cycle perspective excluding occupancy phase. LCA approach provides holistic analysis of materials through their life-span. It tracks the necessary inputs and outputs under the specified scope and performs

relevant information about products. Global warming, eutrophication, and acidification potentials are considered as impact categories in the numerical illustration. These categories have global and long-lasting effects on natural environment.

This study also includes two of the environmental characteristics: Recycled content and Regional material. Using high recycled content material reduces environmental influences resulting from raw material extraction and manufacturing. Besides, encouraging regional material contributes to regional economy and reduces the effects of material transportation. Such characteristics are mostly used as performance criteria in building rating systems such as LEED, BREEAM, SBTool. The intention of this approach is to combine different environmental measures and strengthen the material selection process.

Since there are numerous factors to account for, a computer tool is required in order to select building materials properly. The material selection methodology suggests a new formula in order to evaluate environmental impact of a building. Apart from previous studies in the literature, the scope of the quantification method encompasses the entire building rather than treating the building elements discretely. The new formula is called as environmental impact score. This score value aims to unify the specified environmental impact categories and perform as a single indicator. First, the calculation method gathers all environmental impact values from building elements for each category. Then, it removes different units by applying normalization method. Finally, relative importance weights enhance synthesizing the impact categories into a single indicator. The measure is employed for environmental impact optimization.

The integer programming model optimizes the building environmental impact through a whole-building approach based on alternative materials. The tool tries to obtain the least environmental impact score which leads to minimizing the burdens for each impact category. Besides, the optimization model has three types of constraints in order to fulfill additional requirements and environmental issues. The constraints include criteria from various factors in order to complement the material selection problem. They try to provide a holistic study.

The first constraint is the budget constraint. Economic issues are significant for material selection. The decision maker should include economic considerations to the selection process. The allocated budget should afford the desired building. Second, the model covers design constraint which only validates the required amounts for each building element. It is worth noting that the design phase of this study lacks covering numerous factors such as shape of the building, sizes of windows. The third set of constraints is concerned with material characteristics. The model allows decision makers to assign desired performance criteria values for both recycled content value and regional materials.

In the numerical study, the mathematical model is applied to a single-storey building. The entire building is assumed to comprise of 12 elements. There are candidate materials in order to build any building element. The relevant tools lack providing comprehensive data for building materials. Thus, the required inputs for optimization tool are obtained from various sources. However, they are useful for performing proper analysis for material selection problem. The optimization model is solved by GAMS and the outputs of the study are analyzed.

Chapter 4 displays the results of the numerical study. Then, the outputs are examined in detail. Total cost and total environmental impact values of the building are computed in order to observe the big picture. Moreover, each suggested material by the tool for building elements are investigated comprehensively. The selected materials which possess significant contribution to the building in terms of cost and environmental burden are identified. The reasons beneath notable impacts are underlined.

This study also performs sensitivity analysis in order to integrate our mathematical model with the changing situations in the construction market. Besides, it provides decision-makers to observe various alternative set of material by adjusting allocated budget and weightings. In the sensitivity analysis, the allocated budget is adjusted. It is found that green buildings do not necessarily cost more than conventional buildings in the material purchase stage. My findings are contrary to the perceptions in the marketplace. Moreover, the relative importance weights are adjusted, and the results are observed. It is worthwhile

to note that proper weighting is essential in order to conduct a useful material selection study.

This study is distinctive from previous studies. Firstly, there is not a realistic approach between cost and environmental burdens of building materials. Relevant studies show that it is challenging to reflect environmental properties into cost. Most studies based on material selection try to convert environmental features into cost which is not reasonable. This study performs a more realistic assessment of building materials and distinguishes environmental features and cost in the assessment process.

Besides, the literature lacks fulfilling material selection in a comprehensive way. Most studies are quite restricted and treat material selection problem for single building elements. However, it is challenging and time consuming for the decision-maker to combine different set of materials. Moreover, some studies include various building elements but the elements fail to erect an entire building. The proposed mathematical model selects the best materials for each building element under determined conditions and attempts to form an entire building.

The material selection system can be improved in a number of ways in order to make optimization model more powerful. New environmental factors could be integrated into the mathematical model to perform more in-depth analysis. Many additional aspects could be considered in the optimization program. For instance, inclusion of sustainable site features, shape of buildings, and sizes of windows for illumination enhance the quality of the optimization study.

There are significant shortages in accessing data for regional materials. The construction sector lacks obtaining relevant data. Therefore, establishing databases for alternative materials is of great importance. The scope of the LCA could be enlarged. This study fails to take into account the occupancy stage of LCA. The usage of electricity and water during this period is substantial and should be reduced. The interactions of materials and depletions during occupancy stage should be incorporated with simulation tools. However, this integration requires great efforts to be accomplished.

APPENDIX A: SCREENSHOTS FOR SOFTWARES

ATHENA® EcoCalculator
for residential assemblies

TOTAL IMPACTS BY BUILDING COMPONENT				Fossil Fuel Consumption (tD) TOTAL	GWP (tonnes CO2eq) TOTAL	Weighted Resource Use (tonnes) TOTAL	Acidification Potential (moles of H+ eq) TOTAL	HH Respiratory Effects Potential (kg PM2.5 eq) TOTAL	Eutrophication Potential (g N eq) TOTAL	Ozone Depletion Potential (mg CFC-11 eq) TOTAL	Smog Potential (kg NOx eq) TOTAL
WINDOWS				0	0	0	0	0	0	0	0
WHOLE BUILDING TOTAL				0	0	0	0	0	0	0	0

E. WINDOWS

IN THE YELLOW CELLS BELOW, ENTER THE AMOUNT OF SQUARE FOOTAGE THAT EACH ASSEMBLY USES IN YOUR BUILDING

	FRAME TYPE	DOUBLE GLAZING TYPE	Square footage	Percentage of total	Fossil Fuel Consumption per ft² (tD)	Global Warming Potential per ft² (kg CO2 eq)	Weighted Resource Use per ft² (kg)	Acidification Potential per ft² (moles of H+ eq)	HH Respiratory Effects Potential per ft² (g PM2.5 eq)	Eutrophication Potential per ft² (mg N eq)	Ozone Depletion Potential per ft² (mg CFC-11 eq)	Smog Potential per ft² (g NOx eq)
Average across all window types:												
1	Aluminum - Operable	Low E, Argon Filled	0.0		497.56	43.36	64.02	55.78	500.08	15,427.18	0.16	282.35
2	Vinyl-clad Wood - Operable	Low E, Argon Filled	0.0		790.34	66.48	59.30	115.23	903.94	23,990.63	0.24	545.82
3	Vinyl - Operable	Low E, Argon Filled	0.0		354.59	32.47	73.68	34.02	349.71	11,996.92	0.10	186.58
4	Wood - Operable	Low E, Argon Filled	0.0		490.72	40.58	43.55	37.76	368.67	12,932.08	0.23	195.33
TOTAL WINDOW SQUARE FOOTAGE			0.0									

Note:
Sliding glass door areas should be input as windows on this page

Figure A.1. Screenshot for EcoCalculator.

Building Element for Comparison

Major Group Element

Group Element

Individual Element

Buttons: OK, Cancel, Help

Figure A.2. Selecting building element from BEES.

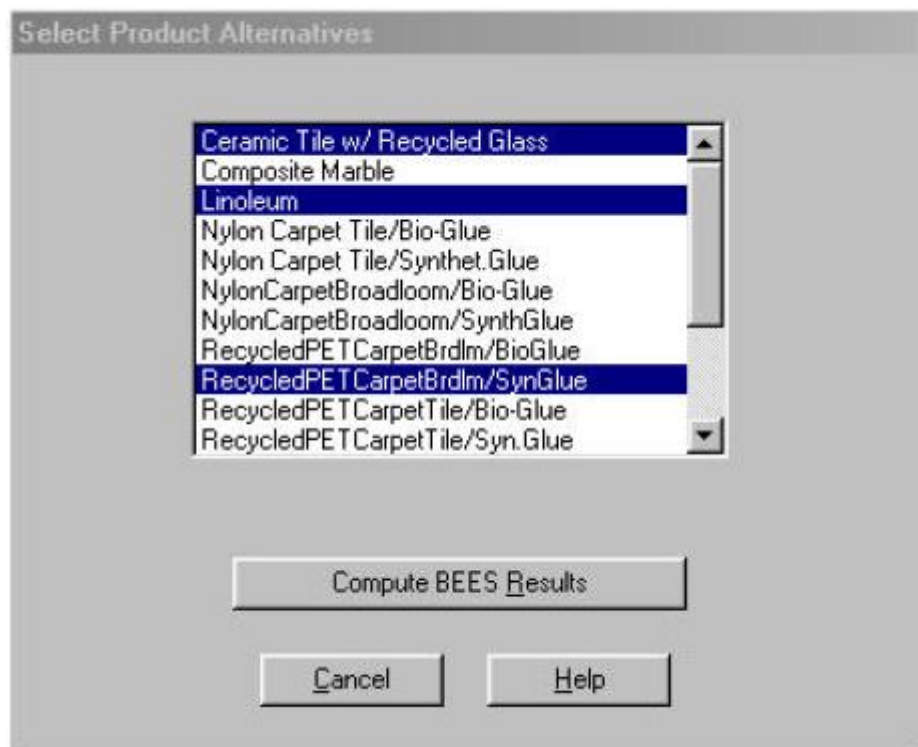


Figure A.3. Selecting building product alternatives from BEES.

Potential Environmental Impact	Units	Raw Results			Weighting (%)	Normalized Results		
		Tile/Glass	Linoleum	PETBrdSyn		Tile/Glass	Linoleum	PETBrdSyn
Acidification	H+	0.4590	0.3243	0.3722	17	17	12	14
Eutrophication	PO4	0.7777	20.5234	1.0676	17	1	17	1
Global Warming	CO2	1783	360	2188	17	14	3	17
Indoor Air Quality	pts	0	50	72	16	0	11	16
Resource Depl.	Index	0.0420	0.0312	0.0569	17	11	8	17
Solid Waste	CFI	0.08	0.03	0.22	16	6	2	16
Land Use								
Water Use								
Air Quality								
Soil								
Total						49	53	81

Potential Economic Impact	Units	Tile/Glass	Linoleum	PETBrdSyn
First Cost	\$	8.53	3.18	2.11
Future Cost	FV\$	0.00	2.15	4.46
Life-Cycle Cost		8.53	5.33	6.57
Discount Rate (%)		42		

Potential Overall Impact		
Tile/Glass	Linoleum	PETBrdSyn
75	58	80
Environ. Wt (%)	50	Econ. Wt (%) 50

Note: Lower values are better

Figure A.4. Viewing BEES summary table.

APPENDIX B: DATA SOURCES

Table B.1. Environmental Impact Values.

Building element	Candidate material	GWP	EP	ACP
Foundation	Poured Concrete	273.68	76.32	93.42
Framing	Steel Framing	6.11	1.44	1.52
	Wood Framing- Treated	3.33	1.78	1.52
	Wood Framing- Untreated	2.22	0.11	0.53
Floor Tile	Ceramic Tile	28.67	4.89	10.69
	Parquet Tile	3.78	0.89	2.00
	Floating Floor Plank	10.00	9.56	9.42
Exterior Wall Finishes	Aluminum Siding	16.56	1.67	5.46
	Cedar Siding	7.67	5.78	2.56
	Vinyl Siding	12.33	2.11	9.67
Exterior Wall Insulation	Blown Cellulose-R13	0.89	0.22	0.46
	Mineral Wool-R13	2.78	0.67	1.38
	Fiberglass Batt-R13	1.11	0.44	0.62
Exterior Wall Sheathing	OSB Sheathing	9.33	18.33	14.00
	Plywood Sheathing	4.56	2.33	1.09
Roof Sheathing	OSB Sheathing	9.33	18.33	14.00
	Plywood Sheathing	4.56	2.33	1.09
Roof Coverings	Asphalt Shingles	15.61	7.16	9.00
	Clay Tile	20.45	5.05	7.79
	Fiber Cement Shingles	30.68	6.72	10.15
Roof Insulation	Blown Cellulose-R38	2.11	0.56	1.08
	Fiberglass-R38	4.56	0.11	2.27
	Mineral Wool-R38	2.00	0.67	1.17
Paint	Consolidated Latex Paint	2.44	0.44	1.05
	Reprocessed Latex Paint	0.89	0.22	0.49
	Virgin Latex paint	1.11	0.22	0.57
Partitions	Gypsum Board	21.67	7.33	9.11
Windows & Doors	Aluminum	752.33	266.67	1288.89
	Vinyl Clad Wood	380.22	133.33	388.89
	Vinyl	481.78	144.44	433.33

Table B.2. Other parameters.

Building element	Candidate material	Cost	a_{ij}	r_{ij}	rm_{ij}
Foundation	Poured Concrete	148.00	101.00	20%	1
Framing	Steel Framing	33.67	442.75	25%	1
	Wood Framing- Treated	29.67		15%	1
	Wood Framing- Untreated	29.78		20%	0
Floor Tile	Ceramic Tile	106.11	133.80	58%	0
	Parquet Tile	104.00		90%	1
	Floating Floor Plank	313.33		0%	1
Exterior Wall Finishes	Aluminum Siding	33.89	143.10	80%	1
	Cedar Siding	51.78		95%	1
	Vinyl Siding	25.78		10%	0
Exterior Wall Insulation	Blown Cellulose-R13	5.67	143.10	85%	1
	Mineral Wool-R13	7.56		82%	1
	Fiberglass Batt-R13	8.44		30%	0
Exterior Wall Sheathing	OSB Sheathing	12.89	143.10	5%	1
	Plywood Sheathing	15.00		10%	1
Roof Sheathing	OSB Sheathing	12.89	160.00	5%	1
	Plywood Sheathing	15.00		10%	1
Roof Coverings	Asphalt Shingles	11.88	160.00	50%	1
	Clay Tile	63.88		0%	1
	Fiber Cement Shingles	28.24		10%	0
Roof Insulation	Blown Cellulose-R38	17.00	160.00	85%	1
	Fiberglass-R38	21.89		30%	1
	Mineral Wool-R38	24.33		82%	1
Paint	Consolidated Latex Paint	8.44	582.40	100%	1
	Reprocessed Latex Paint	7.44		20%	1
	Virgin Latex paint	7.44		40%	1
Partitions	Gypsum Board	8.00	582.40	4%	1
Windows&Doors	Aluminum	203.70	29.90	80%	1
	Vinyl Clad Wood	250.00		50%	1
	Vinyl	157.41		95%	1

APPENDIX C: GAMS CODES

C.1. Gams Codes for the First Model

```

Sets
i materials /1*3/
j elements /1*12/
k impact category /1*3/ ;
table
a(i,j) required amount
      1      2      3      4      5      6      7      8      9      10     11     12
1  101.00  442.75  133.80  143.10  143.10  143.10  160.00  160.00  160.00  582.40  582.40  29.90
2  101.00  442.75  133.80  143.10  143.10  143.10  160.00  160.00  160.00  582.40  582.40  29.90
3  101.00  442.75  133.80  143.10  143.10  143.10  160.00  160.00  160.00  582.40  582.40  29.90
;
table
c(i,j) unit costs
      1      2      3      4      5      6      7      8      9      10     11     12
1   148.00  33.67  106.11  33.89  5.67  12.89  12.89  11.88  17.00  8.44  8.00  203.70
2  120000  29.67  104.00  51.78  7.56  15.00  15.00  63.88  21.89  7.44  120000  250.00
3  120000  29.78  313.33  25.78  8.44  120000  120000  28.24  24.33  7.44  120000  157.41
;

table
r(i,j) recycle
      1  2  3  4  5  6  7  8  9  10  11  12
1   0.2 0.25 0.58 0.8 0.85 0.05 0.05 0.50 0.85 1.00 0.04 0.8
2         0.15 0.9 0.95 0.82 0.1 0.1 0.00 0.30 0.20 0.5
3         0.2 0.00 0.1 0.30 0.10 0.82 0.40 0.95
;

table
rm(i,j) regional material
      1  2  3  4  5  6  7  8  9  10  11  12
1   1  1  0  1  1  1  1  1  1  1  1  1
2         1  1  1  1  1  1  1  1  1  1
3         0  1  0  0  0  0  1  1  1
;

table
e(i,j,k) environmental score
      1      2      3
1.1     273.68     76.32     93.42
2.1
3.1
1.2     6.11     1.44     1.52
2.2     3.33     1.78     1.52
3.2     2.22     0.11     0.53
1.3     28.67     4.89     10.69
2.3     3.78     0.89     2.00
3.3     10.00     9.56     9.42

```

1.4	16.56	1.67	5.46
2.4	7.67	5.78	2.56
3.4	12.33	2.11	9.67
1.5	0.89	0.22	0.46
2.5	2.78	0.67	1.38
3.5	1.11	0.44	0.62
1.6	9.33	18.33	14.00
2.6	4.56	2.33	1.09
3.6			
1.7	9.33	18.33	14.00
2.7	4.56	2.33	1.09
3.7			
1.8	15.61	7.16	9.00
2.8	20.45	5.05	7.79
3.8	30.68	6.72	10.15
1.9	2.11	0.56	1.08
2.9	4.56	0.11	2.27
3.9	2.00	0.67	1.17
1.10	2.44	0.44	1.05
2.10	0.89	0.22	0.49
3.10	1.11	0.22	0.57
1.11	21.6	7.33	9.11
2.11			
3.11			
1.12	752.33	266.67	1288.89
2.12	380.22	133.33	388.89
3.12	481.78	144.44	433.33

```

;
parameters
B allocated budget /70000/
RE recycle ratio /0.20/
REM regional material ratio /0.20/
w(k) weightings /1 0.76, 2 0.16, 3 0.08/
N(k) Normalization values /1 25582, 2 19214, 3 7800200 /
;
variable
z impact objective function ;
Binary variable
y(i,j) ;
Equations
objective environmental impact minimization
economic budget cons
select(j) selection limitation
regional regional material performance criteria
recycle recycle material performance criteria ;
objective.. z =e= sum((i,j,k), (e(i,j,k)*y(i,j)*a(i,j)*w(k))/N(k));
economic.. sum((i,j),c(i,j)*a(i,j)*y(i,j)) =l= B;
select(j).. sum(i,y(i,j)) =e= 1;
regional.. sum((i,j),c(i,j)*a(i,j)*y(i,j)*rm(i,j)) =g= sum((i,j),c(i,j)*a(i,j)*y(i,j))*REM;
recycle.. sum((i,j),c(i,j)*a(i,j)*y(i,j)*r(i,j)) =g= sum((i,j),c(i,j)*a(i,j)*y(i,j))*RE;
;
model impact /all/;
solve impact using mip minimizing z;
options optcr = 0.0

```

C.2. Gams Codes for the Modified Model

```

Sets
i materials /1*3/
j elements /1*12/
k impact category /1*3/ ;
table
a(i,j) required amount
  1      2      3      4      5      6      7      8      9      10     11     12
1  101.00  442.75  133.80  143.10  143.10  143.10  160.00  160.00  160.00  582.40  582.40  29.90
2  101.00  442.75  133.80  143.10  143.10  143.10  160.00  160.00  160.00  582.40  582.40  29.90
3  101.00  442.75  133.80  143.10  143.10  143.10  160.00  160.00  160.00  582.40  582.40  29.90
;
table
c(i,j) unit costs
  1      2      3      4      5      6      7      8      9      10     11     12
1   148.00  33.67  106.11  33.89  5.67  12.89  12.89  11.88  17.00  8.44  8.00  203.70
2  120000  29.67  104.00  51.78  7.56  15.00  15.00  63.88  21.89  7.44  120000  250.00
3  120000  29.78  313.33  25.78  8.44  120000  120000  28.24  24.33  7.44  120000  157.41
;
table
r(i,j) recycle
  1      2      3      4      5      6      7      8      9      10     11     12
1   0.2  0.25  0.58  0.8  0.85  0.05  0.05  0.50  0.85  1.00  0.04  0.8
2         0.15  0.9  0.95  0.82  0.1  0.1  0.00  0.30  0.20         0.5
3         0.2  0.00  0.1  0.30         0.10  0.82  0.40         0.95
;
table
rm(i,j) regional material
  1      2      3      4      5      6      7      8      9      10     11     12
1   1      1      0      1      1      1      1      1      1      1      1      1
2         1      1      1      1      1      1      1      1      1         1
3         0      1      0      0         0      1      1         1
;
table
e(i,j,k) environmental score
  1      2      3
1.1     273.68     76.32     93.42
2.1
3.1
1.2      6.11      1.44      1.52
2.2      3.33      1.78      1.52
3.2      2.22      0.11      0.53
1.3     28.67     4.89     10.69
2.3      3.78      0.89      2.00
3.3     10.00     9.56      9.42
1.4     16.56     1.67      5.46
2.4      7.67      5.78      2.56
3.4     12.33     2.11      9.67
1.5      0.89      0.22      0.46
2.5      2.78      0.67      1.38
3.5      1.11      0.44      0.62

```

```

1.6      9.33      18.33      14.00
2.6      4.56      2.33      1.09
3.6
1.7      9.33      18.33      14.00
2.7      4.56      2.33      1.09
3.7
1.8      15.61     7.16      9.00
2.8      20.45     5.05      7.79
3.8      30.68     6.72     10.15
1.9      2.11      0.56      1.08
2.9      4.56      0.11      2.27
3.9      2.00      0.67      1.17
1.10     2.44      0.44      1.05
2.10     0.89      0.22      0.49
3.10     1.11      0.22      0.57
1.11     21.6      7.33      9.11
2.11
3.11
1.12     752.33     266.67     1288.89
2.12     380.22     133.33     388.89
3.12     481.78     144.44     433.33
;

parameters

RE recycle ratio /0.20/
REM regional material ratio /0.20/
w(k) weightings /1 0.76, 2 0.16, 3 0.08/
N(k) Normalization values /1 25582, 2 19214, 3 7800200 /;
variable
z impact objective function ;
Binary variable
y(i,j) ;
Equations
objective environmental impact minimization
select(j) selection limitation
regional regional material performance criteria
recycle recycle material performance criteria ;
objective.. z =e= sum((i,j,k), (e(i,j,k)*y(i,j)*a(i,j)*w(k))/N(k));
select(j).. sum(i,y(i,j)) =e= 1;
regional.. sum((i,j),c(i,j)*a(i,j)*y(i,j)*rm(i,j)) =g= sum((i,j),c(i,j)*a(i,j)*y(i,j))*REM;
recycle.. sum((i,j),c(i,j)*a(i,j)*y(i,j)*r(i,j)) =g= sum((i,j),c(i,j)*a(i,j)*y(i,j))*RE;
;
model impact /all/;
solve impact using mip minimizing z;
display y.l, y.m;
options optcr = 0.0

```

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