A MODEL FOR SELECTING SUSTAINABLE EXTERIOR WALL BUILDING MATERIALS /PRODUCTS IN HOT, HUMID CLIMATE

BY

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To my ***father***, ***mother***, ***wife*** and all my ***family members***

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All praise is due to Almighty Allah, whom we praise, and from whom seek help and ask forgiveness. Peace and blessings of Allah be upon his slave and his Messenger, Prophet Muhammad, his family, and his companions.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AHP : Analytic Hierarchy Process.

BEES : Building for Environmental and Economic Sustainability.

BREEAM : Building Research Establishment Environmental Assessment Method.

CBA : Cost Benefit Analysis.

EMS : Environmental Management Systems.

EPD : Environmental Product Declarations.

LCA : Life Cycle Assessment.

LEED : Leadership in Energy and Environmental Design.

MAUT : Multi Attribute Utility Theory.

SGBC : Saudi Green Building Council.

USD : Urban Sustainable Development.

USGBC : United States Green Building Council.

VOC : Volatile Organic Compounds.

ABSTRACT

Full Name : Saleh Mubarak Baharetha

Thesis Title : A Model for Selecting Sustainable Exterior Wall Building Materials/ Products in Hot, Humid Climate

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Building materials have a significant impact on achieving more sustainable buildings. At the same time, the huge rates of raw material consumption and production which have happened recently made the proper selection of sustainable building materials in order to incorporate sustainability principles and criteria in building projects inevitability. The aims of this study were to identify criteria affecting the selection of sustainable building materials, investigate the current practice of Saudi design/consulting offices in selecting sustainable building materials, and develop a model, using one of the available decision making techniques to help architects /engineers select sustainable exterior wall building materials in hot, humid climate. A holistic set of 34 sustainable building materials criteria is identified by reviewing state of the art studies concerned with highlighting criteria affecting selecting sustainable building materials. The developed criteria were grouped under four main categories, namely environmental, technological, resource use and socio economic. A questionnaire survey was developed and distributed to 42 engineers to evaluate the derived criteria and investigate their relative importance. The survey results revealed that in addition to the importance of criteria of all categories, the results emphasized the need to address criteria respective to resource use and socio economic categories. Data analysis of the survey also indicated that selecting sustainable building materials is still not implemented widely in Saudi design/consultant offices. A decision making model was developed using Analytic Hierarchy Process (AHP). A case study was conducted to implement the developed AHP model. Data analysis highlighted the high priority of selecting clay brick which had an accumulated weight of 0.521 with only 0.479 for concrete block. The significance of this study is that it will help the building industry adopt a unified set of sustainable building material criteria. In addition, it will aid architects and engineers in their decision making when selecting sustainable building materials.

ملخص الرسالة

الإسم الكامل: صالح مبارك عبدالشيخ باحارثه.

عنوان الرسالة: إطار عمل لإختيار مواد بناء مستدامة لبناء الجدران الخارجية في المملكة العربية السعودية.

التخصص: هندسة معمـــارية.

تاريخ الدرجة العلمية: رجـــــب 1434 هجرية.

مواد البناء لها تأثير كبير في بناء المباني المستدامة. في الوقت نفسه ، أدى ارتفاع معدلات استهلاك وإنتاج مواد البناء مؤخرا إلى حتمية اختيار مواد بناء مستدامه من اجل تطبيق مبادى التنمية المستدامة في بناء المباني . تتمثل أهداف هذه الاطروحة في تحديد المعايير المؤثرة في اختيار مواد البناء المستدامة وتقييم الممارسة الحالية للمكاتب الهندسية السعودية في اختيار مواد البناء المستدامة بالإضافة الى تطوير إطار عمل يساعد المهندسين في عملية اختيار مواد البناء المستدامة. تم تعريف مجموعه شاملة من المعايير تتكون من 34 عامل تتدرج ضمن اربع مجموعات رئيسية هي : العوامل البيئية، العوامل التقنية ، العوامل المتعلقة بمصادر المواد والعوامل المتعلقة بالجوانب الاجتماعية والاقتصادية. تم تقييم هذه العوامل من خلال استبيان تم توزيعه على المكاتب الهندسية في المنطقة الشرقية بحيث شمل 42 مهندسا ومصمما. تؤكد نتائج التقييم على انه بالإضافة الى اهمية جميع العوامل ألا ان هناك تأكيد كبير على اهمية العوامل المتعلقة بمصادر المواد والعوامل المتعلقة بالجوانب الاجتماعية والاقتصادية. كما اشارت نتائج الدراسة الى ان اختيار مواد البناء المستدامة لا يزال لم ينفذ على نطاق واسع في المملكة العربية السعودية .تم تطوير إطار عمل لمساعدة المصممين والمهندسين في اختيار مواد البناء المستدامة. كما تم تطبيق هذا الإطار عن طريق دراسة المفاضلة بين مادتي البلوكات الخرسانة والطوب الاحمر. أشارت نتائج الدراسة الى الاولوية العالية لاختيار مادة الطوب الأحمر حيث كان لها وزن 0.521 مقابل 0.479 لمادة البلوكات الخرسانية. تتمثل أهمية هذه الأطروحة في مساعدة المهندسين والمصممين في عملية إختيار مواد بناء مستدامة .

CHAPTER 1

INTRODUCTION

1.1 Background

Over the last decades, the term “Sustainable Development” has been used worldwide. Sustainable Development (SD) is defined as the “ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland Commission, 1987). It aims to achieve better environmental, social and economic life and use natural resources prudently and effectively (Sev, 2009).

The term “Sustainable Building” refers to a high performance building that is designed, built and operated in an efficient manner. Sustainable buildings have many attributes that contribute toward minimizing the negative environmental impact to the built environment. Those attributes include: energy efficiency, pollution prevention, improved indoor air quality, protecting occupant health and using water more efficiently. Sustainable buildings may have the same cost as conventional buildings, but they consume less energy and provide lower utility bills (RMI, 2007). In addition sustainable buildings are longer lasting, have fewer operational costs and more lead to an improvement in the built environment (Joseph, 2008)

Green building materials are those manufactured, refined and extracted in an environmentally friendly manner. The evaluation of sustainable building materials should include assessing material throughout the stages of their life, from gathering stage to their disposal (Shi, 2009).

However, there are many reasons why people opt to use sustainable materials. Firstly, using sustainable materials is good for the environment. For example, using recycled content materials and sustainably harvested wood will contribute toward reducing the environmental effects of building construction methods. Furthermore, many economic benefits can be reaped by using sustainable building materials. Finally, using green building materials has many practical benefits. For example, water conservation and reuse technologies can lead to a significant results and reduce water use (Yudelson , 2007).

Sustainability in Saudi Arabia

Recently, the government of Saudi Arabia has promoted several initiatives toward implementing sustainability principles and strategies especially with its limited number of natural resources and the absence of the use of renewable energy resources. Such initiatives include wastewater treatment and the positive trends toward increasing the awareness of the population about water scarcity in Saudi Arabia (Hanan, 2010). Also, it has been a number of years since many agencies in Saudi Arabia have played a valuable role in the field of sustainable construction (SC) such as The Presidency of Meteorology and Environment (PME), The National Commission for Wildlife Conservation and Development (NCWCD), The Ministry of Water and Electricity (MoWE) and The Ministry of Municipal and Rural Affairs (MoMRA). These agencies have many responsibilities such as providing a healthy environment, managing waste and raising environmental awareness (Al-Yami, 2005).

Saudi Green Building Council (SGBC)

This organization is a clear example of efforts made toward implementing sustainability principles in Saudi Arabia. Saudi Green Building Council (SGBC) is a public benefit organization which aims to promote and guide the implementation of green building practice in Saudi Arabia and provide a healthy environment. In addition, it provides education and training programs that help in raising public awareness and encouraging the manufacture of green products. Saudi Green Building Council (SGBC) was well established in 2010 (SGBC, 2010).

1.2 Statement of the Problem

Buildings are considered one of the heaviest consumers of energy. In addition, buildings emit large amounts of CO_2 through building materials production, and through buildings construction, renovation and demolition. Figure 1-1 shows the negative environmental impacts of building construction (Joseph, 2010).

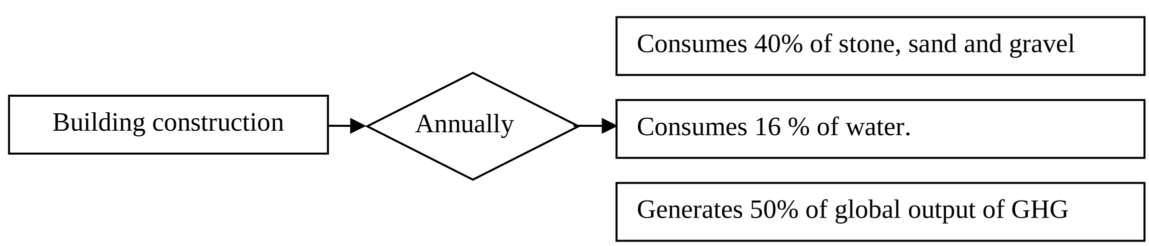


Figure 1-1 Building Construction Environmental Negative Impacts (Joseph, 2010)

In the last few decades, raw material consumption and production has risen dramatically due to the rapid growth of world population between 1963 and 1995 as shown in Figure

1-2. As a result of this, raw materials production was doubled from 4 billion to 10 billion tons (Milani, 2005).

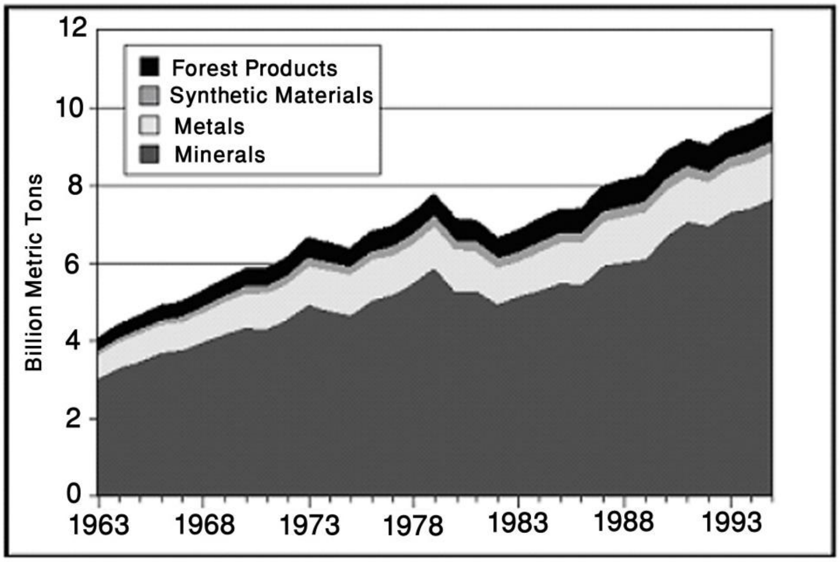


Figure 1-2 World Materials Production 1963-95 (Milani, 2005)

Furthermore, construction materials generate huge amounts of waste annually all around the world and consume large amounts of embodied energy (Lomite, 2009).

There has recently been considerable economic growth due to strong oil prices and ongoing reforms in Saudi Arabia. So, there is a need to use natural resources in an efficient manner. In addition, the significant imbalance of water resources due to economic development in the Arabian Peninsula is coupled with the increased demand for water from 9.95 m^3 billion to 22.6 m^3 billions between 1980 and 1990 (Al-Yami, 2005). Furthermore, in 2001, the highest value of electrical loads in Saudi Arabia rose to 42 gigawatts which equals to 25 times the same value in 1975 (CDIAC, 2012). Moreover, 60 per cent of the Saudi population is under 25. This means that the demand for dwellings and infrastructure will increase in the future (Al-Yami, 2005).

There are many organizations concerned with the study of sustainable buildings such as LEED, BREEAM and Grebe Globe. However, they don't have an agreement on categories, nor on the number and definitions of criteria affecting the selecting of sustainable building materials.

Based on the above discussion, it seems to be that there is a growing need to use sustainable building materials worldwide including Saudi Arabia. Such need requires the development of a model to help architects and engineers select sustainable building materials.

1.3 Objectives

The main objectives of this study are:

1- To survey criteria affecting the evaluation and selection of sustainable building materials.

2- To investigate the practices of Saudi design/consulting offices in selecting sustainable building materials.

3- To develop a model, using available decision making techniques to help architects /engineers select sustainable exterior wall building materials in hot, humid climate (Saudi Arabia as a case study).

1.4 Scope and Limitations

The following describes the scope of the study:

1- The study will be limited to residential and commercial buildings in the Eastern Province of the Kingdom of Saudi Arabia.

2- The surveys will include architectural and consulting companies.

1.5 Significance of the Study

The evaluation and selection of sustainable building materials have not been a prime concern for research in Saudi Arabia. The importance of the study comes from the following:

1- Increasing the awareness of the importance of using proper sustainable building materials.
2- Minimizing the consumption of raw materials in building and construction activities.
3- Choosing materials with low embodied energy and embodied carbon.
4- Promoting the awareness of better environmental, social and economic life.
5- Avoiding materials and products that pose harmful effects to human life.
6- Choosing materials that use resources efficiently by using durable, reusable, recyclable, and renewable materials.
7- The developed model will offer opportunities to designers and architects to select more sustainable exterior wall building materials in their projects.

1.6 Research Methodology

In order to achieve the research objectives, the following detailed stages and phases will be followed.

Stage 1: Surveying Criteria Affecting the Evaluation and Selection of Sustainable Building Materials

The following phases will be followed to achieve the first objective as shown in Figure 1-3.

Literature Review

This phase involves the review of a large body of literature concerned with sustainable development to gain extensive knowledge and good background in issues related to selecting sustainable building products. In this phase the following issues will be reviewed:

- Providing an overview of the definition, classification and measurement of criteria affecting the selection of sustainable building materials.

Interviews

This phase involves conducting interviews with several representative samples of designers, engineers and consultants to investigate sustainable building materials criteria.

Assessing the Surveyed Criteria

The purpose of this phase is to assess the importance of the surveyed criteria and to investigate whether there are other criteria which should be added. This phase will be carried out by conducting a questionnaire survey. The adopted questionnaire consists of two main parts which are: general information about respondents and technical information to assess the relative importance of criteria affecting the selection of sustainable building materials.

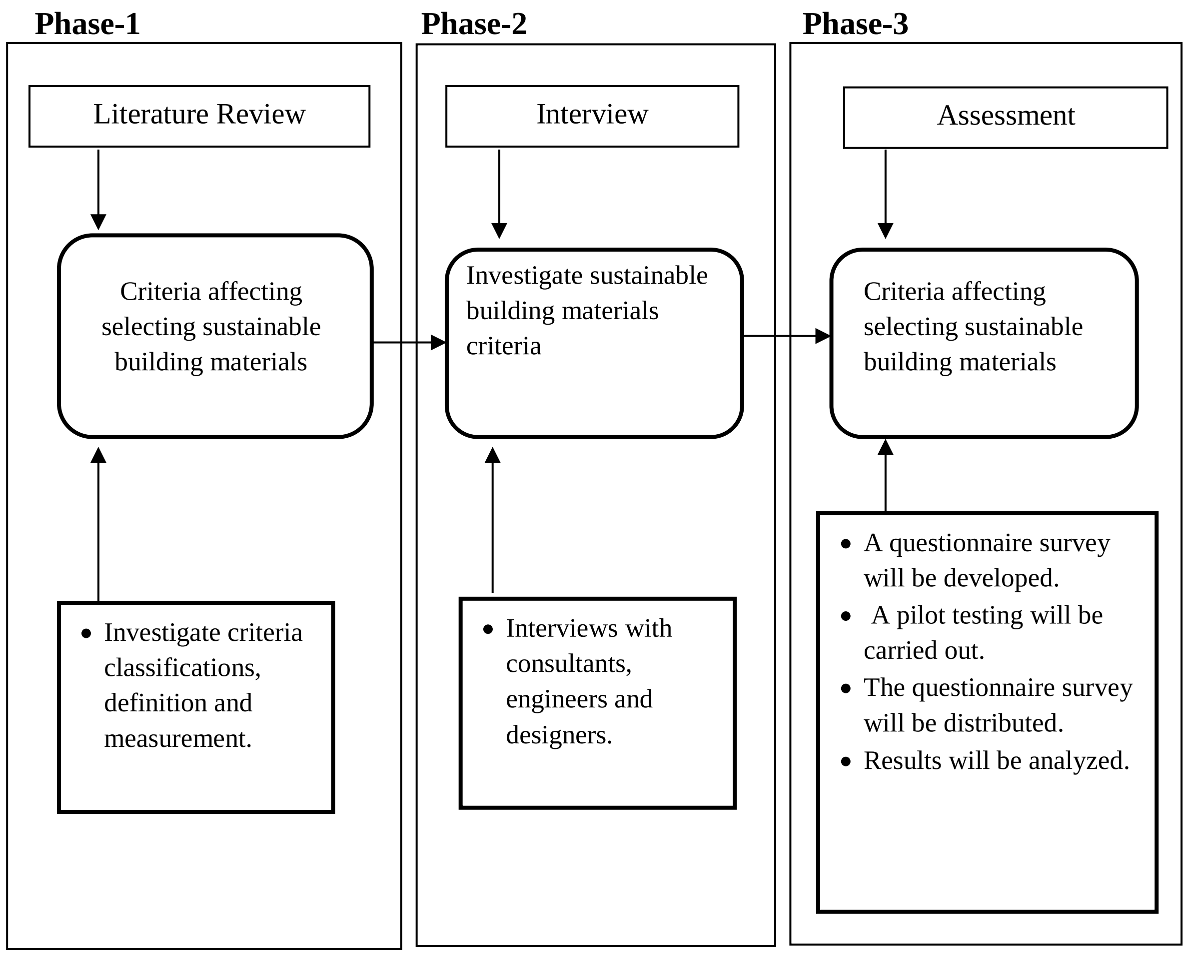


Figure 1-3 Methodology Chart for Achieving the First Objective

Stage 2: Investigating the Practices of Saudi Design/Consulting Offices in Selecting Sustainable Building Materials

The following phases will be followed to achieve the second objective as shown in Figure 1-4.

Literature Review

In this phase, a review of the state of the art literature on sustainability practice in Saudi Arabia will be carried out.

Interviews

This phase involves conducting interviews with several consultants, designers and engineers in the Eastern Province to investigate their awareness of selecting sustainable building materials.

Development of Questionnaire Survey

A questionnaire survey will be developed to explore the degree of awareness of Saudi design/consulting offices in selecting sustainable building materials and what is the barriers they normally face.

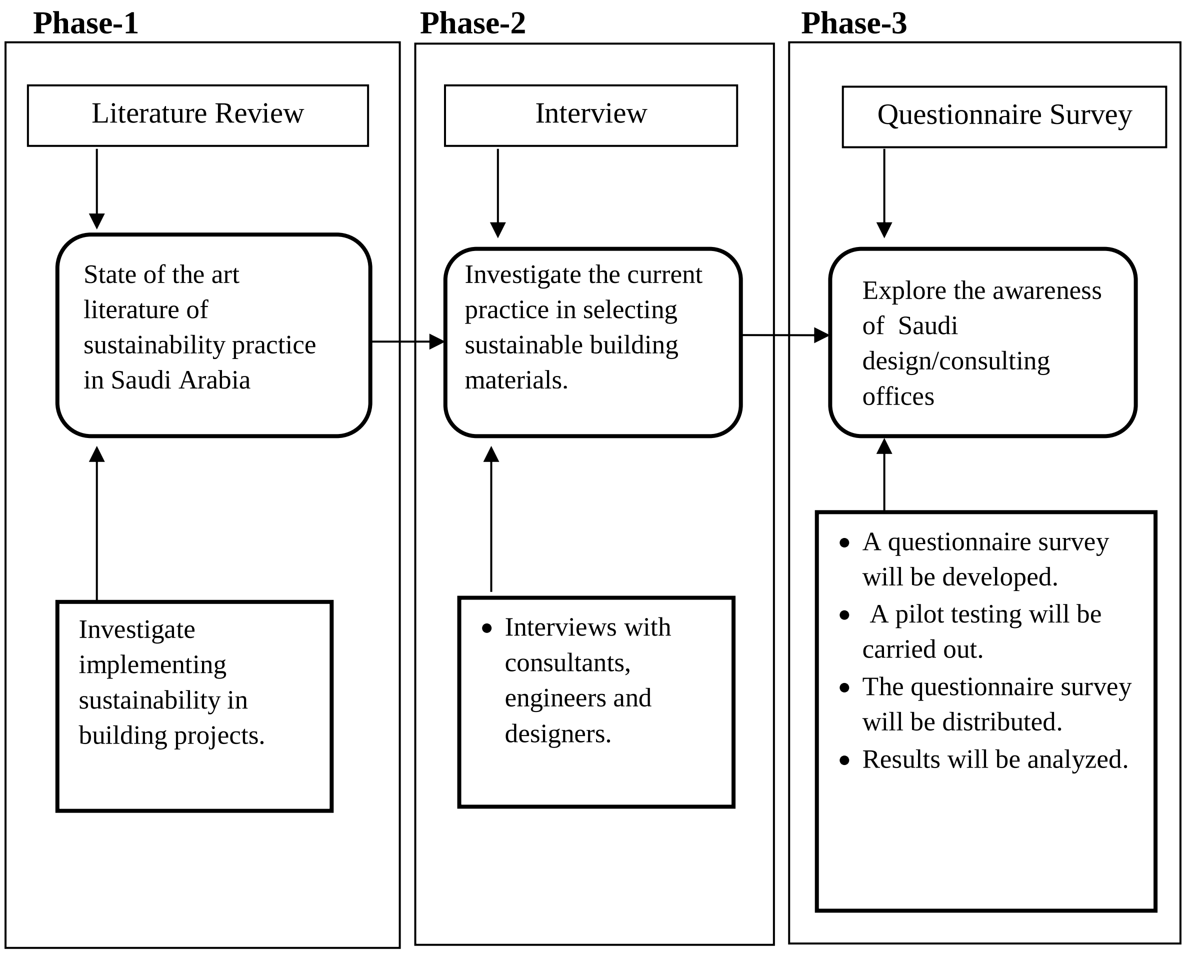


Figure 1-4 Methodology Chart for Achieving the Second Objective

Stage 3: Developing a Model, Using Available Decision Making Techniques to Help Architects /Engineers Select Sustainable Exterior Wall Building

The following phases will be followed to achieve the third objective as shown in Figure 1-5.

Literature Review

This phase involves reviewing the literature to explore decision making techniques, their capabilities and limitations and selecting the most suitable one to be used in selecting sustainable building materials.

Developing a Model

In this phase, a decision making model will be developed using available decision making techniques.

Conducting a Case Study

In this phase, the developed decision making model will be implemented by conducting a case study. The case study involves choosing three exterior wall building materials and using the model to select the most sustainable one. A questionnaire survey will be conducted to assess the sustainable properties of the selected alternatives.

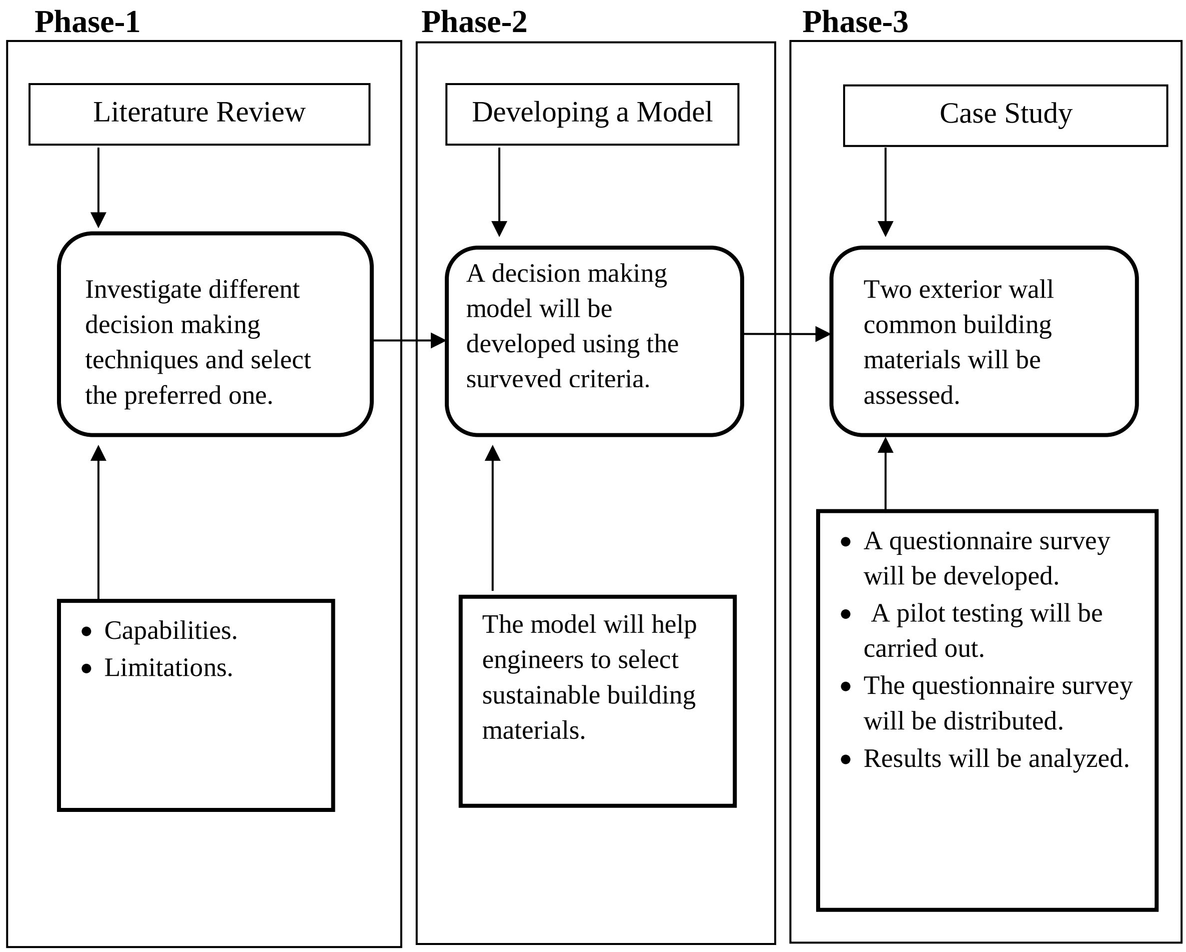


Figure 0-1 Methodology Chart for Achieving the Third Objective

1.7 Thesis Organization

The thesis embraces six chapters organized as follows:

1.7.1 Chapter 1: Introduction

This chapter provides general background of the main topic and the growth of sustainability in Saudi Arabia and the main activities carried out by the Saudi Government to implement sustainability principles in building projects. It also provides an overview of the statement of the study, limitations of the research, main objectives, research methodology and significance of the study.

1.7.2 Chapter 2: Literature Review

This Chapter summarizes the literature review relating to the selection of sustainable building materials. It also reviews the main sustainable building materials rating systems, the technique of selecting sustainable building materials and the main decision making techniques including Analytic Hierarchy Process (AHP) which is a quantitative comparison method used to select a preferred alternative by using pairwise comparisons. Also, it provides an overview of the previous studies in the similar areas of the study's main topic.

1.7.3 Chapter 3: Research Methodology

This chapter presents the methodology adopted in the study in order to achieve its main objectives.

1.7.4 Chapter 4: Data Analysis

This Chapter presents the analysis and results of the data received from the representative sample of architects and engineers.

1.7.5 Chapter 5: Implementation of the Developed Sustainable Building Materials Model

This chapter embraces the conduct of a case study and uses the developed AHP model to select the most sustainable exterior wall building materials. Expert Choice software will be used to make pairwise comparisons between alternatives.

1.7.6 Chapter 6: Conclusions and Recommendations

This chapter provides final conclusions of the study, summarizes the main ideas and outlines the recommendations for further studies in the future.

CHAPTER 2

LITERATURE REVIEW

2.1 Sustainable Development

Building construction has a huge and increasing impact on the environment. The negative environmental impacts and limited number of resources make it necessary to implement sustainability in all aspects of life. Furthermore, the Earth's population has continued to explode in recent years and raw material consumption and production have risen dramatically (Froeschle, 1999).

Sustainable Development (SD) is defined as "the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1987). On the other hand, unsustainable development is a real global threat which causes many risks to the human life such as creating pollution and driving species to extinction. Our world is also facing many social problems which may affect health, wealth and education (Hain, 2006). During the last century, the complexity of over-consumption, excessive pollution and pollution problems became a real threat (Ljungberg , 2007).

2.2 Urban Sustainable Development (USD)

Urban sustainable development aims to improve social quality, create a balance between urban area development and basic services and decrease urbanization costs. Rapid population growth makes it imperative to think about minimizing urbanization costs and providing a better and healthier environment (Chattopadhyay, 2007). The increase of human numbers and activities is the main cause of the consumption of more natural resources and the generation of waste. Recently, cities have posed many negative impacts on the environment such as wasting resources, consumption of more energy, polluting the environment and causing noise and congestion (Alberti, 1969). So, wide awareness has been raised to minimize this problem and decrease the loss of non-renewable resources, taking into account climate changes. In addition, managing cities' basic services such as water and transportation is very important (Chattopadhyay, 2007). Sustainable cities have to consider environmental and social aspects and ensure that sustainability principles are being adhered to (Yuan and Shan, 2006).

2.3 Sustainable Buildings (Green Buildings)

The concept of Green Building (GB) means designing, constructing and maintaining buildings efficiently by using natural resources to decrease energy and water usage and obtain healthy environment (Turcotte, 2006). Green buildings involve providing better living environments with cleaner air and natural light to improve their occupants' performance and decrease operation costs (Kats, 2003). In order to consider any building as a green building, we must protect its ecosystems, reduce energy consumption and improve their occupants' health (Kubba, 2010).

2.4 Sustainable Building Materials (Environmental Protection Building Materials)

Sustainable building materials are those manufactured, refined and extracted in an environmentally friendly manner. They are non-polluting; non-toxic and more satisfactory to human health. Also, sustainable materials are manufactured by using natural, recyclable and renewable resources. In addition, sustainable materials pay great attention to occupants' productivity and provide an ecological and cost effective environment. Wang, 2011 stated that sustainable materials have the following characteristics:

- Sustainable materials are non-polluting and consume low energy.
- Sustainable materials are multifunctional and healthier.
- They have recyclable contents.

Nassar (2003) indicated that in order to construct sustainable buildings, it is of great importance to select sustainable building materials.

2.5 Exterior Wall Building Materials (Normally Used)

It can be argued that the majority of residential buildings in the Eastern Province of Saudi Arabia are built from concrete masonry blocks or clay bricks.

2.5.1 Concrete Masonry Units (CMU)

Worldwide, concrete is the second most consumed material after water (Calkins, 2009). It consists of a mixture of Portland cement, coarse aggregate, fly ash, fine aggregate, air and water as shown in Table 2-1. Portland cement components are calcium carbonate, silica, iron oxide and alumina. Limestone is considered as the main raw material used to produce Portland cement in addition to sand, clay, ironstone and shale.

Table 2.1 Typical Constituents of Concrete (Joseph, 2010).

Constituent	Average Content, wt. %
Portland Cement	9.3
Fly ash	1.7
Fine aggregate	26
Coarse aggregate	41
Water	16
Air	6

In general, concrete has many advantages. It is durable, locally available and has high strength and good resistance to weathering (Calkins, 2009). Also, it is fire resistant and adaptable to different types of climate (Joseph, 2010). In addition, concrete constructions do not need finishes. On the other hand, concrete has many bad environmental impacts. 1.6 billion tons of cement is used annually worldwide to produce concrete. Every ton needs 1.5 tons of fossil fuel energy. A large amount of carbon dioxide (Co_2) is released during Portland cement production causing the most harmful environmental impact. Concrete embodied energy depends on its strength and the amount of Portland cement it contains. On average, concrete embodied energy ranges from 200 to 300 BTU per pound (0.5-0.7 Mj\Kg) (Allen, 2008). The environmental and health impacts of concrete can be minimized and its performance can be enhanced by implementing several strategies and ecological solutions. For instance, fly ash or silica fume can be used to minimize the use Portland cement (Calkins, 2009), (Milani, 2005). In addition, the amount of concrete can be reduced by using floating slab construction instead of building foundation walls. Furthermore, recycling concrete is a good way to reduce its use (Milani, 2005).

2.5.2 Clay Bricks

Clay brick is a durable material with low maintenance and long lasting life. It is made from clay, shale and some solid wastes. The clay brick manufacturing process releases fewer amount of emissions and generates less waste. However its embodied energy is relatively high and it requires more water in the manufacturing process. The clay brick embodied energy ranges from about 1000 to 4000 BTU per pound (2.3-9.3 MJ/KG).While clay brick production requires more energy than concrete, especially in its firing, its natural gas primary fuel source has less environmental impact than coal which is considered as the primary fuel source for producing concrete (Allen, 2008). Clay brick has three main types: extruded brick, molded brick and dry press brick. Extruded bricks are the most common type of bricks today. They are made of a mixture of water, clay and contain many holes and perforations. Molded bricks consist of a mixture of raw wet clay and sand. Then they are pressed and fired at 900–1,000°C. Dry press bricks are much thicker and drier than molded brick and also have sharp edges (Calkins, 2009).

Buildings constructed with brick masonry generate less waste, do not suffer from any indoor quality problems, resist moisture damage and do not need any paint finishes which contain volatile organic compounds (Allen,2008).

2.6 Sustainable Buildings Standards, Rating and Certification Systems

2.6.1 LEED (Leadership in Energy and Environmental Design) (US)

Leadership in Energy and Environmental Design (LEED) is a green building rating system developed by the United States Green Building Council (USGBC) to assess the environmental and sustainable attributes of high-rise residential and commercial buildings. It provides a list of 34 credits worth up to 110 points. It also uses seven categories of criteria as shown in Table 2-2 (USGBC):

Table 2.2 LEED 2002 Credit Categories (USGBC).

LEED Main Categories	Possible Points
Sustainable sites	26
Water Efficiency	10
Energy and Atmosphere	35
Materials and Resources	14
Indoor Environmental Quality	15
Innovation and Design Process	6
Regional Priority	4
Project Totals	**110**

LEED certification depends on meeting these types of criteria and it is classified as shown in Table 2-3 (USGBC):

Table 2.3 LEED Certification Levels and Point Range (USGBC).

Certification Levels	Point Range
Certified	40 to 49
Silver	50 to 59
Gold	60 to 79
Platinum	80 points and above

Currently, LEED credits weight depends on: “greenhouse gas emissions, indoor environmental quality, fossil fuel depletion, particulates, water use, human health (cancer-related), ecotoxicity and land use” (USGBC).

2.6.2 Green Globes (US)

Green Globes certification is a rating system which aims to enhance a building's environmental performance and help designers to develop sustainable buildings that provide healthier environment, consume less energy and use water efficiently. It uses

(LCA) Life Cycle Assessment tool to select building materials and assemblies (Green Globes).

2.6.3 (BREEAM) Building Research Establishment Environmental Assessment Method (UK)

BREEM is a buildings environmental assessment rating system which provides many standards to evaluate performance of buildings through their design, construction and operation stages. The environmental health of buildings, materials and ecology are measured and then given an overall score. According to the value of the overall score, buildings are given either pass, good, very good, or excellent. It sets out a wide range of sustainable criteria including: energy efficiency, emitted pollutants', water conservation, occupants' health and waste management (BREEAM, 2010).

2.6.4 Built Green (US)

Built Green is a non-profit program which aims to develop environmentally friendly and comfortable buildings with high performance. The Built Green program provides a list of sustainable criteria including energy efficiency, conserving natural resources and indoor air quality (Built Green).

2.6.5 Green Star (Australia)

Green Star is a national rating system which aims to assess buildings' environmental performance and raise the awareness of the benefits of sustainable buildings. It provides a list of nine categories that assess buildings' design and construction. The nine categories are broken into several credits and awarded points according to the achievement of Green Star standard (Green Star).

2.7 Techniques for Evaluating Materials and Products

2.7.1 Life-cycle Assessment (LCA)

LCA is a qualitative tool for evaluating the environmental and human impact on materials through their life cycle from cradle-to-grave. Products and materials are examined through their acquisition, manufacture, packing, transportation, operation and ultimate disposal (Calkins, 2009). These main sex steps are then divided into several sub-stages : materials purchasing, storage and waste treatment (Ljungberg, 2007).

There are three main phases in a material's life cycle as shown in Figure 2-.1:

- Pre-Building Phase.
- Building Phase.
- Post-Building Phase.

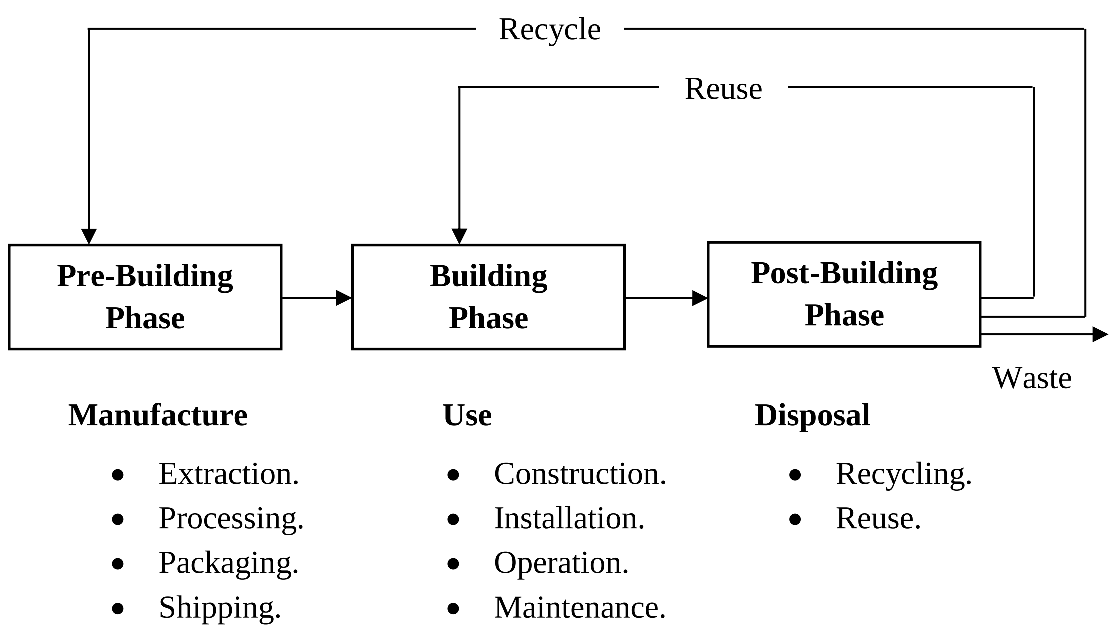


Figure 2-1 Phases of the Building Material Life Cycle (Kim, 1998).

Ljungberg (2007) presented models that help to develop sustainable materials with low environmental impacts. ISO 14001 standard and Life-cycle Assessment approach (LCA) were used in the study. He stated that most environmental problems of using unsustainable materials are caused by the complexity of over-consumption excessive pollution, and pollution problems. A sustainable product was defined as a product that has low environmental impacts. Also, he said that the price of materials and their recyclability and energy efficiency are very important issues in the achievement of sustainability. The results indicated that the most effective way to determine the environmental impacts of products is the Life Cycle Assessment approach. Bovea and Vidal, 2004 applied Life Cycle Assessment methodology to establish criteria for selecting materials with low environmental impact. Wood-based boards and surfaces were evaluated by using the Life Cycle Assessment approach. The results indicated that the environmental impact of standard particleboard is lower than the standard fiberboard. Also, the low density laminate is environmentally preferable to the high density laminate.

2.7.2 Sustainability Assessment (SA)

Sustainability assessment encompasses a list of questions to gather information related to the environmental and human health impacts of materials through their life step. Then information is classified into several categories which are materials acquisition, installation, operation and disposal. Finally information is evaluated according to the project goals (Calkins, 2009).

2.7.3 BEES (Building for Environmental and Economic Sustainability)

BEES is a systematic tool which aims to help designers and builders in selecting green building products. It measures the environmental and economic performance of building materials based on Life Cycle Assessment approach and the American Society for Testing and Materials (ASTM) standard. The life cycle of building materials is divided and analyzed into several stages starting from raw material acquisition and ending by final disposal and waste management (BEES, 2001). Figure 2-2 shows BEES model to measure the environmental and economic performance of building materials.

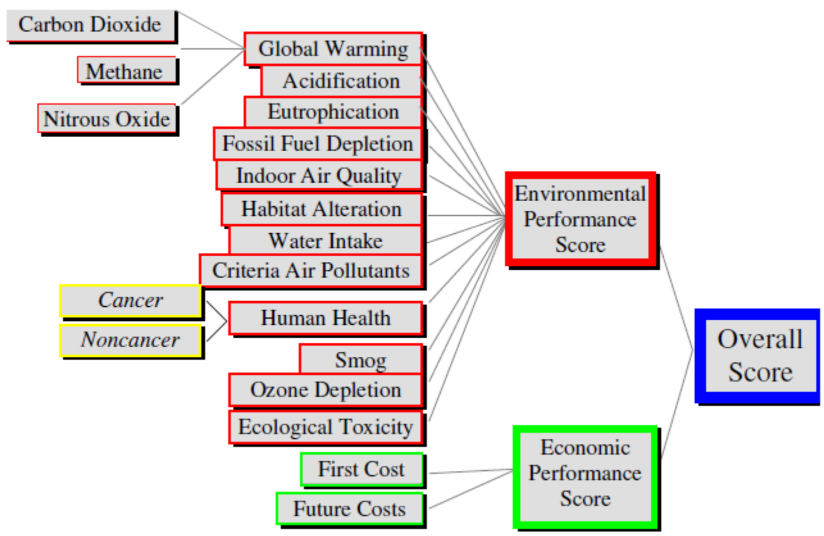


Figure 2-2 BEES overall performance score (BEES, 2001).

2.8 Previous Studies

In this section, previous studies in sustainable building materials evaluation and selection are highlighted.

The evaluation and selection of sustainable building materials has been given broad attention by many authors. Many studies have been conducted on many aspects on the evaluation and selection of sustainable building materials. The following are examples of studies subjected to sustainable building materials evaluation and selection.

Shi (2009) conducted a systematic method based on life Cycle Assessment (LCA) to analyze the green performance of construction materials. He defined sustainable building materials as those economically recycled materials which are extracted, refined and used in an environmentally friendly manner. Sustainable building materials were evaluated in all their life stages including materials acquisition, use and disposal by introducing back propagation neural network (BPNN) and GA-BP hybrid algorithm. The results indicated that back propagation neural network (BPNN) and GA-BP hybrid algorithm are very suitable to assess the performance of building materials because they provide decision makers with high accuracy results. However, the study used the following limited number of sustainable building materials criteria: energy consumption, human health and materials cost.

Castro and Florez (2008) suggested a mixed integer optimization model to help decision makers select suitable building materials. The model used had the ability to maximize the Leadership in Energy and Environmental Design (LEED) rating system credit numbers and improve the environmental performance of sustainable buildings. The study indicated that environmentally friendly materials have many benefits, including saving resources, improving indoor air quality and reducing waste. The results showed that budget is the main factor in determining the success of sustainable buildings. However, only three types of criteria were used in the study, namely indoor environmental quality, and design and budget requirements.

Rezaei and Karami (2008) used Analytic Hierarchy Process (AHP) to select the best sustainable agricultural model. The results indicated the importance of ecological criteria for sustainable agriculture. In his study, he implemented three types of criteria categories. The first type was economic category including productivity, profitability and employment. Social criteria category incorporates life quality, equity and participation. Ecological category contains the efficient use of resources, quality and environmental protection.

Abeysundara and Gheewala (2009) conducted a survey and proposed a matrix to select sustainable materials for school buildings in Sri Lanka based on measuring the environmental, economic and social performance of materials. Building materials used for roofs, floors and the construction of foundations were studied. The results indicated that environmental parameters needs higher consideration in decision-making than social and economic factors. In addition, it was noticed that the environmental analysis is good for long duration evaluation. However, the study used the following limited number of sustainable criteria: constructability, durability, thermal comfort and strength.

Akadiri (2011) presented a decision making approach to assess building materials sustainability. The approach incorporates environmental, economic and social criteria affecting the selecting of sustainable building materials. He said that there was a gap between the existing decision making tools such as Life Cycle Analysis (LCA) and the actual implementation of these techniques in assessing environmental issues. In the study, three types of roof covering materials were assessed based on their sustainability performance. He also indicated that the study will offer stakeholder’s the ability to choose sustainable building materials. However, criteria classification was not based on reviewing the literature. Furthermore, the study missed many important sustainable building materials criteria.

Zhou and Yin (2009) presented an integrated approach to optimize the multi-objectives of material selection using Life Cycle Assessment method (LCA). Materials' environmental, economic and technical characteristics were considered in the study. Zhou and Yin also said that safety and users' health are very important factors when selecting materials. Three types of evaluation indicators of material selection were identified including mechanical, economic and environmental properties as shown in Table 2-4.

Table 2.4 Evaluation Indicators of Materials Selection (Zhou and Yin, 2009)

Mechanical properties	Economic properties	Environmental properties
1. Strength.	1. Purchase cost.	1. Environmental pollution.
2. Stiffness	2. Process cost.	2. Energy consumption.
3. Hardness.	3. Transportation.	
4. Density.	4. Cost of recycle and disposal.	

The study indicated that this system will help designers in selecting building materials.

Nassar and Thabet (2003) used analytic hierarchy process (AHP) to select the optimum building assembly from many alternatives. A heuristic algorithm is also used to search for the best assembly combination among the different building assemblies. However, the selection procedure is limited because assemblies are selected as a group and not independently.

2.9 ISO Standards for Sustainable Development

The ISO 14001 standard, which was first released in 1996, is responsible for meeting organization's environmental challenges and provides requirements for environmental management systems (EMS). It has been implemented by many organizations to ensure their sustainability (Bryden, 2007).

An environmental management system (EMS) enables organizations to identify the environmental impact of its products, improve its environmental performance continually and to implement a systematic approach and demonstrate that all environmental goals have been achieved.

ISO 14001 also offers lots of standards for monitoring the quality of air, water and soil. In addition, it provides the following environment-related standards (Bryden, 2007):

- Waste treatment.
- Sustainability in building construction.
- Quality of water.
- Energy efficiency.
- Recyclability.

ISO 14001 also has positive contribution in the social aspects. It provides many standards related to health, safety and security.

2.10 Classification of Sustainable Building Materials Criteria

A wide scope review of literature in related areas indicates that there is no consistency and no standardized list of criteria for selecting sustainable building materials. Also, the wealth of literature reviewed showed that there is a wide variety between researchers in classifying and defining sustainable materials criteria.

Kim (1998) proposed a method to classify sustainable building materials criteria. He established a list of criteria based on organizing the life cycle of materials into three stages: pre-building; building; and post-building stage. He indicated that evaluating the performance of building materials at each stage of the building life cycle from design, construction to operation is better to achieve a cost-benefit analysis of the whole life of the building.

Zhou and Yin (2009) presented an integrated approach to evaluate and select sustainable building materials by using Life Cycle Assessment method (LCA).They classified sustainable building materials criteria into three main categories, namely mechanical, economic and environmental criteria.

Joseph (2010) said that the integration of environmental, social and economic factors will give the decision maker the ability to easily select the suitable sustainable building materials.

Wang (2009) classified sustainable criteria of energy supply systems into environmental, technical and economic criteria.

Calkins (2009) classified sustainable building materials into several groups based on the following principles as shown in Figure 2-3:

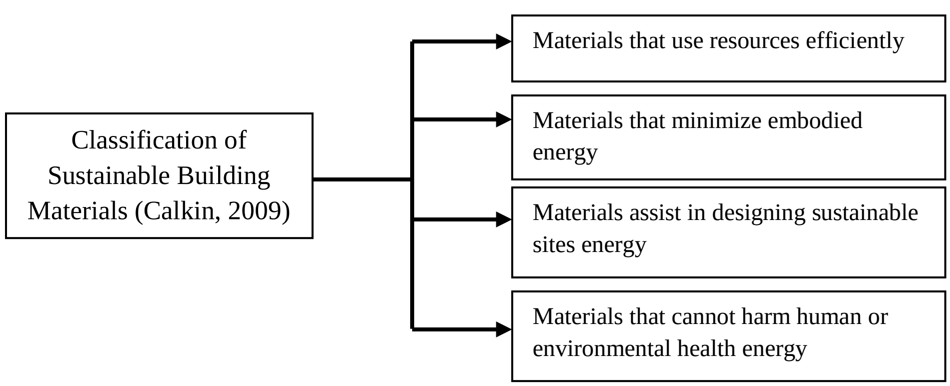


Figure 2-3 Classification of Sustainable Building Materials (Calkin,2009)

Canarslon (2007) applies BREEAM and BEES evaluation tools to evaluate and select sustainable building materials of two selected buildings in Ankara. The environmental impacts of both buildings' basic construction elements and finishes were assessed including roofs, walls, floors and windows. He classified sustainable criteria into three main categories namely: environmental, responsible sourcing and recycling facilities as shown in Figure 2-4.

Pearce (1998) classified criteria of sustainable building materials into four main categories, namely environmental, technological, resource use and socioeconomic criteria.

Yang (2011) developed a specific principle for the selection of green building materials. This principle is based on meeting green ecological and functional attributes.

The functional attributes include:

- Satisfying building functional requirements.
- Having good technological properties.
- Having low total cost.

The green ecological attributes include:

- Having low energy consumption and being non-polluting.
- Saving materials.
- Recyclability.

Akadiri (2011) classified sustainable building materials criteria into environmental, technical and socio-economic criteria.

Chen (2009) summarized a list of criteria for construction methods selection in concrete buildings. Criteria were classified into economic, environmental and social criteria.

LEED certification system identifies the following criteria for sustainable building materials and products: “construction waste management, materials reuse, recycled content, regional materials, rapidly renewable materials and certified wood" (LEED). The majority of these criteria focus on meeting environmental sustainability requirements.

BEES rating system has the goal of evaluating the environmental and economic attributes of building products. However it contains only a limited number of economic attributes including initial cost and future cost.

BREEAM rating system identifies twelve environmental criteria for assessing construction products including: "climate change, ozone depletion, fossil fuel depletion, summer smog, waste disposal, water extraction, minerals extraction, acid deposition, eutrophication, ecotoxity and human toxicity to water" (BREEAM). Figure 2-4 shows the variation in classifying sustainable building materials criteria.

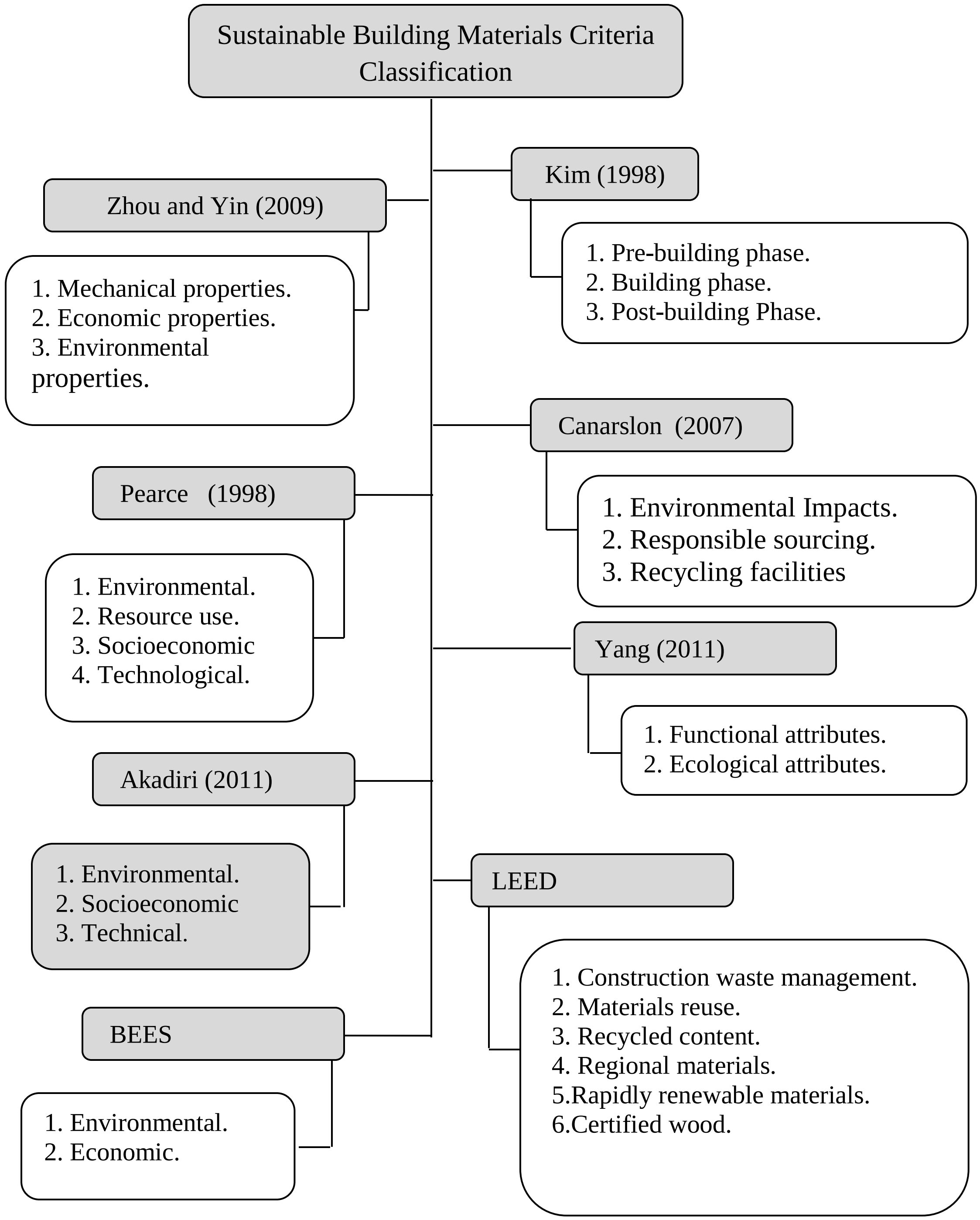


Figure 2-4 Classifications of Sustainable Building Materials Criteria

With the above in mind, it is noticed that the suitable way to classify sustainable building materials criteria is to categorize them into four main categories: environmental, technological, resource use and socioeconomic criteria. This classification gives more clarity and consistency in categorizing all types of sustainable building materials criteria taking into consideration all sustainability principles.

2.11 Environmental, Technological, Resource Use and Socio-Economic Categories

Table 2-5 shows a summary of sustainable building materials criteria classified under four main categories, namely environmental, technological, resource use and socio-economic categories.

Table 2.5 Environmental, Technological, Resource Use and Socio-Economic Building Materials Criteria

Sustainable Building Materials Criteria			
Environmental Category	**Technological Category**	**Resource Use Category**	**Socio-Economic Category**
1. Pollution prevention, (Kim, 1998), (Calkins, 2009). (Wang,2011), (Ellison,2007), (Akadiri, 2011) (Milani,2005) (OCAAP,2004)	1. Durability (GHP, 2010), (Joseph, 2010) (Kim, 1998), (Yudelson, 2007). (Milani,2005),(Akadiri, 2011), (OCAAP,2004)	1. Recyclability (Sev, 2009), (Kim, 1998), (Joseph, 2010).(Calkins 2009). (Wang,2009) (LEED) (Milani,2005) (Kubba,2010) (Yudelson, 2007). (Sev, 2009), (OCAAP,2004).	1. Minimum life cycle costs (Joseph, 2010), (Wang,2011).
2. Water conservation (Joseph, 2010), (Kim, 1998), (Calkins 2009). (Wang,2011),(DETR,2000) (OCAPP,2004),(BIG,2008) (Ellison,2007) ,(GHP,2010) (Milani,2005) (Sev,2009)..	2. Biodegradability (Kim, 1998) (Kubba, 2010).	2. Embodied energy consumption (Sev, 2009), (Kim, 1998), (Calkins 2009). (Milani, 2005).(Yudelson,2007),(Akadiri , 2011), (OCAAP,2004), (Joseph, 2010)	2. Improve indoor air quality (FEMP, 2003), (Calkins, 2009). (Sev, 2009). (Milani, 2005),(GHP, 2010), (Yudelson, 2007), (Kubba,2010).
3. Use of non-toxic or less-toxic materials (Sev, 2009). (Kim, 1998), (Joseph, 2010). (Calkins 2009), (Akadiri, 2011) (Wang, 2011). (Milani,2005) (OCAAP,2004) (WCC,2008).	3. Service Life (Kim, 1998), (OCAAP,2004)	3. Energy efficiency (Sev, 2009), (Ellison, 2007), (Yudelson,2007). (Kim, 1998), (Joseph, 2010), (Akadiri, 2011), (Calkins 2009).(DETR,2000),(BIG,2008) (Wang,2011).	3. Less labor costs (Akadiri ,2011),

Environmental Category	Technological Category	Resource Use Category	Socio-Economic Category
4. Less ozone-depleting substances (DETR,2000), (Akadiri ,2011),	4. Moisture resistance (GHP, 2010).	4. Use of natural resources (Joseph, 2010). (Calkins 2009), (Kim,1998),(BIG,2008) (Wang,2011) (Milani,2005)	4. Affordability (GHP, 2010), (Joseph, 2010). (Yudelson, 2007). (RMI, 2007).
5. Healthfully maintained (GHP,2010), (Wang,2011)	5.Flexibility (Sev,2009)(Joseph,2010), (Sunke,2009) (RMI, 2007), (GHP, 2010)	5- Using certified wood (Calkins, 2009), (LEED). (TCICD, 2004), (Yudelson, 2007).	5. Less disposal costs (Sev,2009), (Akadiri ,2011),
6. No radioactive (Wang,2011)		6. Locally produced (LEED), (GHP, 2010),(Kim, 1998) , (Joseph,2010) (Calkins 2009),(Akadiri, 2011) (TCICD,2004),(Yudelson, 2007), (WCC,2008)	6. Construction waste management (USGBC)(LEED)
7. Methods of extraction of raw materials (Akadiri ,2011) (Calkins,2009)		7. Renewable resources (Kubba,2010), (LEED) (Joseph,2010), (TCICD,2004). (Milani,2005). (Yudelson,2007). (GHP,2010) (Calkins, 2009), (WCC,2008)	7. Thermal comfort (Joseph, 2010). (Sev,2009) (Calkins 2009).(Akadiri,2011).
8. Fire resistance(Akadiri ,2011), (Wang,2011)		8. Reusability (Sev, 2009). (GHP,2010) (Kubba,2010).(LEED), (RMI, 2007),(Milani, 2005), (Wang, 2011).	8. Acoustic comfort (Sev, 2009).
9. Low-VOC assembly (GHP, 2010).(GGEI,2010), :(Calkins, 2009),(			9. Enhance occupants productivity (Joseph, 2010),(FEMP,2003) (RMI,2007) (Sev,2009).
			10. Less construction time, (Sev,2009), (Akadiri, 2011), (Joseph,2010)
			11. Low maintenance costs, (DETR,2000) (Akadiri ,2011), (Joseph,2010)
			12. Aesthetic options (Sev, 2009),(Akadiri, 2011), (Joseph, 2010),

2.11.1 Environmental Category

Most environmental challenges are caused by climate changes. Increased greenhouse gas and carbon dioxide emissions have posed very bad impact on buildings' environmental performance (DETR, 2000). Building materials are the main cause of the negative impact on ecosystems and the environment. The majority of these impacts occur during the materials acquisition process including the loosing of topsoil and the generation of a huge amount of emissions and waste (Calkins, 2009) (OCAPP, 2004).

In 2003, the document Environmental Product Declarations (EPD) was released by the European Commission. EPD has the goal of investigating the environmental performance of products, materials and services. It is based on Life Cycle Assessment (LCA) according to the ISO-standards. EPD is a multicriteria system giving environmental information through all product life cycle stages, from manufacture, construction to disposal (Thorneus, 2010).

Based on the review of the literature, environmental sustainable building materials criteria are as follows:

Pollution Prevention: “Pollution prevention is defined to mean the use of processes or practices that reduce or eliminate the use of hazardous substances and the generation of pollutants or wastes at the source” (EMS, 1997). According to DETR (2000), waste materials and release of contaminants to the atmosphere are major sources of pollution. Akadiri (2011) indicated that the main sources of pollution are soil, water and air. Kim, 1998 stated that onsite waste processing of water and air and all contaminants released during the manufacturing process is a good way to reduce the amount of pollution. Based on reviewing the literature, it is noticed that there is inconsistency in the definition of “pollution prevention” and “low emitting” criteria. For instance, pollution was defined by (Milani, 2005 ; Kats, 2003 ; DETR, 2000) as the emissions produced from factors, both human and emissions released during materials cleaning. They also indicated that fossil fuels release many types of air pollutants such as oxides of nitrogen (NOx), which causes smog, Sulfur Dioxide (SO2 or SOx), which causes acid rain, and carbon dioxide (CO2). However, in defining “low emitting” criteria, Calkins, 2009 said that emissions include: carbon dioxide (CO2), nitrogen oxides (NOx), sulfur oxides (SOx), carbon monoxide (CO), hydrogen chloride (HCl) and total hydrocarbons. The following are different terminologies which describe “pollution prevention” criteria: using non-polluting materials (Wang, 2011),using low emitting materials (Calkins 2009), minimizing pollution (Akadiri, 2011) and pollution prevention (Ellison, 2007; Kim, 1998; Wang, 2009; Milani, 2005; DETR, 2000; OCAAP ; 2004; Kates,2003) as shown in Table 2-15. Based on the above explanation, this criterion should be named “pollution prevention”, because this gives it an inclusive definition furthermore there are about six authors who chose this name. Quantities of emissions are measured in kilogram/metric ton (Calkins, 2009). Pollution prevention can also be measured by “ASTM E1609 - 01 Standard Guide for Development and Implementation of a Pollution Prevention Program” which provides pollution prevention guidelines to reduce or eliminate emissions.

Water conservation: Water conservation is defined as “water management practices that improve the use of water resources to benefit people or the environment ”, or “any beneficial reduction in water use, loss, or waste ”(WCEP,2007). According to GBHP (2010), water conservation can be achieved by selecting materials that reduce the amount of water consumed in buildings. Kim (1998) stated that the water conservation process can be implemented by recycling the used water and using rainwater in irrigation. Calkins (2009) indicated that water used in manufacturing and construction processes is often polluted by contaminants. He added that it also poses a disposal risk if it is not treated. According to Kats (2003), green buildings conserve water in different ways by: using potable water efficiently, capturing gray water and reclaiming water used. LEED indicated that there should be a reduction of waste water by 20 or 30 percent by implementing innovative technologies and replacing old plumbing fixtures (Kubba, 2010). Akadiri (2011) indicated that there are large amounts of water consumed during materials extraction, processing and delivering. The following are different terminologies which describe "water conservation" criteria: using low water use materials (Calkins, 2009; Milani, 2005), water treatment and conservation (Kim, 1998), efficient use of water (Kubba, 2010) and water conservation (Joseph, 2010; GHP, 2010; OCAPP, 2004; Kates, 2003; BIG, 2008; Sev, 2009), as shown in Table 2-15. Based on the above explanation, this criteria should be named as "water conservation", because it is comprehensive and includes all water reduction and treatment processes. Water conservation is measured in cubic feet (ft3), cubic meters (m3) or gallons. Water conservation in buildings can also be measured by "ASTM E2635 - 08 Standard Practice for Water Conservation in Buildings through in Situ Water Reclamation" which sets guidelines for water conservation in buildings.

Use of non-toxic or less toxic materials: Toxic materials are defined as "materials with an oral (lethal dose) LD50 at or below 300 mg/kg, a dermal LD50 at or below 1,000 mg/kg, or an LC50 at or below 4 mg/l" (ERC, 2012). According to GHP (2010), non-toxic materials include materials which emit few reproductive toxicants and carcinogens.

Kim (1998) and Akadiri (2011) indicated that non- or less toxic materials are those which pose fewer health risks to building occupants. Toxic materials like asbestos mostly affect sensitive people such as sick people and infants. They are also harmful to installers when disposing of them after their life has ended. However, thinking about fiberglass or PVC will contribute toward decreasing the serious damage of toxicity (WCC, 2008). Kubba (2010) stated that in order to minimize effects of toxicity, we should select materials that do not require frequent oiling, store harmful materials outside the building and select materials that are not poisonous and do not cause cancer. The following are different terminologies which describe “use of non-toxic or less-toxic materials” criteria: low toxicity (Joseph,2010; OCAAP,2004) using non-toxic materials, (Sev, 2009; Kubba, 2010) , using materials that avoid toxic chemicals (Calkins 2009) , “zero or low toxicity” (Akadiri, 2011), the use of non-toxic or less toxic materials (Kim, 1998; GHP, 2010), toxicity (WCC,2008) and using materials with low toxic emissions (Mailani,2005) as shown in Table 2-15. Based on the above explanation, this criteria should be named “Use of non-toxic or less toxic materials” because it is an inclusive definition. Toxicity is measured in mg/kg by lethal dose 50 percent (LD 50) method which is based on determining the dose that will result in the death of half of the tested population (Bell, 2009). Building materials toxicity can also be measured by “ASTM E1678 - 10 Standard Test Method for Measuring Smoke Toxicity for Use in Fire Hazard Analysis” which determines the lethal toxic potential.

Less ozone depleting substances: Ozone depletion is defined as “destruction of ozone in the ozone layer attributed to the presence of chlorine from manmade Chloroflourocarbons CFCs and other forces” (Margaret, 2000). DETR (2000) mentioned this criteria, but he did not define it. Akadiri (2011) named this criteria as “Ozone depletion potential”. Ozone depletion is measured by determining the amount of Chloroflourocarbons (CFCs). CFCs are compounds made by humans and are considered as the main cause of ozone depletion (BEES). Indoor ozone can be monitored by “ASTM D5110 - 98(2010) Standard Practice for Calibration of Ozone Monitors and Certification of Ozone Transfer Standards Using Ultraviolet Photometry”.

Healthfully maintained: Healthfully maintained materials are defined as “materials that require only simple, non-toxic, or low VOC methods of cleaning”(GHP, 2010). Wang (2011) mentioned this criterion, but he did not define it. This criterion can be measured by “ASTM D6361 / D6361M - 98(2010)e1 Standard Guide for Selecting Cleaning Agents and Processes” which helps in selecting the best cleaning process considering environmental pollution.

No radioactive: A radioactive material is defined as “a substance that contains unstable–radioactive–atoms that give off radiation as they decay” (EU, 1999). Building materials are the main source of various types of radiation. The amount of radium in building materials should not exceed 200Bq m-3 (EU, 1999). Wang (2011) mentioned this criterion, but he did not define it. Table 2-6 shows typical and maximum activity concentration of common building materials measured in becquerels per kilogram Bq Kg-1 (EU, 1999). Radiation can also be measured by “ASTM E512 - 94(2010) Standard Practice for Combined, Simulated Space Environment Testing of Thermal Control Materials with Electromagnetic and Particulate Radiation”.

Table 2.6 Typical and Maximum Activity Concentration of Common Building Materials (EU, 1999).

Material	Typical activity concentration (Bq kg^{-1})			Maximum activity concentration (Bq kg^{-1})		
Most common building materials (may include by-products)	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K
Concrete	40	30	400	240	190	1600
Aerated and light-weight concrete	60	40	430	2600	190	1600
Clay (red) bricks	50	50	670	200	200	2000
Sand-lime bricks	10	10	330	25	20	700
Natural building stones	60	60	640	500	310	4000
Natural gypsum	10	10	80	70	100	200
Most common industrial by-products used in building materials						
By-product gypsum (Phosphogypsum)	390	20	60	1100	160	300
Blast furnace slag	270	70	240	2100	340	1000
Coal fly ash	180	100	650	1100	300	1500

Methods of extraction of raw materials: Materials extraction starts from harvesting, transporting and processing raw materials until they became a semi-completed material. Building materials are extracted by different methods. Akadiri (2011) and Calkins (2009) mentioned this criterion, but they did not define it. This criterion can be measured subjectively by determining whether the materials are extracted in a sustainable or non-sustainable way.

Fire resistance: Fire resistance is defined as “the ability of a component of the construction of a building to satisfy for a stated period of time or all of the appropriate criteria specified in the relevant part of British Standard 476” (FCTG, 2000). Akadiri (2011) mentioned this criteria but he did not define it. Wang (2011) named this criteria as “fire prevention”. Fire resistance can be measured by the furnace temperature measurements method (Sultan, 2006). The fire-resistive properties of building materials are also measured by “ASTM E119 - 00a Standard Test Methods for Fire Tests of

Building Construction and Materials" based on the duration of the time in which a material can resist fire before the first critical point is reached. In addition, fire resistance can also be measured by British Standard 476 which tests the behavior of materials to establish whether they are combustible or non-combustible.

Low-VOC assembly: Low volatile organic compounds -VOC materials are "materials installed with minimal VOC-producing compounds, or no-VOC mechanical attachment methods and minimal hazards" (GHP, 2010). Kim (1998) defines this criterion as "volatile organic compounds (VOCs) that continue to be emitted into the air long after the materials containing them are installed". Calkins (2009) and GGE (2010) mentioned this criterion but they did not define it. This criterion is expressed by Yudelson (2007) as low emitting materials terminology. The amount of VOCs in materials and products is determined by "ASTM D7143 - 11 Standard Practice for Emission Cells for the Determination of Volatile Organic Emissions from Indoor Materials/Products". VOC emissions are also measured by full spectrum sensors in mg/m3. GGEI, 2010 stated that product emissions should meet the following criteria shown in Table 2-7.

Table 2.7 Product Emissions Criteria within 168 Hours of Testing (GGEI, 2010).

Applicable to All Products		
Parameter	Full Levels (Applicable for Building Construction Materials and Finishes, Wood Finishes, Countertops, Casework, Visual Display Products, and Furniture Workstations, Casegood Systems, and Movable Walls)	Half Levels (Applicable for OEM Materials, Mattresses and Bedding, Seating, Individual Casegoods, Tables, Workstation Components, Shelving, and Children's Furniture)
Total VOCs (TVOC)[1]	≤ 0.5 mg/m³	≤ 0.25 mg/m³
Formaldehyde	≤ 0.05 ppm	≤ 0.025 ppm
Total Aldehydes[2]	≤ 0.1 ppm	≤ 0.05 ppm
Individual VOCs[3]	≤ 0.1 TLV	≤ 0.1 TLV
Listing of measured carcinogens and reproductive toxins as identified by California Proposition 65, the U.S. National Toxicology Program (NTP), and the International Agency on Research on Cancer (IARC) must be provided.		
Applicable to Specific Products Only		
4-Phenylcyclohexene[4]	≤ 0.0065 mg/m³	≤ 0.0033 mg/m³
Respirable Particles[5]	≤ 0.05 mg/m³	≤ 0.025 mg/m³

2.11.2 Technological Category

Based on the review of literature, technological sustainable building materials criteria are as follows:

Durability: Durability is defined as "the ability of a building, its parts, components and materials to resist the action of degrading agents over a period of time" (Sereda, 1978). According to Calkins (2009), durable materials extend the useful life of buildings and reduce the need of virgin resources. Also, they have fewer operation costs and need less frequent replacement than conventional materials which need to be replaced more often (Akadiri, 2011) and (Kim, 1998). The following are different terminologies which describe "durability" criteria: using durable materials (Calkins, 2009; GHP, 2010; OCAAP, 2004) using materials with great durability (Milani, 2005), "life expectancy" (Akadiri, 2011), and durability (Kim, 1998; Yudelson, 2007; Joseph, 2010) as shown in Table 2-16. Based on the above explanation, this criterion should be named "durability", because it is an inclusive definition. The durability of materials is measured by determining for how long the material can meet its performance requirements. Durability can also be measured by "ASTM F148 - 02(2007) Standard Test Method for Binder Durability of Cork Composition Gasket Materials".

Biodegradability: The biodegradability of materials can be defined as "their potential to naturally decompose when discarded" (Kim, 1998). Kim also stated that while biodegradable materials rapidly decompose, non-biodegradable materials normally take a long time to return to the earth. Kubba (2010) indicated that building materials have many different degradation times. The biodegradability of materials is measured by determining the degradation time (days, months, years). "ASTM D6692 - 01 Standard Test Method for Determining the Biodegradability of Radiolabeled Polymeric Plastic Materials in Seawater" provides measurements of the biodegradability of plastic materials.

Service life: Service life e is defined as "The actual period of time during which the building or any of its components performs without unforeseen costs or disruption for maintenance and repair" (Canadian Standard Association). ISO defines service life as "The period of time after installation during which a building or its parts meets or exceeds the performance requirements". According to Kim (1998), longer life materials normally save costs of installation and labor, require less replacement and produce less landfill waste. This criterion is named by (OCAAP, 2004) as "having long useful life materials". However, it should be named as "longer life" because this name is clear. The life of materials is measured by the entire useful age of materials (years). The service life of building materials is predicted by "ASTM E632 - 82(1996) Standard Practice for

Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials”.

Moisture resistance: Moisture resistive materials are those which “inhibit the growth of biological contaminants in buildings” (GHP, 2010). Moisture is measured by determining the percentage of the mass of water vapor to the mass of dry air. Also, moisture resistance can be measured by “ASTM D4502 - 92(2011) Standard Test Method for Heat and Moisture Resistance of Wood Adhesive Joints”.

Flexibility: Flexibility means the ability to use materials for different purposes (Sunke, 2009). The following are different terminologies which describe “flexibility” criteria: not rebuilding (Calkins, 2009), having greater design flexibility (Joseph, 2010; RMI, 2007), (GHP, 2010) and flexibility (Sev, 2009; Sunke, 2009) as shown in Table 2-16. Based on the above explanation, this criterion should be named “flexibility”, because this name gives more clarity. Materials with greater flexibility are those which can be used for more purposes.

2.11.3 Resource Use Category

Based on the review of literature, the resource use sustainable building materials criteria are as follows:

Recyclability: Recyclability is defined as a “material’s capacity to be used as a resource in the creation of new products” (Kim, 1998). According to GHP (2010), recyclable materials are manufactured by using scrap or waste and easily reused at the end of their life. LEED stated that recycling means “the collection and remanufacture of materials into a new material or product, typically different from the original”. Kubba (2010) indicated that energy used in the manufacturing process is less and emissions generated are fewer than the use of virgin contents. Kubba also stated that recyclable materials contribute significantly in preserving embodied energy, but they should be stored and collected to reduce waste sent to landfills. Akadiri (2011) indicated that selecting recyclable materials is very important to reduce demolition waste. The following are different terminologies which describe “Recyclability” criteria: using circulated materials (Wang, 2011), recycled contents (LEED), using recyclable materials, (Sev, 2009; GHP, 2010; Milani, 2005; Kubba, 2010; OCAAP, 2004) “potential for recycling and reuse” (Akadiri, 2011) and using reclaimed materials (Calkins, 2009; Yudelson, 2007) and recyclability (Kim, 1998) as shown in Table 2-17. Based on the above explanation, this criterion should be named “Recyclability”, because this is an inclusive definition. The recyclability of materials is measured by determining the ratio of the recycled materials to the total materials consumption (Bailey, 2008). Table 2-8 shows recycling storage area guidelines based on overall building square footage (USGBC).

Table 2.8 Recycling Storage-area Guidelines Based on Overall Building Square Footage (USGBC).

Commercial Building Square Footage (sf)	Minimum Recycling Area (sf)
0 to 5,000	82
5001 to 15,000	125
15,001 to 50,000	175
50.001 to 100,000	225
100,001 to 200,000	275
200,001 or greater	500

Embodied Energy Consumption: Embodied energy is the amount of energy used in materials production until they are available for use. It includes energy required for manufacturing a material, energy required for raw materials transportation to the factory and energy used in assembling building materials (Joseph, 2010). According to Kim (1998), embodied energy includes energy consumed in collecting raw materials and transporting them to the site. Kim also stated that minimally processed materials such as stone normally have lower embodied energy than other materials such as plastic. Joseph, 2010 also stated that a proper selection of sustainable building materials can offer a reduction of 10–15% of total embodied energy. According to Akadiri (2011), selecting low embodied energy building materials is very important to construct energy efficient buildings. The following are different terminologies which describe “embodied energy consumption” criteria: embodied energy reduction (Kim, 1998; Sev, 2009; Yudelson, 2007), consuming low energy to produce raw materials (Wang, 2011), “embodied energy within material” (Akadiri, 2011), embodied energy (WCC,2008; Joseph, 2010) and using materials that have low embodied energy (Calkins, 2009; Milani, 2005; OCAAP,2004) as shown in Table 2-17. Based on the above explanation, this criteria should be named “embodied energy consumption” because it is easier to understand. Embodied energy is measured in *MJ/kg*. Table 2-9 shows embodied energy of common building materials.

Table 2.9 Embodied Energy of Common Building Materials (Kim,1998).

Material	**Virgin** *MJ/kg*	**Recycled** *MJ/kg*
Aluminum	196	27
Polyethylene	98	56
PVC	65	29
Steel	40	18

Table 2-10 shows embodied energy and embodied carbon of common building materials.

Table 2.10 Embodied Energy and Embodied Carbon of Common Building Materials (Joseph, 2010).

Type of Material (1 ton)	Embodied Energy (MJ/ton)	Embodied Carbon (kg of CO2/ton)
Limestone	196	27
Stone/gravel chipping	300	16
Rammed earth	450	24
Soil cement	850	140
Concrete, unreinforced (strength 20 MPa)	990	134
Concrete, steel reinforced	1,810	222
Soft-wood lumber (large dimensions, green)	1,971	101
Soft-wood lumber (small dimensions, green)	2,226	132
Portland cement, containing 64–73% of slag	2,350	279
Portland cement, containing 25–35% of fly ashes	3,450	585
Local granite	5,900	317
Engineering brick	8,200	850
Tile	9,000	430
Soft-wood lumber (small dimensions, kiln dried)	9,193	174
Steel, bar and rod	19,700	1,720
Polypropylene, injection molding	115,100	3,900

It is important here to note that embodied energy constitutes a large part of a building's total energy during its life as shown in Figure 2-5 (Crowther, 1999).

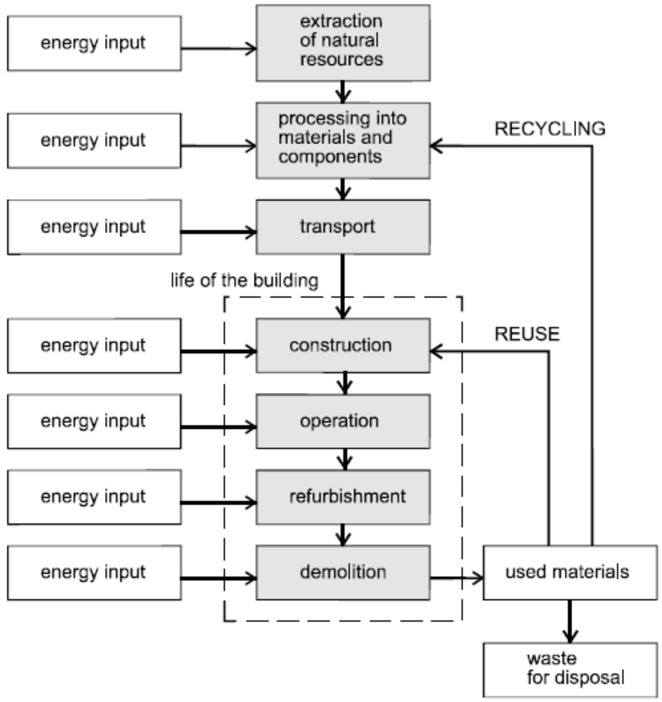


Figure 2-5 Stages of Energy Input During Buildings Life (Crowther, 1999).

Energy Efficiency: "Energy efficiency encompasses all changes that result in a reduction in the energy used for a given energy service (heating, lighting...) or level of activity" (WEC, 2012). According to GHP (2010), energy efficient materials contribute significantly toward reducing energy consumption in buildings, heat transfer through building envelope as well as operational costs. Kubba (2010) indicated that using energy in an efficient manner is very important to save money on utility bills and reduce manufacturing costs. Kim (1998) stated that selecting materials with high thermal insulation is the best way to reduce energy used by buildings. He also said that the energy efficiency of building materials is a function of R-value which measures their thermal insulation ability. Akadiri (2011) indicated that huge amount of energy is consumed during building materials production, construction and operation. The following are different terminologies which describe "energy efficiency" criteria: using low energy consumption materials (Wang, 2011; Calkins 2009; Ellison, 2007), energy saving (Akadiri, 2011) and energy efficiency: (Kim, 1998; Joseph, 2010; Kubba, 2010; Yudelson, 2007; DETR, 2000; BIG, 2008; GHP, 2010) as shown in Table 2-17. Based on the above explanation, this criterion should be named as “energy efficiency” because it is clear and lots of authors have chosen it. Energy efficiency is measured by calculating energy intensity which represents the ratio between energy use (output) and energy service demand (input) (Forsstrom, 2011). Table 2-11 shows the amount of energy reduction in green buildings.

Table 2.11 Energy Reduction in Green Buildings as Compared with Conventional Buildings (USGBC).

	Certified	Silver	Gold	Average
Energy Efficiency (above standard code)	18%	30%	37%	28%
On-site Renewable Energy	0%	0%	4%	2%
Green Power	10%	0%	7%	6%
Total	**28%**	**30%**	**48%**	**36%**

Use of Natural Resources: “Natural resources are materials found in nature that people use to meet their needs” Hababou, 1982. There are two main types of natural resources: geological resources and botanical resources (timber). Geological resources include: soil, sand clay, aggregates, rocks and limestone (Hababou, 1982). Kubba (2010) indicated that building materials are either natural or synthetic. While natural materials such as timber are unprocessed or minimally processed, synthetic materials such as plastic are processed in industries. Kim (1998) stated that man-made materials have higher embodied energy than natural materials. He also added that they cause more damage to the environment and require more processing. According to Calkins (2009) and Akadiri (2011), the use of natural resources contributes significantly to lessen the negative environmental impacts and decrease the amount of waste and air pollution. The following are different terminologies which describe “using natural resource” criteria: using natural materials (Kim , 1998; Yudelson,2007), rational use of natural resources (Joseph, 2010; Calkins 2009; BIG, 2008) and using materials that are organically grown (Milani,2005) as shown in Table 2.17. Based on the above explanation, this criteria should be named as “using natural resource”, because it is an inclusive definition. This criteria can be measured by determining the percentage of natural resources used to produce the material.

Using certified wood: The Forest Stewardship Council (FSC) defined certified wood as “wood grown and developed using responsible forestry management techniques” (Forest Stewardship Council, 2012). Wood is considered as a green material because it is renewable and has low embodied energy. However, it should be harvested in a sustainable way and meet the standards developed by The Forest Stewardship Council (USGBC). The following authors mentioned this criteria: (Calkins, 2009; TCICD, 2004; OCAAP, 2004; LEED; Yudelson, 2007).

Locally produced: LEED defined regional materials as those “extracted and manufactured within the designated region”. LEED stated that the main goal of using regional materials is to reduce the need for transporting products and thus reduce air pollution caused by using vehicles. Joseph (2010) indicated that transporting bulky materials requires a large amount of fuel energy. He also added that using locally produced materials can decrease the environmental impact and help to establish the local economy. The following are different terminologies which describe the “using locally produced materials” criteria: using locally available materials (TCICD, 2004), using regional materials (LEED), the use of local material (Calkins, 2009; Joseph, 2010;

Akadiri, 2011), local resources (WCC, 2008) and using locally harvested and processed materials (Yudelson,2007) as shown in Table 2-17. Based on the above explanation, this criterion should be named "using locally produced materials", because this definition means selecting materials that are locally extracted and processed. This criterion is measured by LEED standards which require that 10-20 % of building materials should be extracted, gathered, and manufactured regionally within 500 miles far from the location of buildings.

Renewable resources: The renewable resource is "any type of resource that can be regenerated at a rate that is at least equal to the speed with which humanity can consume that resource" (WG, 2012). According to GHP (2010), renewable materials are those harvested from sustainable resources. LEED indicated that replacing finite raw materials with renewable materials is very important to reduce their use and depletion. Joseph (2010) and Calkins (2009) stated that the use of renewable contents will lead to a closed-loop materials life cycle and reduce environmental burdens. The following are different terminologies which describe "renewable resources" criteria: using materials which are made from renewable resources (Calkins, 2009), using rapidly renewable resources (Yudelson, 2007; TCICD,2004), renewable resources (WCC,2008) and using recycled contents (Kim, 1998; Kubba,2010), renewable materials (GHP, 2010) and rapidly renewable materials (LEED) as shown in Table 2-17. Based on the above explanation, this criterion should be named "renewable resources" because this definition gives more clarity. This criteria can be measured by determining the percentage of renewable resources to the overall resources.

Reusability: LEED defines materials reusability as "the salvage and reinstallation of materials in their original form”. LEED also indicated that the percentage of reused materials should be between 5-10-30 percent of the total building materials. Salvaging materials is very important to reduce cost, landfill waste, embodied energy and to reduce the need to harvest virgin materials (LEED). The following are different terminologies which describe “reusability” criteria: using reusable materials (Wang, 2011), using materials which are designed for disassembly (DfD) potential (Calkins, 2009), the reuse of building materials (RMI, 2007; Sev, 2009; GHP, 2010), reusability (Kim,1998), materials reuse (LEED) and the use of easily reused materials (Milani, 2005) as shown in Table 2-17. Based on the above explanation, these criteria should be named “reusability” because this definition is very clear. Percentage of reused materials can be calculated by the following equation (USGBC):

$$\text{Percentage Reused Materials} = \frac{\text{Cost of Reused Material (\$)}}{\text{Total Materials Cost (\$)}} \times 100$$

2.11.4 Socio economic Category

Enhancing the health of occupant's, wellbeing, productivity and improving the aesthetic quality of the building envelope are some examples of benefits gained from selecting sustainable building materials. In addition, social benefits include increasing occupant's communication between occupants and decreasing the amount of stress. However, choosing unsustainable materials poses major hazards to occupants' health. They harm indoor air quality and expose occupants to toxic substances. For example, Volatile Organic Compounds (VOCs) are released from some building materials and affects a human's eyes and nose. Cultural aspects and fashion trends should also be considered when selecting sustainable materials. So, sustainable materials must be popular and follow local legislation (Ljungberg, 2007). Based on the review of literature, socio-economic sustainable building materials criteria are as follows:

Minimum life cycle costs: Life cycle costs is defined as “the total discounted dollar cost of owning, operating, maintaining, and disposing of a building or a building system over a period of time” (EED,1999). According to FEM (2003), sustainable materials may have higher or equal initial costs, but the overall life cycle costs are typically lower than traditional materials. FEM also indicated that building materials life cycle costs can be minimized by reusing and saving virgin materials. This criterion is named by Wang (2011) as “using materials with low total costs”. Joseph (2010) mentioned this criteria, but he did not define it. This criterion should be named “minimum life cycle costs”, because this definition is inclusive. Building materials life cycle costs can be measured by “ASTM E917 - 05(2010) Standard Practice for Measuring Life Cycle Costs of Buildings and Building Systems”.

Improve indoor air quality: Indoor air quality is defined as “the indoor air concentrations of pollutants that are known or suspected to affect people’s comfort, environmental satisfaction, health, or work or school performance”(ASHRAE, 2010). According to Calkins (2009), many end users and workers are exposed to harmful coatings, sealers, and adhesives which contain chemical ingredients leading to air pollution. Kubba (2010) stated that inadequate ventilation and inefficient filtration are the main causes of poor indoor-air quality. Research and experience in green building emphasized the direct impact of indoor air quality to the health of building occupants. In order to improve indoor air quality, zero- or low emitting building materials must be used.

In addition, onsite stored materials must be protected from moisture damage during construction. Maximizing daylight and views can also contribute to providing a healthy environment (Kubba, 2010). This criterion is also mentioned by the following authors: (FEMP, 2003; Sev, 2009; Milani, 2005; GHP, 2010; Yudelson, 2007). Akadiri (2011) named this criteria "impact of material on air quality". Indoor air quality can be measured by the " *inAir*" tool which "determines the concentration of carbon dioxide (CO2) and hazardous airborne particles in the air" (Kim,2009). Indoor air quality is measured by "ASTM D6245 - 07 Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation". In addition, ASHRAE Standard 62.1-2010 also provides guidelines for acceptable indoor air quality.

Less Labor Costs: Labor costs are defined as "core expenditure borne by employers for the purpose of employing staff" (European Commission, 2012). Labor costs contribute significantly toward reducing or increasing the overall costs of buildings. Akadiri (2011) mentioned this criterion, but he did not describe it. Labor costs can be measured in dollars.

Affordability: TSRI (2007) defined affordable housing as "housing that should not cost more than 30 percent of a household's gross income regardless of whether they are living in market or non-market housing". GHP (2010) indicated that the percentage of the cost of affordable materials should be within the projects' overall budget. The following authors mentioned this criterion, but they did not define it: (Joseph, 2010; Yudelson, 2007; RMI, 2007). Affordability is measured by determining the ratios of materials prices to income (Whitehead, 2009).

Less disposal costs: disposal costs are defined as "the anticipated value at the end of the economical life span of a building and include expenditures for demolition, preparation for recycling and/or re-use and disposal as waste" (DETR, 2000). The following authors mentioned this criteria, but they did not define it :(Joseph, 2010), and (Sev, 2009). Akadiri (2011) named this criterion as "disposal cost". Disposal costs are measured by calculating average costs per ton.

Construction waste management: Construction waste management is defined as "the practice of minimizing and diverting construction waste, demolition debris, and land-clearing debris from disposal and redirecting recyclable resources back into the construction process" (WBDG, 2012). According to LEED, 50-75 % of non-hazardous waste should be recycled. LEED also indicated that construction waste management aims to recycle non-hazardous waste resulting from construction and demolition and reuse it in the manufacturing process. Kim (1998) indicated that in order to reduce waste, we should manufacture products in a more efficient way and reduce the amount of scrap results from the production process, molding and trimming or from damaged products. The following are different terminologies which describe "construction waste management" criteria: reduction in construction waste (Kim, 1998; Sev, 2009), elimination or reduction of generated waste (Joseph,2010), reducing construction waste (Yudelson,2007), "amount of likely wastage in use of material" (Akadiri, 2011) and construction waste management (LEED) as shown in Table 2-18. Based on the above explanation, this criteria should be named "construction waste management", because it is an inclusive definition. This criterion is measured in tons/cy (tons per cubic yard). Table 2-12 shows a construction waste management summary of some building materials.

Table 2.12 Sample Construction Waste Management Diversion Summary (USGBC).

Diversion/Recycling Materials Description	**Diversion/Recycling Hauler or Location**	**Quantity of Diverted/Recycled Waste**	**Units (tons/cy)**
Concrete	ABC Recycling	138.0	tons
Wood	Z- Construction Reuse	10.2	tons
Gypsum Wallboard	ABC Recycling	6.3	tons
Steel	Recycle Steel Collectors	1.1	tons
Crushed Asphalt	Onsite Reuse	98.2	tons
Masonry	ABC Recycling	6.8	tons
Cardboard	ABC Recycling	1.6	tons
Total Construction Waste Diverted		262.2	tons
Landfill Materials Description	**Landfill Hauler or Location**	**Quantity of Diverted/Recycled Waste**	**Units (tons/cy)**
General Mixed Waste	XYZ Landfill	52.3	tons
Total Construction Waste Sent to Landfill			52.3 tons
Total of All Construction Waste			314.5 tons
Percentage of Construction Waste Derived From Landfill			83.4 %

Thermal comfort: "Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE). According to FEMP (2008), improving the ventilation and thermal condition systems of buildings is very important to reduce sick building symptoms. Kubba (2010) stated that in order to provide an excellent thermal environment, operable windows should be used as well as HVAC system should meet the requirements of ASHRAE 55-2004. Akadiri (2011) indicated that occupants' health and productivity are greatly affected by achieving better thermal conditions. The following authors mentioned this criterion, but they did not define it: (Joseph, 2010; Sev, 2009) (Calkins 2009; Akadiri, 2011). ASHRAE 55-2004 provides guidelines to achieve better thermal comfort conditions. It stated that thermal comfort conditions should satisfy the following six factors shown in Table 2-13. The allowable radiant temperature is shown in Table 2-14.

Table 2.13 Thermal Comfort Primary Factors (ASHRAE 55-2004)

Thermal Comfort Primary Factors	
Metabolic rate	Radiant temperature
Clothing insulation	Air speed
Air temperature	Humidity

Table 2.14 Allowable Radiant Temperature Asymmetry (ASHRAE 55-2004)

Radiant Temperature Asymmetry °C (°F)			
Warm Ceiling	Cool Wall	Cool Ceiling	Warm Wall
< 5 (9.0)	< 10 (18.0)	< 14 (25.2)	< 23 (41.4)

Acoustic comfort: Acoustic comfort is defined as "providing an acoustic environment that is conducive to speech intelligibility, speech privacy, low distractions and annoyance, and concentration where appropriate" (Roy, 2011). Acoustic comfort in buildings is essential to achieve the occupants' satisfaction. A good acoustic environment should maintain noise levels at certain rates that cannot affect human activities. Many facilities such as schools require the provision of quiet spaces that prevent reverberation and allow teachers and students to speak and communicate effectively (LEED). Sev (2009) mentioned this criteria, but he did not define it. Sound is measured in decibels (dB). "ASTM E90 - 09 Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements" provides measurements for sound transmission between building partitions such as walls, doors, windows and ceilings.

Enhance occupants' productivity: The occupants' productivity is typically affected by many factors such as social communication, daylight, thermal comfort, acoustic comfort, aesthetic options and connection to nature (FEMP, 2003). The following are different terminologies which describe “Enhancing occupants' productivity” criteria: improving occupants’ health and productivity (Joseph, 2010; Sev, 2009; RMI, 2007) and improving occupants' performance (FEMP, 2003) as shown in Table 2.18. This criterion should be named “Enhancing occupants' productivity” because this definition gives more clarity. Occupants' productivity can be measured subjectively by determining whether they express a high or low level of productivity.

Less construction time: construction time is defined as the duration of time spent while constructing building materials. Construction time has a significant impact in decreasing or increasing overall building costs. This criterion was mentioned by Sev (2009), but he did not define it. Joseph, 2010 stated another name for this criterion which is “the ability to construct quickly”. Akadiri (2011) named this criterion “buildability”. However, this criterion should be named “less construction time”, because this name indicates that building materials should be manufactured in the shortest possible time. Construction time can be measured by “ASTM E2691 - 09 Standard Practice for Job Productivity Measurement” which measures construction production rate.

Low maintenance costs: Maintenance costs are defined as “the cost of any actions carried out to retain an item in, or restore it to an acceptable condition” (Al-khatam, 2003). Using durable materials decreases scheduled maintenance and overall replacement and repair costs. For example, flyash concrete has higher durability than Portland cement concrete (FEMP, 2003). The following are different terminologies which describe “Low maintenance costs” criteria : reduced maintenance and replacement costs (Joseph, 2010), low maintenance costs (DETR, 2000) and maintenance costs (Akadiri, 2011) as shown in Table 2-18. Based on the above explanation, this criterion should be named “low maintenance costs", because it is an inclusive definition. Maintenance costs are measured in dollars.

Aesthetic options: The general appearance of building materials affects the occupants' performance and productivity in many ways. People, normally prefer looking at attractive materials. Akadiri (2011) indicated that buildings with acceptable appearance and greater prestige are preferable to plain buildings. The following are different terminologies which describe "aesthetic options" criteria: aesthetic characteristics (Joseph, 2010; Sev, 2009) and aesthetics (Akadiri, 2011). However, this criterion should be named "aesthetic options", because this definition gives more clarity. The aesthetic options of building materials can be measured subjectively by determining whether they have an ugly, acceptable or good appearance.

As in much of what was discussed above, Tables 2-15, 2-16, 2-17 and 2-18 show the inconsistency in the terminologies of sustainable building materials criteria.

Table 2.15 Environmental Sustainable Building Materials Criteria Terminologies Variation

Sustainable Building Materials Criteria	Criteria Terminologies
Environmental Category	
1. Pollution prevention**.**	Use non-polluting materials (Wang, 2011). Use low emitting materials : (Calkins 2009), Pollution prevention: (Ellison, 2007), (Kim, 1998), (Wang, 2007), (Milani, 2005) (DETR, 2000),(Kates,2003),(OCAAP,2004). Minimise pollution (Akadiri, 2011).
2. Water conservation	Use low water use materials :(Calkins, 2009), (Milani,2005) Water treatment / conservation : (Kim , 1998), Water conservation: (Joseph, 2010), (GHP, 2010), (OCAPP, 2004), (BIG, 2008), (Sev, 2009), (Kates,2003). Efficient use of water: (Kubba, 2010).
3. Use of non-toxic or less-toxic materials	Low toxicity : (Joseph,2010), (OCAAP,2004) Nontoxic : (Sev, 2009), (Kubba, 2010). Use materials that avoid toxic chemicals (Calkins 2009). Use Low or non-toxic materials**:** (GHP, 2010), (Kim, 1998), "Zero or low toxicity" (Akadiri, 2011). Use materials with low toxic emissions: (Milani, 2005). Toxicity (WCC, 2008).
4. Less ozone-depleting substances	Less ozone-depleting substances : (DETR,2000), "Ozone depletion potential" (Akadiri, 2011).
5. Healthfully maintained	Healthfully maintained: (GHP,2010), (Wang,2011)
6. No radioactive	No radioactive: (Wang,2011).
7. Methods of extraction of raw materials	"Method of raw material extraction": (Akadiri ,2011) (Calkins,2009)
8. Fire resistance	Fire prevention :(Wang,2011), Fire resistance: (Akadiri ,2011)
9. Low-VOC assembly	Low VOC assembly: :(Calkins, 2009),(GHP,2010). (GGEI,2010), Low emitting materials :(Yudelson,2007)

Table 2.16 Technological Sustainable Building Materials Criteria Terminologies Variation

Sustainable Building Materials Criteria	Criteria Terminologies
Technological Category	
1. Durability	Using durable materials :(Calkins, 2009), (GHP, 2010), (OCAAP,2004) Use materials with great durability: (Milani, 2005). "Life expectancy" (Akadiri, 2011). Durability: (Kim, 1998), (Yudelson,2007),(Joseph,2010)
2. Biodegradability	Biodegradability : (Kim , 1998), (Kubba, 2010).
3. Service lfe	Longer Life : (Kim,1998), Having a long useful life (OCAAP,2004)
4. Moisture resistance	Moisture resistant: (GHP, 2010).
5. Flexibility	Greater design flexibility (Joseph, 2010), (RMI, 2007), (GHP, 2010). Don't rebuild :(Calkins, 2009). Flexibility: (Sunke, 2009), (Sev, 2009).

Table 2.17 Resource Use Sustainable Building Materials Criteria Terminologies Variation

Sustainable Building Materials Criteria	Criteria Terminologies
Resource Use Category	
1. Recyclability	Using circulated materials : (Wang,2011) Recyclable materials (Sev, 2009). (GHP, 2010). (Milani, 2005), (Kubba, 2010), (OCAAP,2004). Recycled content (LEED) Recyclability (Kim, 1998). “Potential for recycling and reuse” (Akadiri, 2011). Using reclaimed materials (have recycling potential) :(Calkins,2009), (Yudelson,2007)
2. Embodied energy consumption	Embodied energy reduction: (Kim, 1998), (Sev, 2009), (Yudelson, 2007). Consuming low energy to produce raw materials (Wang, 2011). Use materials that have low embodied energy: (Calkins, 2009). (Milani,2005), (OCAAP,2004). “Embodied energy within material” (Akadiri, 2011). Embodied energy (WCC,2008), (Joseph, 2010)
3. Energy efficiency	Energy efficiency: (Kim, 1998). (Joseph,2010), (Kubba,2010), (Yudelson,2007).(DETR,2000),(BIG,2008). (GHP, 2010). Energy saving (Akadiri, 2011). Using low energy consumption materials (Wang, 2011). (Calkins 2009), (Ellison, 2007).
4. Use of natural resources	Rational use of natural resources: (Joseph, 2010), (Calkins 2009), (BIG, 2008). Natural materials : (Kim , 1998), (Yudelson,2007) Use materials that are organically-grown (natural materials) : (Milani,2005)
5. Using certified wood	Using certified wood: (Calkins, 2009). (TCICD, 2004), (Yudelson, 2007). LEED, (OCAAP,2004)
6. Locally produced	Locally available: (TCICD, 2004). Regional Materials: LEED Use Local Materials: (Calkins, 2009),(Akadiri, 2011) (Joseph,2010). Locally harvested and processed: (Yudelson, 2007). Local resources (WCC,2008)
7. Renewable resources	Use materials which are made from renewable resources (Calkins, 2009). Use rabidly renewable resources: (Yudelson, 2007),(TCICD,2004). Recycled contents (Kubba,2010), (Kim , 1998), Renewable materials (GHP, 2010) Renewable resources (WCC,2008) rapidly renewable materials (LEED)
8.Reusability	Reusable: (Wang, 2011). Use materials which have design for disassembly (DfD) potential: (Calkins, 2009). Reusability (Kim,1998) Reuse building materials: (RMI, 2007), (Sev, 2009). (GHP,2010) Use easy reused materials: (Milani, 2005). Material reuse: LEED.

Table 2.18 Socio economic Sustainable Building Materials Criteria Terminologies Variation

Sustainable Building Materials Criteria	Criteria Terminologies
Socio economic Category	
1.Minimum life cycle costs	Using materials with low total costs (Wang ,2011). Minimum life cycle costs (Joseph, 2010),
2.Improve indoor air quality	Improve indoor air quality: (FEMP, 2003), (Calkins, 2009). (Milani, 2005). (Sev, 2009). (GHP, 2010), (Yudelson, 2007), (Kubba,2010). "Impact of material on air quality" (Akadiri, 2011).
3. Less labor costs	(Akadiri, 2011).
4. Affordability	Affordability: (Joseph, 2010), (GHP, 2010), (Yudelson, 2007). (RMI, 2007).
5. Less disposal costs	Less disposal costs: (Joseph, 2010), (Sev, 2009). "Disposal cost" (Akadiri, 2011)
6.Construction waste management	Construction waste management : LEED Reduction in construction waste: (Kim, 1998), (Sev, 2009). Elimination or reduction of generated waste: (Joseph,2010), "Amount of likely wastage in use of material" (Akadiri, 2011) Reduce construction waste : (Yudelson,2007)
7.Thermal comfort	Thermal comfort: (Joseph, 2010), (Calkins 2009). (Akadiri,2011),(Sev, 2009).
8. Acoustic comfort	Acoustic comfort: (Sev, 2009).
9.Enhance occupants productivity	Improved occupant's health and productivity: (Joseph, 2010), (Sev, 2009), (RMI, 2007). Improve occupants performance : (FEMP,2003),
10. Less construction time	Ability to construct quickly: (Joseph, 2010). Buildability (Akadiri, 2011). Less construction time :(Sev,2009)
11.Low maintenance costs	Reduced maintenance and replacement costs: (Joseph, 2010). Low maintenance costs: (DETR, 2000), Maintenance costs(Akadiri, 2011).
12. Aesthetic options	Asthetics (Akadiri, 2011) Aesthetic characteristics (Joseph, 2010), (Sev, 2009),

Table 2-19 shows the measurements and subjective assessment of sustainable building materials criteria.

Table 2.19 Sustainable Building Materials Criteria Measurements

Criteria	Measured Criteria	Subjective Criteria	Measurement Units/ Standards or Subjective Measurement
Environmental Category			
1. Pollution prevention**.**	*		kilogram/metric ton ASTM E1609-01
2. Water conservation	*		Cubic feet (ft.3), cubic meters (m3) or gallons. ASTM E2635 - 08
3. Use of non-toxic or less-toxic materials	*		Mg/kg (Milligram per kilogram) Lethal dose 50 percent (LD 50) :the dose that will result in the death of half of the tested population. For example (1 hour, 1 month, 1 year). ASTM E1678 – 10
4. Less ozone-depleting substances	*		The amount of CFCs (chlorofluorocarbons). ASTM D5110 - 98(2010)
5. Healthfully maintained	*		ASTM D6361 (helps to select the best cleaning process considering environmental pollution) .
6. No radioactive	*		Bq Kg-1(becquerels per kilogram). ASTM E512 - 94(2010)
7. Methods of extraction of raw materials		*	Sustainably extracted – non sustainably extracted
8. Fire resistance	*		Time/temperature (1 hour- 2-hour- …..) ASTM E119-00a British Standard 476
9. Low-VOC assembly	*		mg/m3 ASTM D7143 - 11
Technological Category			
1. Durability	*		Time (For how long time the material can met its performance requirement) ASTM F148 - 02(2007)
2. Biodegradability	*		Time (days-months-years). ASTM D6692-01
3. Service life	*		Years. ASTM E632-82(1996).
4. Moisture resistance	*		Percentage of mass of water vapor to the mass of dry air. ASTM D4502 - 92(2011)**.**
5. Flexibility	*		Number of uses
Resource Use Category			
1. Recyclability	*		The ratio of the recycled material to the total material consumption
2. Embodied energy consumption	*		*MJ/kg* (megajoules/kilogram)
3. Energy efficiency	*		Energy intensity (the ratio between energy use (input) and energy service demand).

Criteria	Measured Criteria	Subjective Criteria	Measurement Units/ Standards or Subjective Measurement
4. Use of natural resources	*		Percentage of natural resources.
5. Using certified wood		*	Certified – not certified (FSC) standard.
6. Locally produced	*		Within 500 miles away from site
7. Renewable resources	*		Percentage of renewable contents
8.Reusability	*		One time- two times- more
Socio-Economic Category			
1.Minimum life cycle costs	*		ASTM E917 $ dollar (High cost – less cost)
2.Improve indoor air quality	*		ASTM D6245 – 07 ASHRAE Standard 62.1-2010 It is also measured by" *inAir*" tool which determines the concentration of Carbone Dioxide (CO2) and hazardous airborne particles in the air.
3. Less labor costs	*		$ dollar (High cost – less cost)
4. Affordability	*		The materials prices to income ratios.
5. Less disposal costs	*		Average cost per ton
6.Construction waste management	*		Tons/cy (cubic yard)
7.Thermal comfort	*		ASHRAE 55-2004
8. Acoustic comfort	*		ASTM E90 – 09
9.Enhance occupants productivity		*	More productive – less productive
10. Less construction time	*		ASTM E2691-09
11.Low maintenance costs	*		Dollars
12. Aesthetic options		*	Ugly – acceptable - good

2.12 Current Practice of Sustainability in Saudi Arabia

There are several researches which have discussed implementing sustainability principles in building construction in Saudi Arabia.

Hanan (2010) investigated energy and water consumption in residential buildings in Saudi Arabia in order to achieve more sustainable buildings in the future. A residential building situated in Jeddah city was selected as a case study. The building energy and water consumption was investigated using simulation software packages. The study concluded by suggesting some guidelines which would lead to the construction of sustainable buildings in Saudi Arabia. Such guidelines include improving thermal insulation of exterior walls, placing windows properly to maximize natural daylight and promoting waste recycling.

Al-Yami (2005) explored sustainable construction principles in Saudi Arabia and emphasized the great efforts made by the Saudi government toward obtaining a good and better environment. Furthermore, he indicated that there was a lack of awareness of establishing sustainable construction principles in Saudi Arabia. Also, he made semi-structured interviews with twelve experts working in different public sectors and explained the obstacles of implementing sustainable construction in Saudi Arabia.

Siddiqui (2012) investigated the impact of sustainable building design from the construction management point of view. An existing building design was analyzed and a variant design was modified to increase LEED certification points. The impact of sustainability costs was identified by conducting Life Cycle Cost Analysis (LCCA).The study indicated that although green buildings have substantial initial costs, they gain more benefits than conventional buildings during the buildings' useful life.

Susilawati and Al-Surf (2011) conducted a current study to explore obstacles facing implementation of sustainability in the housing sector in Saudi Arabia and investigate the level of people's knowledge. They said that the harsh dry climate, water scarcity and the rapid urbanization are major challenges facing the implementation of sustainable housing in Saudi Arabia. They conducted a web-based survey distributed to 693 engineers chosen from the Saudi Council of Engineers. 52.2% of the respondents were not aware of sustainable housing issues. The study suggested many sustainable methods to be implemented in Saudi Arabia including passive solar design and natural ventilation. Moreover, the authors suggested some recommendations to encourage the implementation sustainable housing in Saudi Arabia. Such recommendations include applying sustainable codes in construction, organizing several workshops for architects and stakeholders, and using media to inform people of the importance of sustainability.

Based on the above discussion, it is noticed that although Saudi Arabia has established remarkable development in urbanization and rapid increase in infrastructure, the local market is still not aware of implementing sustainability principles. Moreover, the number of buildings which incorporate passive solar design and energy conservation strategies and the number of LEED certified buildings in Saudi Arabia is very limited. So, there is a growing need to study the awareness of sustainability practices in Saudi consulting offices.

2.13 Decision Making Techniques and Methods

2.13.1 Definition

Decision making methods are rational processes that provide decision makers with critical thinking skills to make a decision and choose from several alternatives. Steps such as identifying the main purpose and assessing alternatives are followed in order to make a decision through involving a scored criterion and alternative (Baker, 2001).

According to UK DTLR (2001), the decision making process should follow the following steps:

- Identifying objectives.
- Identifying options for achieving the objectives.
- Identifying the criteria to be used to compare the options.
- Analysis of the options.

- Making choices.
- Feedback.

However, there are several techniques used for decision making and solving problems. Those techniques include:

2.13.2 Maximin and Maximax Methods

This method is used to maximize the minimal performing criterion. The ranking of alternatives depends on the strength of their weakest attribute. The preferred alternative is the one which has the highest score for its weakest attribute. The Maximin method is very limited because it measures only comparable criteria so they can be measured on a common scale (Linkov, 2004).

2.13.3 Multi-Attribute Utility Theory (MAUT)

Multi-Attribute Utility Theory is used in general by customer driven organizations. It plays a valuable role in evaluating products. The overall evaluation is defined as a weighted addition of its evaluation with respect to its relevant value dimensions (Schafer, 1999).

Also MAUT is used to collect dissimilar measures into high-level preferences. Criteria in MAUT are based on importance. MAUT is suitable when there are many alternatives with complex decisions and multiple criteria (Baker, 2001). However, this method is limited because it requires only meaningful input without any obscurities (Steward, 1992).

2.13.4 Cost Benefit Analysis (CBA)

Cost Benefit Analysis (CBA) is a decision making technique indented mainly to provide information related to the improvement of the quality of public policies. The main purpose of improving the quality is to measure social wellbeing that a policy conveys to society. Its valuations are based on willingness-to-pay or to accept UK DTLR (2001). CBA also tries to provide evidence concerning economic benefits, specially when a decision is needs to be made (Carlin, 2005). CBA method is limited because it can only measure the economic attributes of products.

2.13.5 Conjunctive and Disjunctive Methods

In conjunctive and disjunctive methods, there are no attributes needed to be measured. In the conjunctive method, the minimum performance starting edge for all attributes must be met. However, the disjunctive method requires the alternative to exceed the given starting edge for at least one attribute. Alternatives are discarded when they cannot meet the performance starting edge level. The preferred alternative is the last one to be discarded. This method is limited, because it does not have the ability to evaluate all alternatives based on determined criteria (Linkov, 2004).

2.13.6 Kepner-Tregoe Decision Analysis (K-T)

K-T Decision Analysis is suitable in the case where there are only a few criteria and complex decisions. It is a comparison technique in which a group of experts have to rank alternatives based on their own judgment. The number of the team members depends on the quality of the data involved. Alternatives are given a score individually based on their level of meeting the objective required. The closer the alternative is to meeting the objectives, the higher the score it is given. The alternative which has the highest total scores is the preferred one (Baker, 2001). This criterion is limited, because it cannot measure alternatives with a large number of criteria.

2.13.7 Pros and Cons Analysis Technique

This method is suitable when there are few discriminating criteria, few alternatives and simple decisions. The qualities and defects of the alternatives are identified and their pros and cons are then compared. The preferred alternative is the one which has the strongest pros and the weakest cons (Linkov, 2004).This criteria is limited, because it cannot evaluate a large number of alternatives with more criteria.

2.13.8 Analytic Hierarchy Process (AHP)

AHP is a quantitative comparison method which relies on the judgments of experts and is used to select a preferred alternative by using pair-wise comparisons (Saaty, 2008a).

This technique is based on humans who have the ability to make relative judgments and absolute judgments. AHP organizes the main purposes by dividing parameters into main and subcategories. Then a pairwise comparison can be made to determine the relative importance of these categories. After that, judgments will be translated into numbers by providing some quantitative methods. AHP is suitable when there are multiple criteria as well as quantitative and qualitative criteria. (Baker, 2001).

According to (Saaty, 1980), (Saaty, 2008a) the following steps should be followed to make a decision as shown in Figure 2-7:

1- Define the problem and determine the kind of knowledge sought.
2- Structure the decision hierarchy with the goal of the decision at the top.
3- Construct a set of pairwise comparison matrices.
4- Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below .

Figure 2-6 shows the AHP hierarchy model.

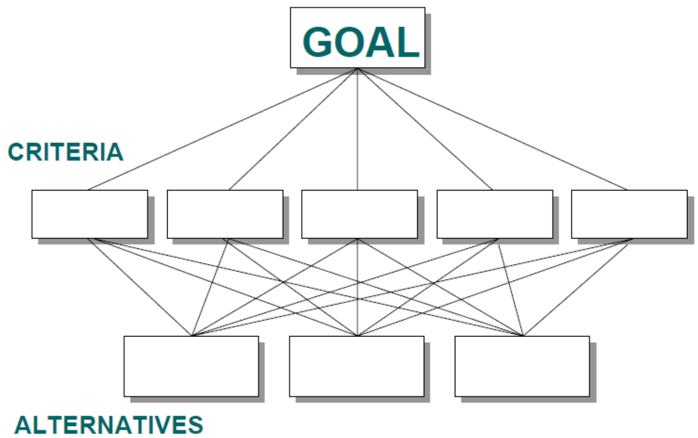


Figure 2-6 AHP Hierarchy

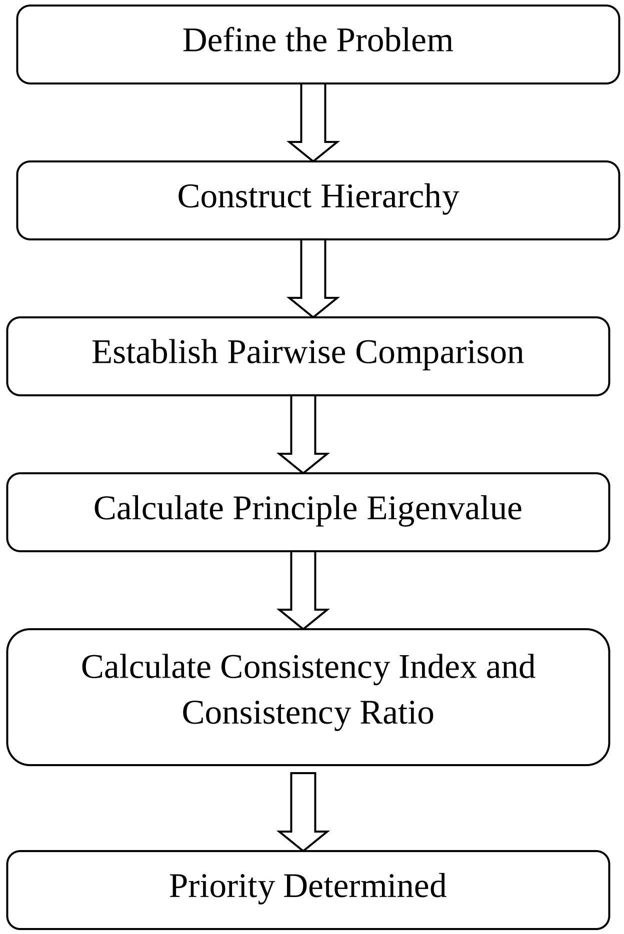


Figure 2-7 AHP Method Chart

Advantages of AHP: AHP relies on the judgments of experts, provides subjective and objective evaluation and has higher accuracy calculation. Also, AHP has the ability to provide group decision making and reduce bias in the evaluation process.

Furthermore, the unique advantage of AHP is that it provides an inconsistency index which is very important to let the decision maker know the rate of the consistency rate of his judgment. Also AHP produces error-free results because it has the ability to deal with any error (Acidify, 2011). Moreover, AHP is a flexible technique with more precise results. It also simplifies problems by dividing them into many parts, making their assessment very clear (Tahrir, 2008).

2.14 Expert Choice Software (EC)

Expert Choice Software is a multiattribute decision software based on the analytic hierarchy process (AHP) methodology which was developed by Saaty. It has been available for more than twenty years. Expert Choice Software is very helpful in examining problems that have multiple criteria. Alternatives are evaluated by using Analytic Hierarchy process (Fernandez, 1996). Expert Choice Software is widely used for commercial, governmental and academic purposes. It provides a structure for the entire decision making process, an improved communication and a faster decision making (Rose, 2005).

Expert Choice Software has two methods to develop a decision model: construction and assisted construction. First, the pros and cons of alternatives are listed and criteria are developed. Then, criteria are grouped into clusters which have a general objective (criteria) (Fernandez, 1996).

2.14.1 Primary Application Areas

Expert Choice Software is used in many application areas such as project portfolio management, resource allocation/capital budgeting, strategic planning, source/vendor/product selection and risk assessment (Rose, 2005).

2.14.2 The Evaluation and Choice Module

This module is considered as the principle component of Expert Choice. Models are first constructed by using the evaluation and choice module. Next, a comparison assessment is performed by using either pairwise comparison mode or ratings comparison mode (Fernandez, 1996).

2.14.3 Pairwise Comparison Mode

Pairwise comparison mode is good for a small number of alternatives. There are three common types of comparison: importance, preference, and likelihood. Each type uses three assessment modes: verbal mode, graphical mode and numerical mode (Fernandez, 1996).

2.14.4 Ratings Comparison Mode

Ratings comparison mode is suitable when there are large numbers of alternatives. It compares alternatives against specific standards rather than criteria (Fernandez, 1996).

2.14.5 Synthesizing final results

There are two methods for synthesizing final results: a distributive method and an ideal method. In the distributive method, criteria weights are distributed among alternatives, while in the ideal method, weights are assigned to the most preferred alternatives (Fernandez, 1996).

2.14.6 Sensitivity Analysis

Sensitivity analysis examines the sensitivity of the results which are based on subjective expert assessment. Expert choice software provides many graphics models for performing sensitivity analysis such as: performance, dynamic, gradient, dimensional plot and differences. It also provides many tools which contribute to the increase of the flexibility of sensitivity analysis (Fernandez, 1996).

CHAPTER 3

RESEARCH METHODOLOGY

This chapter aims to present the research methodology that will be followed to achieve the research objectives. The main objectives of this research are to identify criteria affecting evaluation and selection of sustainable building materials, investigate the practices of Saudi design/consulting offices in selecting sustainable building materials and to develop a decision making model to help architects and engineers in the selection of sustainable building materials in Saudi Arabia.

3.1 Development of Questionnaire Survey

In this step, a questionnaire survey will be developed and distributed to a representative sample of designers, engineers and consultants to investigate sustainable building materials criteria. The developed survey contains four main parts as follows:

Part 1: It contains general information about respondents such as their position in their organization, years of experience and the nature of their organization.

Part 2: This part aims to explore the level of designers' / architect' awareness in sustainability issues and investigate their ways in selecting building materials and barriers they face.

Part 3: The main goal of this part is to develop a universal set of sustainable building materials criteria and investigate their level of importance.

Part 4: This part contains aims to make pairwise comparisons between all criteria and sub criteria affecting the selection of sustainable building materials.

Part 5: The main aim of this part is to make pair wise comparisons between all sustainable building materials alternatives with respect to all criteria.

3.1.1 Identification of the Population Sample Sizes

The sample of respondents that completed the survey and assessed the identified sustainable building materials criteria consisted of architects/ engineers who work in consultant offices in the Eastern Province were obtained from the Chambers of Commerce.

The sample size was determined using the following equations (kish, 1995):

no = (*p***q*)/v2……………..… (1.1)

n = no/ [1+ (no/N)]………… (1.2)

Where:

no: First estimate of sample size

***p*:** The proportion of the characteristic being measured in the target population.

***q* :** Completion of *p* or 1-*p*.

V: The maximum percentage of standard error allowed (10% for this study)

N: The population size.

n: The sample size.

Note: To maximize the sample, both ***p*** and ***q*** are each set at **0.5**.

3.1.2 Pilot-testing of the Questionnaire Survey

A pilot survey was sent to three experts in selecting sustainable building materials before the final distribution of the questionnaire survey for the following purposes:

- Reviewing the comprehensiveness and clarity of all questions.
- Incorporating additional sustainable building materials criteria.
- Testing the applicability of the average time provided to answer all questions.

The pilot testing resulted in rewording or reordering some questions in order to be clear to the respondents.

3.2 Distributing the Tested Questionnaire Survey

This stage involves distributing the pilot-tested questionnaire survey to a representative sample of designers/engineers in the Eastern Province of Saudi Arabia to explore their sustainability awareness and assess the importance of criteria affecting selecting sustainable building materials.

3.3 Data Analysis

This stage involves statistically analyzing all data received from respondents by calculating importance index and agreement index. Also, Expert Choice Software was used to analyze the fourth and fifth parts of the questionnaire survey.

3.3.1 Calculation of Importance Index

The importance and agreement index will be calculated using Excel Software by implementing the following equation (Dominowski 1980).

$$\textbf{Importance index } \mathrm{I} = \frac{\sum_{i=0}^{3} aixi}{3 \sum xi} \times 100 \quad \%$$

Where:

i = Response category index where i= 0,1, 2, 3

a_i = Wight given to i response where i= *0, 1, 2, 3*

x_i = variable expressing the frequency of i as illustrated in the following:

x_0 = frequency of "Extremely Important" response corresponding to a_0 = 4.

x_1 = frequency of "Very Important" response corresponding to a_1 = 3.

x_2 = frequency of "Not Important" response corresponding to a_2 = 2.

x_3 = frequency of "Extremely not Important" response corresponding to a_3 = 1.

3.4 Analytic Hierarchy Process

In this stage, factors priority index will be obtained by using Expert Choice Software which is based on Analytic Hierarchy Process (AHP). AHP is a powerful tool for making decisions. It starts with formulating the problem into a four level hierarchy framework. The top level identifies the main goal. The second and third level represent criteria and sub-criteria sequentially. Decision making alternatives are presented in the fourth level (Saaty, 2008a). In order to choose the most sustainable building materials, the following steps should be followed:

3.4.1 Step 1: Defining the Problem

The case study problem for this particular study concerns the selection of the most sustainable exterior wall building material. The selection process must consider the holistic list of sustainable building materials criteria developed in Chapter 2.

3.4.2 Step 2: Developing a Hierarchy Model

This step involves constructing all factors affecting the selection of sustainable building materials into a hierarchy model. The top level of the hierarchy starts with the overall goal and the decision alternatives lie on the last level. The powerful decision making computer software, Expert Choice, will be utilized to structure the decision model. “Selecting Sustainable External Wall Building Materials” is the model name. It lies on level 0 of the model. The main criteria are inserted in level 1 while sub criteria are located at level 2. Finally, the selection alternatives are inserted at the last level of the hierarchy model. The hierarchy model of selecting sustainable external wall building materials was built by Expert Choice Software as shown in Figure 3-1. Sustainable building materials main categories models are shown in Figures 3-2, 3-3, 3-4, and 3-5.

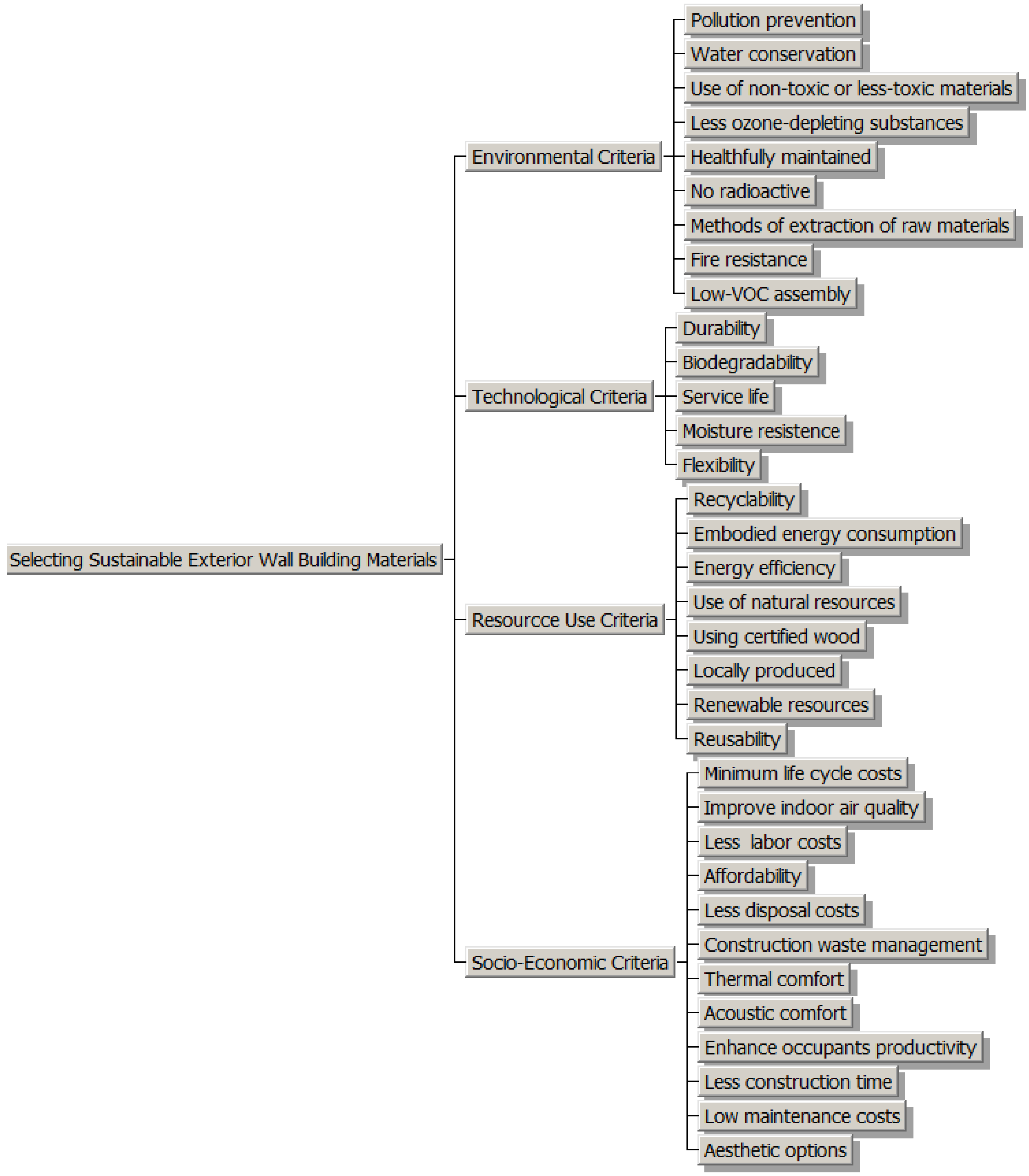


Figure 3-1 The Hierarchy Model of the Selection of Sustainable Exterior Wall Building Materials

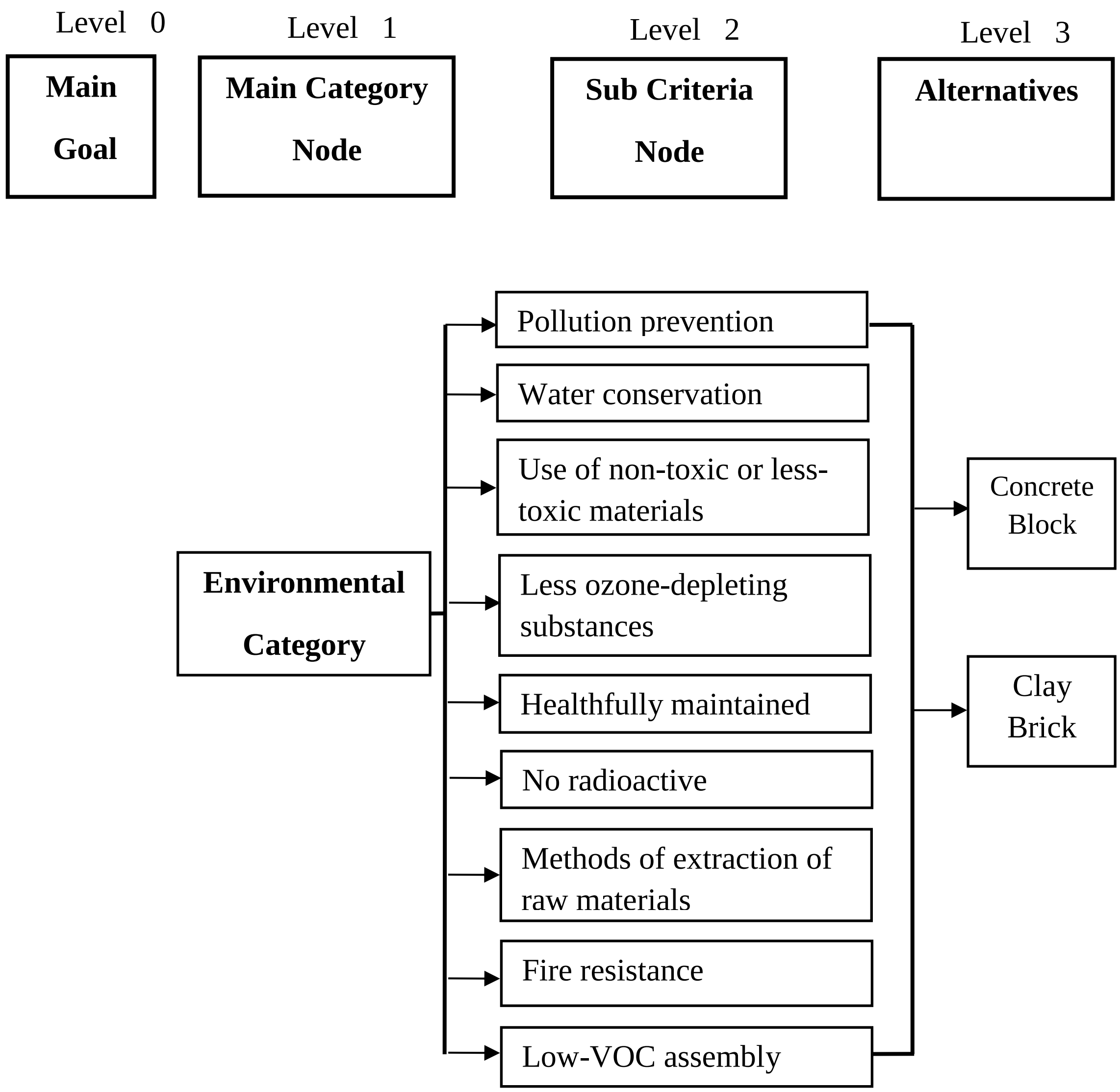


Figure 3-2 Model of Environmental Category Node

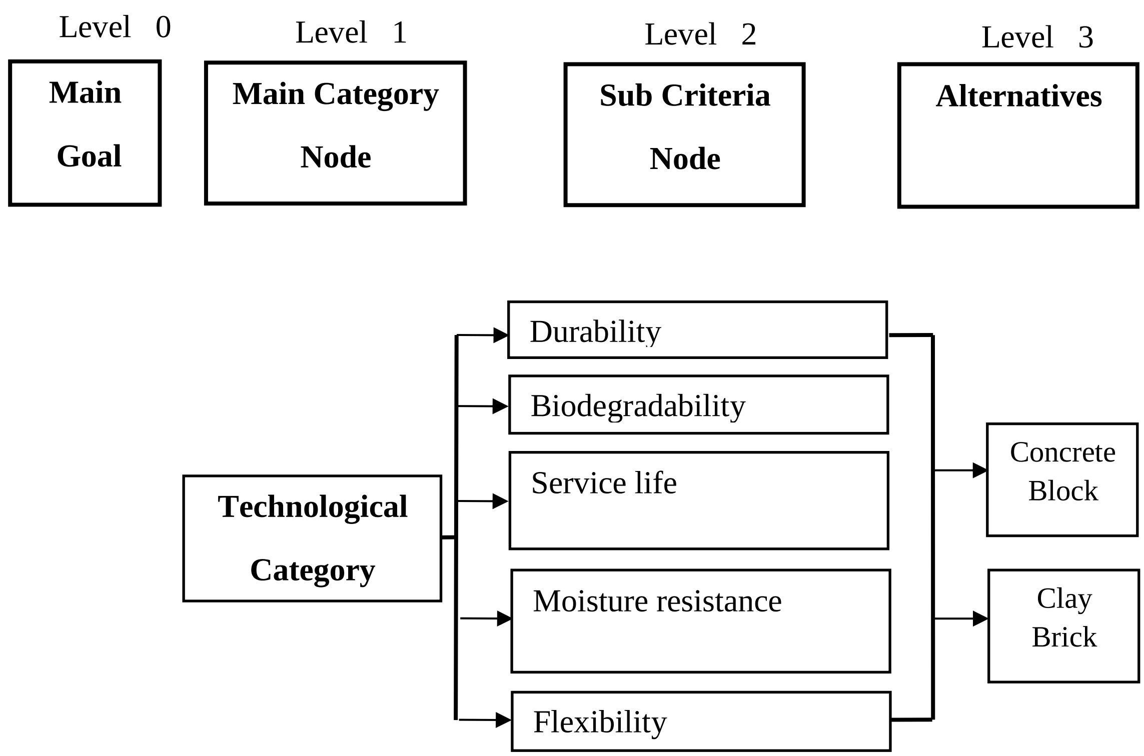


Figure 3-3 Model of Technological Category Node

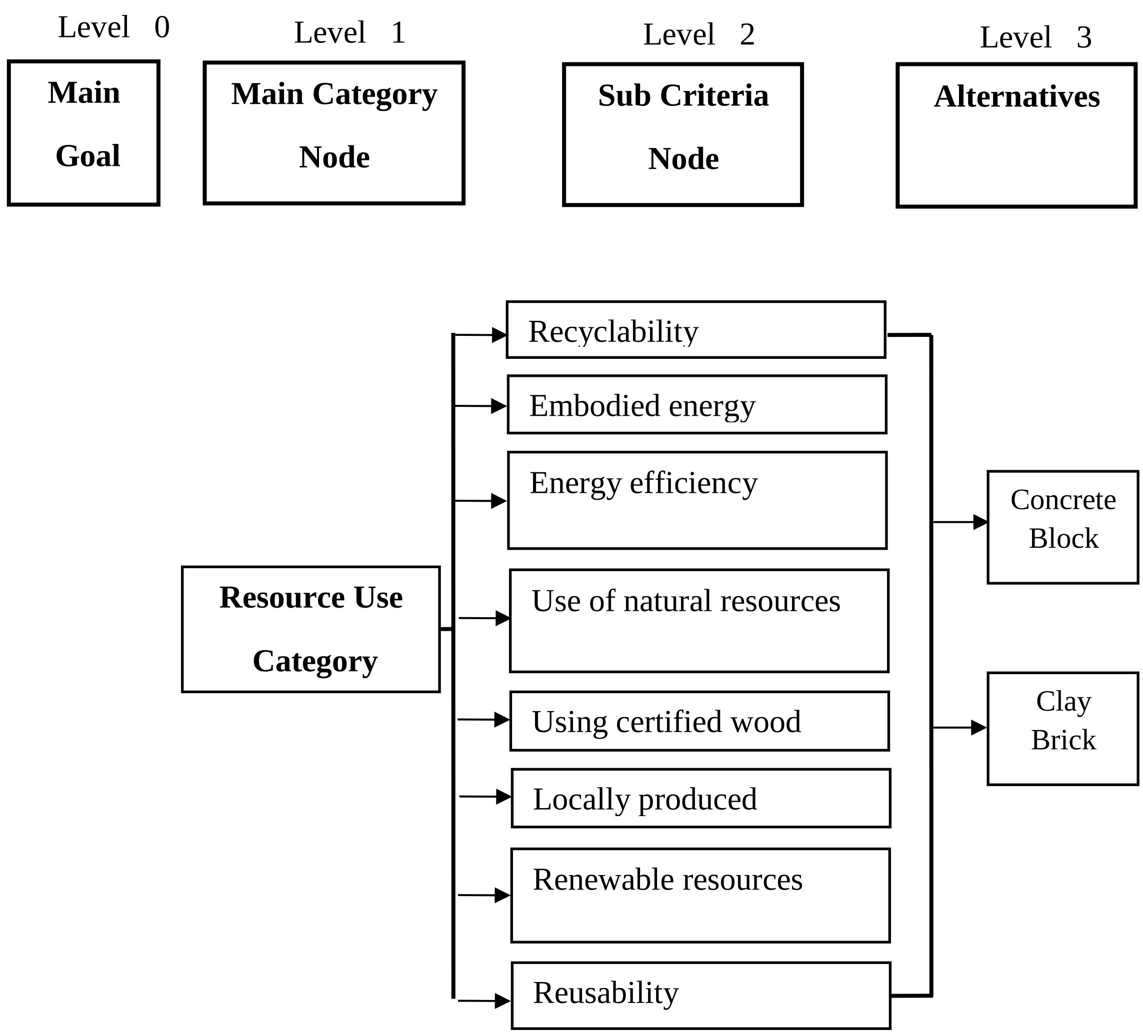


Figure 3-4 Model of Resource Use Category Node

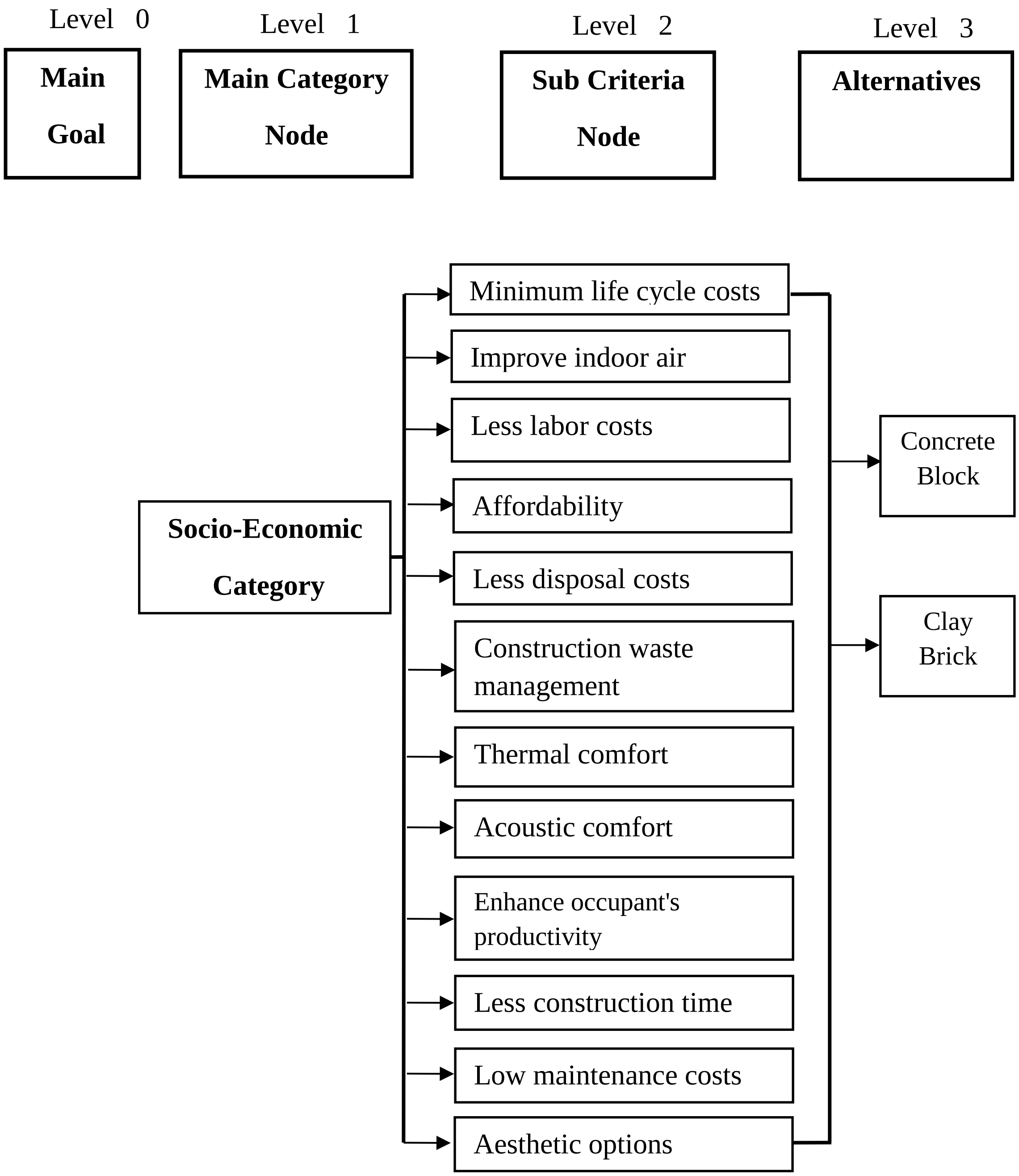


Figure 3-5 Model of Socio-Economic Category Node

3.4.3 Step 3:Pairwise comparisons

After constructing the hierarchy model, the next step is to conduct a pairwise matrix to evaluate all criteria affecting the selection of sustainable building materials. The pairwise comparisons are performed to calculate the relative importance of one criterion with respect to another at all hierarchy levels. The total number of comparisons equals $n \times (n - 1)/2$. The complexity of the comparison matrix depends on the number of criteria at each level. There are two types of measurement, namely relative measurement and absolute measurement. While alternatives are compared with respect to the level above in relative measurement, they are excluded in the absolute measurement. In pair wise comparison, a scale of (1, 2, 3, ……, 9) is used to generate the relative preference of each criterion with another one at each level of the hierarchy. The value 1 means that the two criteria compared have the same importance and the value 9 means that one criterion is more important than the other. The inverse values (1/3, 1/5, ….., 1/9) are used when we compare less important criterion with more important criterion and the values 2, 4, 6, and 8 are intermediate values (Saaty, 2009). Table 3-1 shows the scale of pairwise comparisons.

Table 3.1 Scale for Pairwise Comparison (Saaty, 2008 b)

Intensity of Importance	Definition	Explanation
1	Equal value	Tow activities are of equal value
3	Slightly more value	An activity is slightly favor over the other
5	Strong value	An activity is strongly favor over the other
7	Very strong value	An activity is favored very strongly over another and its dominance is demonstrated in practice.
9	Extreme value	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	When compromise is needed
Reciprocals	Reciprocals for inverse values	

In Table 3-2 the left set of the criteria represent the criteria being compared and named by C1, C2, C3, ….., Cn. The weight of these criteria is presented by wC1, wC2, wC3, ….., wCn respectively. The ratios of weights of these criteria are presented in Table (3.2). Reciprocal values are used when we reverse the comparison of two criteria. For instance, when C1 is scored 3 when compared to C2, C2 is scored 1/3 when compared to C1 (Saaty, 2009).

Table 3.2 Simple Matrix of Pairwise Comparisons

Criteria	C1	C2	C3	→	Cn
C1	wC1/wC1	wC1/wC2	wC1/wC3		wC1/wCn
C2		wC2/wC2	wC1/wC1		wC2/wCn
C3			wC3/wC3		wC3/wCn
→					
Cn					wCn/wCn

Table 3-3 shows an example of pairwise comparison of technological criteria.

Table 3.3 Example of Pair wise Comparisons of Technological Criteria

Criteria	Durability	Biodegradability	Service life	Moisture resistance	Flexibility
Durability	1	3	5	3	5
Biodegradability	1/3	1	3	1	3
Service Life	1/5	1/3	1	1/3	3
Moisture resistance	1/3	1	3	1	
Flexibility	1/5	1/3	1/3	1/3	1

3.4.4 Step 4:Establishing Priorities

The quantified judgments on pairs (Ci, Cj) of a set of criteria (C1, C2, …, Cn) are presented in a matrix as the follows **(**Al-Jaroudi, 1998):

- A =(a_{ij}), (I, j= 1, 2, 3, ………n)
- If a_{ij}= x then aji= 1/x
- If i=j then aij = aji= 1

$$
\mathbf{A} = \begin{bmatrix} 1 & a12 & a13 & a14 \\ 1/a12 & 1 & a23 & a24 \\ 1/a13 & 1/a23 & 1 & a34 \\ 1/a14 & 1/a24 & 1/a34 & 1 \end{bmatrix}
$$

3.4.5 Step 5:Synthesizing the Pairwise Comparison

After performing the pairwise matrix comparisons, the priority vectors of all criteria are calculated by the following equation (Ariff, 2008):

$$W_i = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_i^n a_{ij}}, i, j = 1, 2, \ldots n \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

A-Calculate the sum of each column. For example, the sum of the first column can be calculated as the following:

$$\sum_i^n a_{ij} \quad = 1 + 1/3 + 1/5 + 1/3 + 1/5 = 2.067.$$

B-Divide the elements found in each column by this sum as follows:

$$\frac{a_{ij}}{\sum_i^n a_{ij}} \quad = 1/2.067 = 0.484$$

C-Calculate the summation of the resulting new rows as follows:

$$\sum_{j=1}^{n} \frac{a_{ij}}{\sum_i^n a_{ij}} \quad = 0.484 + 0.529 + 0.405 + 0.529 + 0.333 = 2.281$$

D-Divide the sum of rows by the number of elements of the comparison as follows:

The sum of rows / number of elements = 2.281 / 5 = 0.456

Table 3-4 shows the synthesized matrix for comparison:

Table 3.4 Synthesized Matrix for the Pairwise Comparisons

Criteria	Durability	Biodegradability	Longer Life	Moisture resistance	Flexibility	Total row	Priority Vector
Durability	0.484	0.520	0.405	0.529	0.333	2.281	0.456
Biodegradability	0.161	0.176	0.243	0.175	0.200	0.957	0.191
Service Life	0.097	0.059	0.081	0.059	0.200	0.496	0.099
Moisture resistance	0.161	0.176	0.243	0.176	0.200	0.957	0.191
Flexibility	0.097	0.059	0.027	0.059	0.067	0.308	0.062
						$\sum$	1.00

3.4.6 Step 6:Consistency

To avoid the inconsistency in the subjective judgments, a process called “consistency verification” is performed. The degree of consistency of comparisons is determined by calculating the consistency ratio (CR) which represents the ratio of consistency index (CI) to random index (RI). The following steps are followed to calculate the consistency ratio:

A- Calculate the eigenvalue (λ max) by multiplying the priority vector by the right matrix of the judgments to obtain a new vector as shown in Table 3-5:

Table 3.5 Calculating New Vectors

0.456	1 1/3 1/5 1/3 1/5	+ 0.191	3 1 1/3 1 1/3	+ 0.099	5 3 1 3 1/3
					New Vector
+ 0.191	3 1 1/3 1 1/3	+ 0.062	5 3 3 3 1	=	2.409 1.017 0.503 1.017 0.314

For example, the new vector of the first row is calculated as following:

Then: 0.456(1) + 0.191(3) + 0.099(5) + 0.191(3) + 0.062(5) = 2.409

Next: Calculating the sum of new vectors divided by prior vectors as follows:

The sum of new vectors/ priority vectors: 2.409/0.456 = 5.279; 1.017/0.191 = 5.312; 0.503/0.099 = 5.075; 1.017/0.191 = 5.312; 0.314/0.062 = 5.089

B- Calculate the consistency index (CI):

CI = (λmax-1) (n-1)

λ max = sum of new vectors/ numbers of elements = (5.279 + 5.312 + 5.075 + 5.312 + 5.089) /5 = 5.213

CI = (λ max–n)/ (n–1) = (5.213–5)/(5–1) = 0.053

C- Calculate the consistency ratio by using the following formula:

CR= CI/RI (Consistency index / random index)

According to Saaty (1990), the random index values are as follows, as shown in Table 3-6

Table 3.6 Values of Random Index

Size of matrix (n)	1	2	3	4	5	6	7	8	9	10	11	12
Random Index (RI)	0	0	0.58	1.90	1.12	1.24	1.32	1.41	1.45	1.51	1.90	1.58

So, the random index of a 5 elements matrix is 1.12.

CR = CI/RI = 0.053/1.12 = 0.05 (CR < 0.1)

Table 3-7 shows consistency ratio values:

Table 3.7 Calculation of Consistency Ratio

Criteria	D	B	S	M	F	Priority Vector (PV)	New Vector (NV)	NV/PV	
D	1	3	5	3	5	0.456	2.409	5.279	
B	1/3	1	3	1	3	0.191	0.017	5.312	
S	1/5	1/3	1	1/3	3	0.99	0.503	5.075	CR = CI/RI = 0.05
M	1/3	1	3	1	3	0.191	0.017	5.312	
F	1/5	1/3	1/3	1/3	1	0.062	0.314	5.089	
						Total ∑		26.067	
Maximum eigenvalue (λ max)								5.213	
CI = (λ max–n)/ (n–1) = (5.213–5)/(5–1) = 0.053									

3.4.7 Developing the Model

Based on the steps illustrated above, the model of selecting sustainable building materials was developed using the criteria identified in chapter 2. The model has the goal of helping architects/engineers select sustainable building materials. Figure 3-6 shows the developed model.

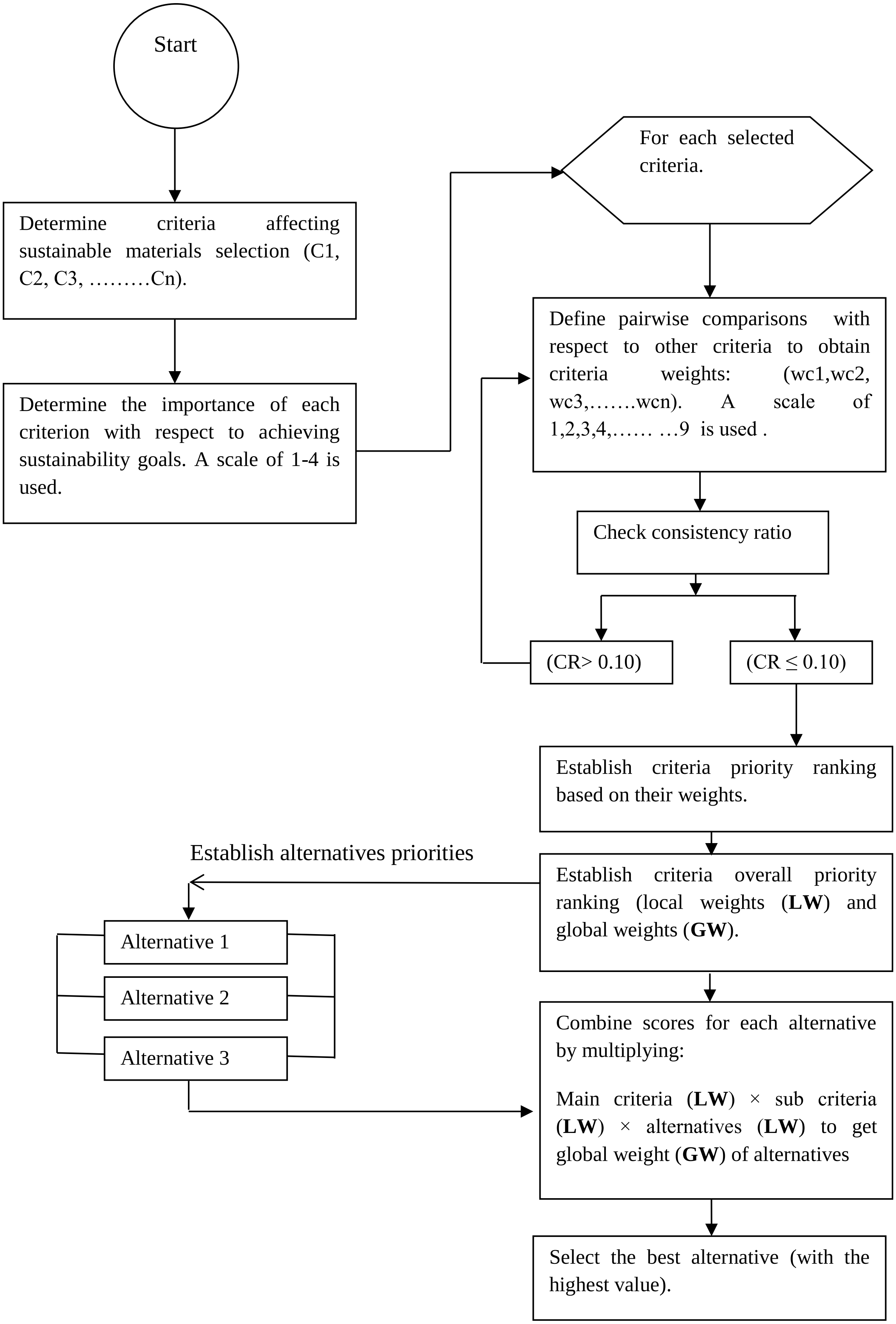


Figure 3-6 Sustainable Building Materials Selection Model

CHAPTER 4

DATA ANALYSIS AND RESULTS

4.1 Introduction

This chapter presents the results and analysis of the respondents' answers to the questionnaire survey and the comments they made. It also embraces a discussion of the obtained results.

4.2 Development of Questionnaire Survey

The main aim of conducting a questionnaire survey is to collect data from respondents. The survey was distributed to a representative sample of architects/engineers working in different private and public organizations in the Eastern Province. It consisted of five main parts, namely general information, sustainability awareness, development of sustainable building materials selection criteria, pairwise comparison of criteria affecting the selection of sustainable exterior wall building materials and pairwise comparison of exterior wall building materials alternatives.

4.3 Identification of Population and Sample Size

The population of this study is limited to the registered consulting offices in the Eastern Province of Saudi Arabia. A list of 145 offices was obtained from the Chamber of

Commerce of the Eastern Province. The sample sizes are calculated by the following equation as described in Chapter 3:

In Eastern province, sample size (n) = 25/ [1+ (25/145)] = 21

While the distributed surveys were about 69. The number of received surveys was 42 (61 % response rate) which is more than the sample size calculated above.

4.4 Distribution of the Tested Questionnaire Survey

This step involves distributing the tested questionnaire survey to architects/engineers who are working in the Eastern Province. The respondents were firstly asked to answer some general questions related to collect some basic factual data. Then, they were asked to indicate their level of sustainability awareness. Next, they were asked to specify their perceived relative importance of criteria affecting selecting sustainable building materials. Experts who are experienced in sustainable building practice and are LEED certified were asked to make pairwise comparisons between all sustainable materials main categories and respective criteria as well as building materials alternatives.

4.5 Data Analysis

The area of this section was grouped under the following headings

- Part one: general information.
- Part two: sustainability awareness.
- Part three: development of sustainable building materials selection criteria.

- Part four: pairwise comparison of criteria affecting the selection of sustainable exterior wall building materials.

- Part five: pairwise comparison of exterior wall building materials alternatives.

4.5.1 General Information

This part aims to collect basic factual data about the respondents who answered the survey. It started by asking them about their position in their organization, years of experience they have and general information about the nature and size of their organizations. The data received was analyzed using statistical techniques, including percentages, numerical terms and simple graphs.

Respondents' Positions in Their Organizations

The respondents were asked to specify their role in their organizations by choosing one of the three main categories: “engineer/architect”, “manager”, “supervisor”, or any other position they are holding. As illustrated in Figure 4-1, the results indicated that the majority of respondents 66 % (28 architects/engineers out of a total of 42) are either practicing as architects or engineers. It was also noticed that 23% (10 respondents out of a total of 42) are practicing as project managers, and 9 % (4 respondents out of a total of 42) are practicing as supervisors.

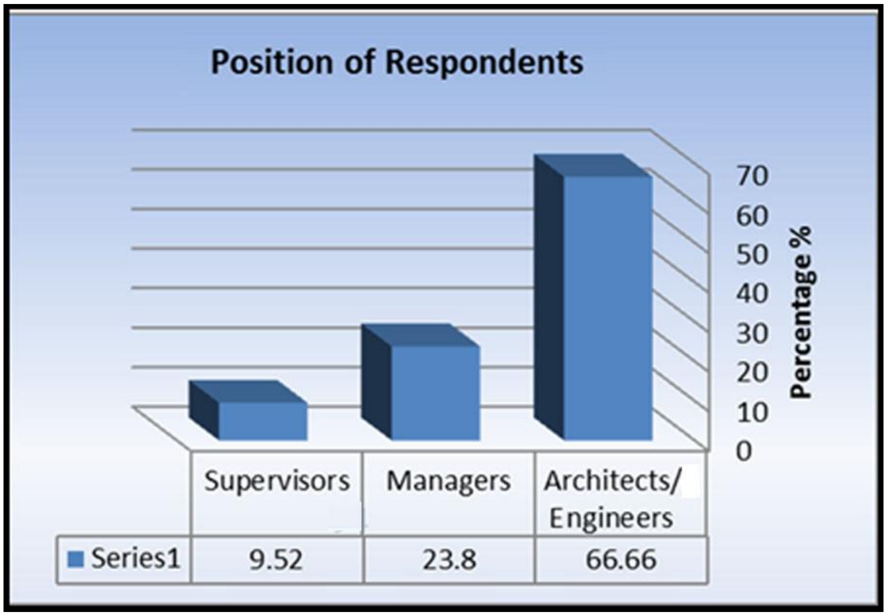


Figure 4-1 Respondent's Positions in Their Organizations

Respondents' years of Experience

The study considers the respondents' years of experience. The years of experience were classified into four main categories: "1-5 years", "6-10 years", "11-15 years" and "more than 15 years". The results showed that 21 % of the respondents (9 architects/engineers out of a total of 42) had been practicing for more than 15 years, 30 % (13 architects/engineers out of a total of 42) have experience ranging between 11-15 years, 21 % (9 architects/engineers out of a total of 42) have an experience ranging between 6 - 10 years, while 26 % (11 architects/engineers out of a total of 42) have at least 5 years or less as shown in Figure 4-2.

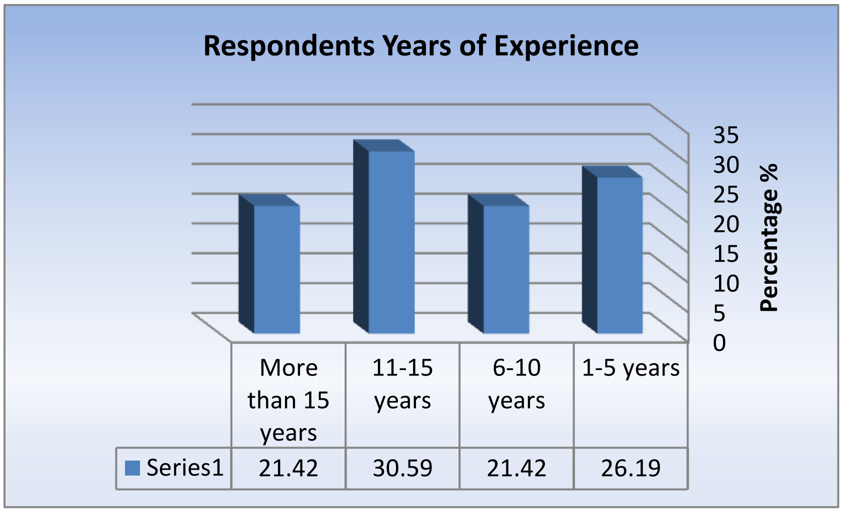


Figure 4-2 Respondents Years of Experience

The Nature of Respondents' Organizations

The respondents were asked to specify the nature of their organizations whether they are private or governmental. The results showed that 66 % of the respondents (28 architects/engineers out of a total of 42) worked in the private sectors, while 33 % (14 architects/engineers out of a total of 42) worked in governmental organizations as shown in Figure 4-3. Therefore most of the data obtained from the questionnaire survey were collected from architects/engineers working in private sectors.

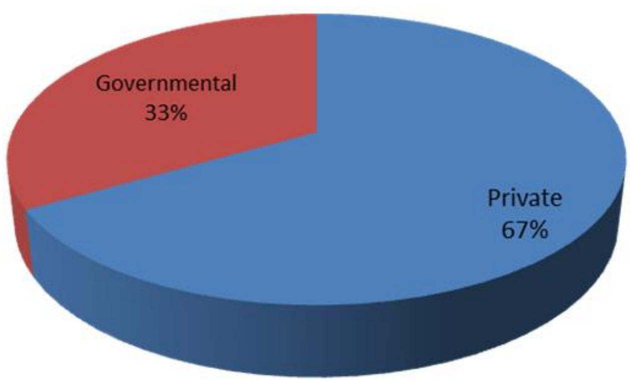


Figure 4-3 Respondents Organization's Nature

Types of Projects Carried out by Organizations

To clarify this question to the respondents, three categories of building types were classified, namely commercial, residential, institutional and industrial.

As shown in Figure 4-4, the results indicated that 61 % of the respondents (26 architects/engineers out of a total of 42) worked in commercial and residential projects, 16 % (7 architects/engineers out of a total of 42) worked in institutional projects, while 21 % of the respondents (9 architects/engineers out of a total of 42) worked in industrial projects.

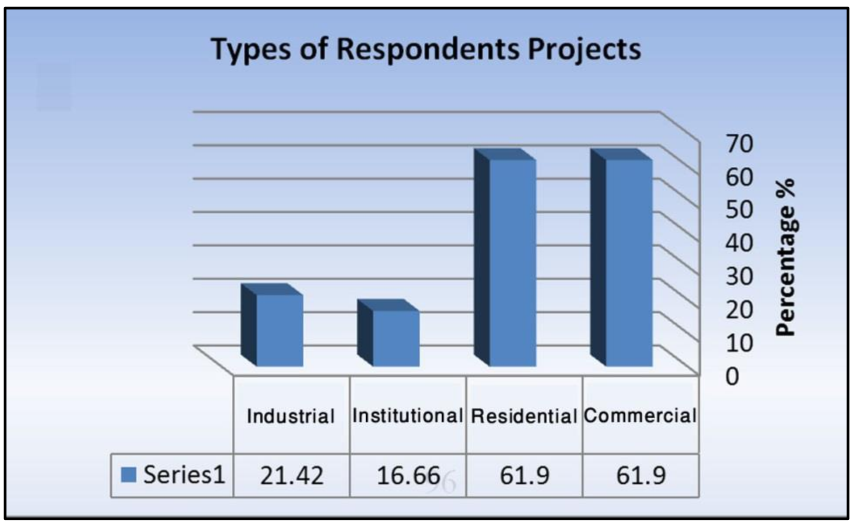


Figure 4-4 Respondents Organization's Projects

Size of Organizations

To determine the size of organizations, the respondents were asked to indicate the number of employees in their organizations. The results showed that the 69% of the respondents (26 architects/engineers out of a total of 42) worked in small size organizations while 31 % worked in large organizations that have more than 300 employees.

4.5.2 Sustainability Awareness

The main aim of the second part of the survey is to gain insight into the current practice of selecting building materials in Saudi design/consultant offices. To perform this task, a series of interviews was conducted with a representative sample of architects/engineers in the Eastern Province of Saudi Arabia. The majority of the respondents agreed that the selection of sustainable materials is very important to minimize the consumption of raw materials and provide a better environmental, social and economic life. In addition, they claimed that the heavy consumption of natural resources contributes significantly in increasing negative impacts on the environment. They also claimed that the “cost” and “availability” criteria are mostly used criteria when selecting materials and the “owner” has the absolute responsibility in selecting building materials. So, they stressed that owners' sustainability awareness must be increased so that they can pay more attention to the selection of sustainable materials in building projects.

To explore the awareness of respondents, they were firstly asked to indicate their level of awareness of sustainability issues in selecting building materials by choosing one of the following levels of awareness: extremely aware, moderately aware, slightly aware and not at all aware. The results suggest that 66 % of the respondents (28 architects/engineers out of a total of 42) were moderately aware of sustainability issues in selecting building materials, 16% were strongly aware, 9 % were slightly aware and 7 % were not aware at all as shown in Table 4-1. According to similar studies done by Crawley (1999) and Ding (2008) it was observed that considering sustainability issues during earlier design stages is very important to design more sustainable building projects. Also, Elhag (2001) indicated that this also contribute significantly in decreasing the overall cost of buildings.

Table 4.1 Levels of Sustainability Awareness

Extremely aware	Moderately aware	Slightly aware	Not at all aware
Percentage %	Percentage %	Percentage %	Percentage %
16.66	66.66	9.52	7.14

To investigate how the respondents had heard about the term sustainable development, the respondents were asked to indicate how they had heard about the term "sustainability". The results showed that 40 % of the respondents (17 architects/engineers out of a total of 42) had heard about it by reading journals and magazines, 9 % by reading building materials brochures, 26 % by surfing the Internet, 14 % through the media or by studying at universities, while 5 % of the respondents had not heard about the term "sustainability" as shown in Table 4-2.

Table 4.2 The Way by Which Respondents Heard About the Term "Sustainability"

Journals and Magazines	Brochures	Internet	Other	Never heard about sustainability
Percentage %	Percentage %	Percentage %	Percentage %	Percentage %
40.74	9.52	26.19	14.28	5.52

Respondents were then asked to indicate the source from which they collect information when selecting building materials as shown in Table 4-3. According to the data obtained, it is found that 66 % of respondents (28 architects/engineers out of a total of 42) select building materials based on the information they have found in brochures. This is in line with a similar study conducted by Tas (2008) where respondents ranked "brochures" second as a source of information for selecting building materials. However, it is very clear that the big problem is that information is not updated in brochures when new building materials are brought onto the market. The study also showed that 21 % of respondents select building materials depending on gaining knowledge from websites, and only 17 % select building materials based on meeting LEED requirements. Despite the fact that 66 % of respondents indicated that they were moderately aware of sustainability principles, it was surprising that only 17 % were guided by meeting LEED building materials requirements when selecting building materials.

Table 4.3 The Source of Collected Information Used in the

Manufacturing brochures	Internet	LEED rating system
Percentage %	Percentage %	Percentage %
66.66	21.66	16.66

Respondents were also asked to indicate the criteria according to which they make decisions when selecting building materials as shown in Table 4-4. The survey responses showed that the majority of respondents 76 % (32 architects/engineers out of a total of 42) select building materials based on their clients' wishes. This is in line with a study conducted by Gann and Salter (2002) and Akadiri (2011) which observed that clients' highest degree of involvement in selecting building materials was because they are responsible for the cost of buildings and the improvement of buildings performance. The results also showed that 11 % of respondents select building materials based on their own decision, 11 % based on the contractors' decision and 4 % based on meeting building codes. Some respondents indicated that they consult other companies when selecting building materials.

Table 4.4 Decision Making When Selecting Building Materials

Based on clients desire	Based on contractors decision	Based on meeting building codes	Based on your own decision
Percentage %	Percentage %	Percentage %	Percentage %
76.19	7.14	4.76	11.90

An interesting observation is that the survey responses showed that only three respondents have been involved in selecting building materials in building projects. Two of these experts have been practicing for less than three years, while the third one has between 3-5 years of experience. The percentages of sustainable projects for all of them were less than 30 % of all their building projects and all of them were using LEED rating system in selecting building materials. Another interesting observation is that only one respondent has been practicing in a LEED certified building.

Sustainability Consideration Issues

To investigate to what extent architects and engineers are practicing sustainability issues in selecting sustainable building materials, respondents were asked to score their level of agreement or disagreement where ‘1= strongly disagree’ to ‘4 = strongly agree’ as shown in Table 4-5. As illustrated in Chapter 3 the agreement index was calculated as follows:

$$\text{Agreement Index (AI)} = \frac{4 \times (n1) + 3 \times (n2) + 2 \times (n3) + 1 \times (n4)}{4(n1 + n2 + n3 + n4)} \times \%$$

The agreement index was classified as follows to reflect the respondents' answers:

The agreement index of (0 - < 25 %) is classified as ‘‘Strongly disagree’’; (25 - < 50 %) is classified as ‘‘Disagree’’; (50 - < 75 %) is classified as ‘‘Agree’’; and (75 - 100 %) is classified as ‘‘Strongly agree’’ as shown in Table 4-5.

Table 4.5 Mean Value and Importance Index Ranges

Scale description	Mean range	Agreement index (%)
Strongly disagree	0.00 – 0.99	II < 25
Disagree	1.00 – 1.99	25.00 ≤ II < 50.00
Agree	2.00 – 2.99	50.00 ≤ II < 75.00
Strongly agree	3.00 – 4.00	75.00 ≤ II ≤ 100

Table 4-6 shows the respondents' degree of agreements or disagreements of different sustainability issues

Table 4.6 Sustainability Assessment Consideration

Statement	Strongly agree 4	Agree 3	Disagree 2	Strongly disagree 1	Agreement Index	Mean Value
	Percent %	Percent %	Percent %	Percent %		
Selecting sustainable building materials is very important to construct more efficient buildings	59.52	40.47	0.00	0.00	89.88	3.59
Some building materials have negative impacts to the environment and human health	69.04	28.57	19.04	7.14	77.97	3.11
Buildings contractors and owners should be aware of the importance of selecting building materials	69.04	30.59	0.00	0.00	97.02	3.88
Building materials initial cost is more preferred to life cycle costs.	69.04	30.59	16.66	16.66	71.42	2.85
Sustainable building materials criteria should be incorporated in building codes?	69.04	21.42	30.59	26.19	59.52	2.38

The results showed that the biggest concern in implementing sustainability in the selection process is to increase the contractor's and client's awareness of the importance of selecting sustainable building materials, with agreement index (AI) of 97 %. This was followed by the importance of selecting sustainable building materials (AI= 89 %); the confirmation of the negative impacts of some building materials to the environment (AI 77 %) and the preference of the initial cost to the life cycle cost (AI =71 %). The incorporation of selecting sustainable building materials in the local building codes was rated last with an agreement index of (59 %). One possible reason for that is that respondents believe that implementing sustainable building materials will cost them more than ordinary building materials. However, in a study done by Boyle (2000), some respondents indicated that implementing sustainability in building projects will not substantially increase the cost.

Barriers against Selecting Sustainable Building Materials

The findings revealed that the current practice of sustainability in building projects in the Eastern Province is facing lots of problems. Such problems are summarized below in Table 4-7. Respondents were asked to score their level of agreement or disagreement where ‘1= strongly disagree’ to ‘5 = strongly agree’ to identify obstacles against selecting sustainable materials in building projects.

Table 4.7 Barriers of Selecting Sustainable Building Materials

Barriers	Strongly agree 4	Agree 3	Disagree 2	Strongly disagree 1	Agreement Index %	Mean Value
	Percent %	Percent %	Percent %	Percent %		
Lack of Information of sustainable materials specification	69.04	26.19	4.76	0.00	91.07	3.64
Financial cost	73.80	19.04	7.14	0.00	91.66	3.66
The clients do not care about selecting and demanding sustainable building materials	80.59	14.28	4.76	0.00	94.04	3.76
Unawareness of the requirements of selecting sustainable building materials	64.28	19.04	9.52	7.14	85.11	3.40
No governed or municipal code requires selecting sustainable building materials	59.52	26.19	14.28	0.00	86.30	3.45
Culture (accustomed to use materials)	19.04	19.04	40.47	21.42	58.92	2.35
Construction techniques are limited	19.04	21.42	45.23	14.28	61.30	2.45
It is difficult to use unconventional materials	45.23	35.71	19.04	0.00	81.54	3.26

Lack of Information of sustainable materials specification

The findings indicated that the lack of available information that describes the properties and specifications of sustainable building materials constitutes a major obstacle against selecting sustainable building materials. Most of the designers and engineers do not know what types of sustainable building materials are available in the market and what the technical properties of these materials are. In addition, the lack of experienced people in this field is also a major obstacle. Some respondents suggested that government should provide funding for training and educational activities to allow the public to gain more knowledge about the specifications of sustainable building materials.

Financial cost

The financial cost was rated second of all the barriers with an agreement index of 91 %. Most building projects have certain budgets that lead most designers and engineers to attempt to decrease the initial costs of building materials. According to Akadiri (2011), the biggest concern of respondents was the cost of building materials. This is also in line with a study done by Demkin (2008) which observed that controlling buildings budgets is a major concern for all building team members including owners, clients and designers. That. Also, authors such as Kunzlick (2003) and Ofori (2004) indicated that ‘‘cost’’ constitutes a major barrier against selecting sustainable building materials. This barrier can be overcome if designers take into consideration that selecting sustainable building materials will decrease operation costs and save huge amounts of energy.

The clients do not care about selecting and demanding sustainable building materials

This was rated first by the respondents with an agreement index of 94%. This barrier can be overcome if the government provides a special market for sustainable building materials, so that clients will appreciate the huge difference between sustainable and non-sustainable building materials and their big important energy saving role and their role in providing better environmental, social and healthy life.

Unawareness of the requirements of selecting sustainable building materials

About 85 % of the respondents claimed that the unawareness of sustainable building materials requirements including installation and implementation constitutes a major concern. Edward (2008) indicated that the lack of experiencing sustainability issues is the main reason for the incorrect implementation of sustainability in the construction of buildings.

No governed or municipal code requires selecting sustainable building materials

The local building code does not include the specification of sustainable materials. 86 % of the respondents claimed that this constitutes a major barrier against selecting sustainable building materials. In addition, some respondents indicated that sustainable building materials criteria shouldn't be included in the specification of sustainable materials because they believe that this will increase building costs. Authors such as Cabugueira (2004) indicated that incorporating sustainability in building regulation will encourage people to selecting sustainable building materials. However, Miozzo (2002) claimed that it will stop innovation in constructing buildings because people will implement similar building materials.

Culture

58 % of respondents claimed that the reason they did not select sustainable building materials was because they were not accustomed to using them locally.

Construction techniques are limited

39 % of respondents claimed that the local construction techniques were powerful and did not constitute a big obstacle against constructing sustainable building materials.

It is difficult to use unconventional materials

81 % of respondents indicated that implementing unconventional materials constitutes a big obstacle against selecting sustainable building materials.

Respondents were also asked to add any other obstacles that were not mentioned. The following barriers were added as follows:

- Lack of incentives to apply sustainable building materials.
- Lack of people experienced in selecting sustainable building materials.

4.5.3 Development of Sustainable Building Materials Selection Criteria

The second objective of this study is to develop a comprehensive list of sustainable building materials criteria considering all environmental, economic and social sustainability principles to help architects/ engineers select more sustainable materials in building projects.

In light of the variation in classifying and defining sustainable building materials shown in Chapter 2 and considering all sustainability fundamentals comprising environmental, economic and social aspects, it is proposed to classify sustainable building materials criteria into four main categories, namely environmental, technological, resource use and socioeconomic categories, as further elaborated in Chapter 2.

The purpose of the third part of the questionnaire survey is to explore the respondents' opinion about the relative importance of all sustainable building materials criteria and any other criteria needed to be added. To clarify the meaning of these criteria to the respondents, a brief definition of each criterion was written. The respondents were asked to choose the most appropriate answer that describes the relative importance of criteria affecting selecting sustainable building materials as follows:

- Extremely important (4)
- Very important (3)

- Not important (2)

- Extremely not important (1)

Calculation of the Importance Index

As illustrated in Chapter 3, the importance index and mean value have been calculated using Excel Software based on the following equation:

$$\text{Importance index (II)} = \frac{4 \times (n1) + 3 \times (n2) + 2 \times (n3) + 1 \times (n4)}{4(n1+n2+n3+n4)} \times \%$$

The importance index was classified as follows to reflect the respondents' answers:

The importance index of (0 - < 25 %) is classified as ‘‘Extremely not important’’; (25 - < 50 %) is classified as ‘‘Not Important’’; (50 - < 75 %) is classified as ‘‘Very important’’; and (75 - 100 %) is classified as ‘‘Extremely important’’ as shown in Table 4-8.

Table 4.8 Mean Value and Importance Index Ranges

Scale description	Mean range	Importance index (%)
Extremely not important	0.00 – 0.99	II < 25
Not important	1.00 – 1.99	25.00 ≤ II < 50.00
Very important	2.00 – 2.99	50.00 ≤ II < 75.00
Extremely important	3.00 – 4.00	75.00 ≤ II ≤ 100

The above ranges are used to measure each variable using a range from 1 to 100. A summary of the assessed criteria's mean values importance indexes, category ranking and overall ranking is shown below in Table 4.9.

Table 4.9 Mean Values and Importance Indexes of the Assessed Criteria

Criteria		Mean Value	Importance Index(II) %	Ordinal Scale	Category Ranking	Overall Ranking
Environmental Category			**76.58**			
1	Pollution prevention	3.45	86.30	Extremely Important	1	3
2	Water conservation	3.35	83.92	Extremely Important	2	7
3	Use of non-toxic or less-toxic materials	3.04	76.19	Extremely Important	5	16
4	Less ozone-depleting substances	2.97	74.40	Very Important	6	18
5	Healthfully maintained	2.905	72.61	Very Important	7	19
6	No radioactive	2.71	67.85	Very Important	8	23
7	Methods of extraction of raw materials	2.54	63.69	Very Important	9	26
8	Fire resistance	3.23	80.95	Extremely Important	4	12
9	Low-VOC assembly	3.33	83.33	Extremely Important	3	8
Technological Category			**78.58**			
1	Durability	3.69	92.26	Extremely Important	1	1
2	Biodegradability	2.76	69.04	Very Important	4	22
3	Service life	3.26	81.54	Extremely Important	3	11
4	Moisture resistance	3.42	85.71	Extremely	2	4

				Important		
5	Flexibility	2.61	65.74	Very Important	5	24
Resource Use Category			**81.61**			
1	Recyclability	3.42	85.71	Extremely Important	3	<u>4</u>
2	Embodied energy consumption	3.33	83.33	Extremely Important	5	<u>8</u>
3	Energy efficiency	3.61	90.47	Extremely Important	2	2
4	Use of natural resources	2.88	72.02	Very Important	7	20
5	Using certified wood	2.61	65.47	Very Important	8	25
6	Locally produced	3.69	92.26	Extremely Important	1	1
7	Renewable resources	3.19	79.76	Very Important	6	13
8	Reusability	3.35	83.92	Very Important	4	6
Socio-Economic Category			**79.29**			
1	Minimum life cycle costs	3.33	83.33	Extremely Important	3	<u>8</u>
2	Improve indoor air quality	3.19	79.76	Extremely Important	6	14
3	Less labor costs	2.47	61.90	Very Important	10	27
4	Affordability	3.30	82.73	Extremely Important	4	8
5	Less disposal costs	3.14	78.57	Extremely	7	15

				Important		
6	Construction waste management	3.28	82.59	Extremely Important	5	10
7	Thermal comfort	3.02	75.59	Extremely Important	8	16
8	Acoustic comfort	2.80	70.23	Very Important	9	21
9	Enhance occupants productivity	3.38	84.52	Extremely Important	2	5
10	Less construction time	3.33	83.33	Extremely Important	3	<u>8</u>
11	Low maintenance costs	3.42	85.71	Extremely Important	1	<u>4</u>
12	Aesthetic options	3.33	83.33	Extremely Important	3	<u>8</u>

4.6 Discussion of Results

As mentioned in Chapter 2, criteria affecting selecting sustainable building materials were classified into four main groups, namely environmental, technological, resource use and socio-economic criteria. Under each main category, there are many sub criteria. As shown in Table 4-9 no other criterion was added by the respondents. Below is a discussion of environmental, technological, resource use and socio economic categories.

4.6.1 Environmental Category

This category includes nine criteria, namely pollution prevention, water conservation, use of non-toxic or less toxic materials, less ozone-depleting substances, healthfully maintained, no radioactive, methods of extraction of raw materials, fire resistance and low-VOC assembly. According to Table (4.8), "pollution prevention" was rated to have the first priority in the environmental category with an II value of 86.30. Among the whole eight environmental criteria, it is noticed that all the criteria were rated as extremely important except the following three criteria, namely less ozone-depleting substances, healthfully maintained, no radioactive and methods of extraction of raw materials which were recorded as having very important levels with an II of 74.40, 72,61, 67,85 and 63.69 respectively. However, the environmental category, which has an average importance index of (II = 76.58) was considered to have the last priority compared to the other categories. This basically emphasizes that environmental issues are not strongly recommended by designers and engineers when selecting building materials.

4.6.2 Technological Category

This category includes five criteria, namely durability, biodegradability, service life, moisture resistance and flexibility. Among all these criteria, three were highlighted as having “extremely important” levels. These criteria are durability, service life and moisture resistance with an II of (II = 92.26, 81.54 and 85.71) respectively. “Durability” was ranked as first priority in the technological criteria and also it was considered as the highest among all sustainable building materials criteria. However, the technological category which has an average importance index of (II =78.58) was considered to be rated as third when compared with the other categories.

4.6.3 Resource Use Category

This category embraces eight criteria, namely recyclability, embodied energy consumption, energy efficiency, and use of natural resources, using certified wood, locally produced, renewable resources and reusability. “Locally produced” was rated as first in the resource use category with an importance index of (II = 92.62) and also it was considered to have the highest importance index out of all the sustainable building materials criteria. It is also observed that all resource use category criteria were rated as “extremely important" except the use of natural resources and using certified wood with an importance index of (II = 72.02 and 65.47) respectively. However, the resource use category which has an average importance index of (II = 81.61) was considered to have the highest priority of all categories.

4.6.4 Socio-Economic Category

This category embraces twelve criteria, namely minimum life cycle costs, improvement of indoor air quality, fewer labor costs, affordability, less disposal costs, construction waste management, thermal comfort, acoustic comfort, enhancement of occupants' productivity, less construction time, low maintenance costs and aesthetic options. “Low maintenance costs” was rated as first in the socioeconomic category with an importance index of (II = 85.71) and also it was highlighted as having the fourth priority among the whole sustainable building materials criteria. This is good evidence that maintenance costs are a major concern among designers when selecting building materials. Of all the twelve socio economic criteria, it is observed that only three criteria are rated as “very important”, namely fewer labor costs and acoustic comfort with an importance index of (II=61.90 and 70.23) respectively. It is also observed that “less labor costs” was rated to as having the lowest priority among all sustainable building materials criteria. Some engineers claimed that obtaining low salaried labor would inversely affect the quality of the installation of building materials. The results also indicated that the socio economic category which has an average importance index of (II = 79.29) was considered to have the second priority among all categories.

According to the results obtained from Table 4-89, it is noticed that none of the 34 criteria fall under the “very important” level. This greatly emphasizes the importance of the derived criteria in selecting sustainable building materials.

Discussion

This Chapter has presented the results revealed from the distributed questionnaire survey. It investigated the current practice and sustainability awareness of the designers/architects and highlighted the main obstacles that face them when selecting sustainable building materials. The questionnaire survey was distributed to a representative sample of architects/engineers working in different firms in the Eastern Province of Saudi Arabia. The data collected from the questionnaire survey were analyzed by using various statistical techniques such as importance indexes and frequencies.

According to the results analysis, it is found that there is a big gap and incongruity between what architects/engineers believe and their actual practice of sustainability principles. For example, when they were asked to identify their level of sustainability awareness, 66 % of respondents indicated that they were moderately aware. However only 16 % of respondents claimed that they select building materials based on LEED rating system and the majority of them depend only on manufacturing brochures when selecting building materials.

The results also revealed that only three respondents have been involved in selecting building materials in building projects. Two of these experts have been practicing for less than three years, while the third one has between 3-5 years of experience.

In terms of the obstacles that face architects/engineers when selecting sustainable materials, respondents showed that the most serious obstacle is that clients do not ask to select and implement sustainable building materials in their own buildings. “Financial cost” also constitutes a big barrier against selecting sustainable building materials

The results also confirmed the clients' full responsibility and involvement in selecting building materials. It was also clear from the study that “cost” and “availability” are the mostly used criteria by clients in the selection process. A similar study conducted by Akadiri (20011) observed that cost, project duration and environmental issues are the criteria most used in the selection of building materials. There is therefore an urgent need to implement the developed holistic list of sustainable building materials criteria.

The next Chapter presents a case study showing the implementation of the developed Analytic Hierarchy Model in the evaluation and selection of various building materials alternatives.

CHAPTER 5

IMPLEMENTATION OF THE DEVELOPED ANALYTIC HIERARCHY PROCESS MODEL

5.1 Introduction

To implement the developed model, a case study will be conducted to solve the problem of exterior wall building material selection using Analytic Hierarchy Process (AHP). The proposed case study intended to select the most sustainable exterior wall building materials that will be most satisfactory in the construction of buildings in the Eastern Province of Saudi Arabia considering all criteria identified in Chapter 2. The two proposed exterior wall building materials alternatives were: concrete block and clay brick. In this chapter, the AHP model will be used to analyze data obtained from three sustainable buildings experts -with two LEED AP- who were asked to make pairwise comparisons between all main and sub criteria as well as exterior wall building materials alternatives. The fourth and fifth part of the questionnaire survey (shown in Appendix I) were designed to collect data using the preference ranges proposed by Saaty (2008 b). The questionnaire intended to analyze the respondents' pairwise comparison judgments for sustainable building materials criteria and exterior wall building materials alternatives. The consistency level was then evaluated and data were analyzed using Expert Choice Software.

5.2 Pairwise Comparison of Main Categories

The three sustainable buildings experts- with two LEED AP- were asked to fill the pair-wise comparison matrix and compare the four main criteria in relation to the main goal (selecting the most sustainable exterior wall building material) using a scale of 1-9. Then, Expert Choice Software was used to analyze the responses of each respondent and to assess the consistency ratio (CR). The judgements of the three experts were combined. According to Saaty (2008 b), the consistency ratio (CR) is acceptable if it is equal or less than 0.1 ($CR \leq 0.10$).

Table 5-1 shows pairwise comparisons for all main criteria. As shown, it is clearly observed that environmental criteria are 3 times more important than socio economic criteria. This also means that socio economic criteria are 3 times less important than environmental criteria. It is also observed that the weight of comparing any criteria to itself always equal 1.

The overall ranking of the four main criteria categories affecting selecting sustainable exterior wall building materials is shown in Figure 5.1. As shown, data are presented in a bar graph showing the greatest and least priority of main categories. It is observed that environmental criteria had the highest priority among all environmental criteria with a weight of 0.477, followed by socio economic criteria with a weight of 0.195, then resource use criteria that had a weight of 0.171 and lastly technological criteria with a weight of 0.158. In addition, it can also be noticed from Figure 5-.1 that the judgments of comparison matrix are consistent because consistency ratio is less than 0.10 ($CR = 0.009 < 0.10$).

Table 5.1 Pairwise Matrix for Main Categories

Scale Points	Environmental Category	Technological Category	Resource Use Category	Socio-Economic Category
Environmental Criteria	1	2.57	2.46	3.00
Technological Criteria		1	1	1.44
Resource Use Criteria			1	1.18
Socio-Economic Criteria				1
Underlined values indicate the preference of the compared criteria at the head of the matrix.				

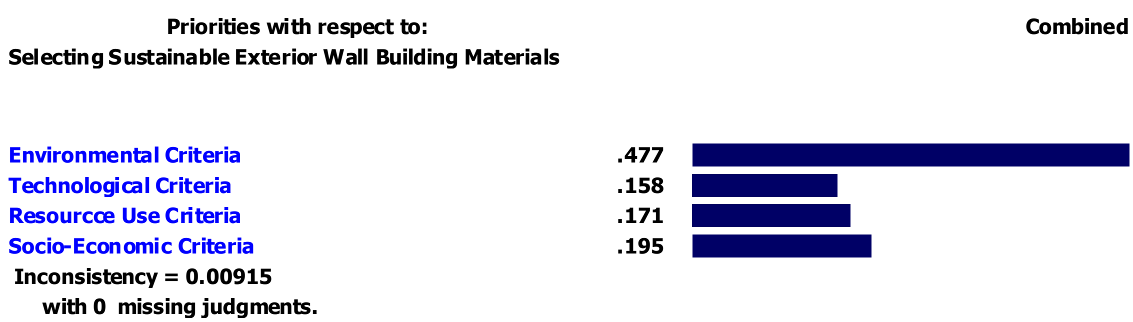


Figure 5-1 Overall Ranking with Respect to Main Categories

5.3 Pair-wise Comparisons of Environmental Category

Table 5-2 shows pairwise comparisons for all environmental criteria. The relative importance of each criterion was compared with respect to each other using Expert Choice Software. The overall ranking of environmental criteria is shown in Figure 5-2. It presents the priorities of all environmental criteria with respect to the main goal (selecting the most sustainable exterior wall building material). The obtained data are presented in a bar graph showing the greatest and lowest priority of environmental criteria. It is also clearly observed that "use of non-toxic or less toxic materials" criteria had the highest priority among all environmental criteria with a weight of 0.201. It appears that the reproductive toxicants that pose more unhealthy risks to occupants and which are emitted from some building materials are considered as one of the most negative impacts that must be taken into consideration when selecting building materials. This is followed by "pollution prevention" that had a weight of 0.158. This also emphasizes the importance of reducing or eliminating the use of hazardous substances and the contaminants released to the atmosphere. The third priority was given to the "water conservation" criterion that had a weight of 0.153. It is also noticed that the lowest priority was given to the methods of extraction of raw materials criteria with a weight of 0.047. Figure 5-2 also shows that the judgements of comparison matrix of environmental criteria are consistent because consistency ratio is less than 0.10 ($CR = 0.06 < 0.10$).

Table 5.2 Pairwise Matrix for Environmental Category

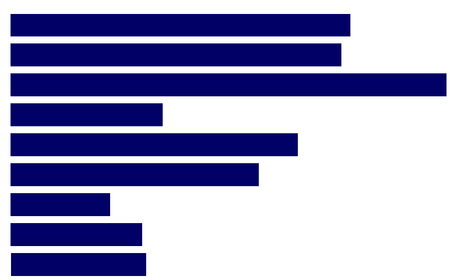
	Pollution conservation	Water conservation	Use of non-toxic or less-toxic materials	Less ozone-depleting	Healthfully maintained	No radioactive	Methods of extraction of raw materials	Fire resistance	Low-VOC assembly
1.Pollution prevention	1	1.70	1.44	1.21	2.02	2.02	2.26	2.08	2.46
2.Water conservation		1	2.26	1.70	1.08	1.11	5.27	5.12	3.55
3.Use of non-toxic or less-toxic materials			1	1.91	2.75	2.08	4.21	2.46	1.44
4.Less ozone-depleting				1	1.70	2.26	1.44	1.28	1.44
5.Healthfully maintained					1	2.08	4.71	2.46	1.81
6.No radioactive						1	3.55	1.44	3.55
7.Methods of extraction of raw materials							1		1.44
8.Fire resistance								1	1.18
9.Low-VOC assembly									1

Underlined values indicate the preference of the compared criteria at the head of the matrix.

Priorities with respect to: **Combined**

Selecting Sustainable Exterior Wall Building Materials
>Environmental Criteria

Pollution prevention	.158	
Water conservation	.153	
Use of non-toxic or less-toxic materials	.201	
Less ozone-depleting substances	.070	
Healthfully maintained	.133	
No radioactive	.116	
Methods of extraction of raw materials	.047	
Fire resistance	.061	
Low-VOC assembly	.062	



Inconsistency = 0.06
with 0 missing judgments.

Figure 5-2 Overall Ranking with Respect to Environmental Category

5.4 Pairwise Comparison of Technological Category

Pairwise comparisons for technological criteria are shown in Table 5-3. All technological criteria were compared with each other with respect to the main goal. Figure 5-3 presents the overall ranking of technological criteria. As shown, "durability" had the highest priority among all technological criteria with a weight of 0.316. This indicated that selecting more durable materials is very important to extend a building's useful life and decrease operation costs. Then, service life had the second priority with a weight of 0.30. This emphasizes that selecting building materials with a longer life expectancy is very important to save costs of installation and labor as well as to produce less landfill waste. The third priority was given to the "moisture resistance" criterion. Figure 5-3 also shows the consistency of the judgments of comparison matrix of technological criteria (CR = 0.04 < 0.10).

Table 5.3 Pairwise Matrix for Technological Category

	Durability	Biodegradability	Longer Life	Moisture resistant	Flexibility
1. Durability	1	2.46	1.00	2.26	3.27
2. Biodegradability		1	<u>2.92</u>	<u>1.44</u>	<u>1.44</u>
3. Longer Life			1	2-92	1.44
4. Moisture resistant				1	2.08
5. Flexibility					1
Underlined values indicate the preference of the compared criteria at the head of the matrix.					

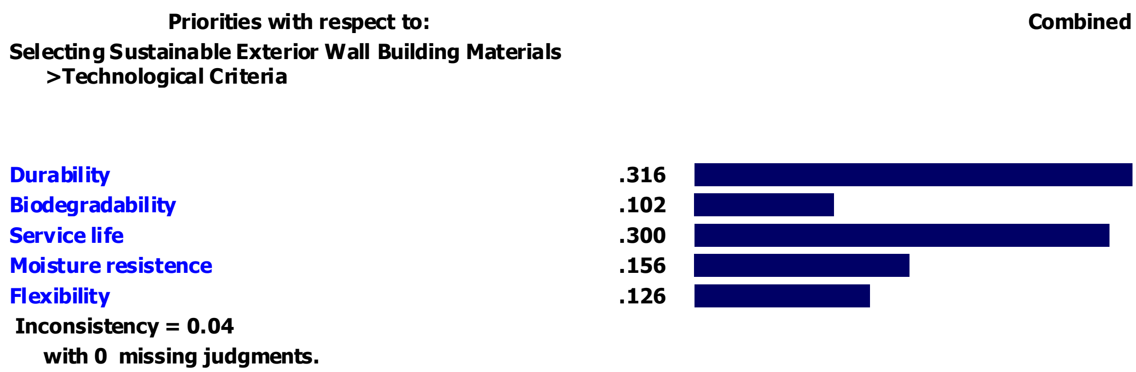


Figure 5-3 Overall Ranking with Respect to Technological Criteria

5.5 Pairwise Comparison of Resource Use Category

Table 5-4 shows pair wise comparisons for all resource use criteria. The relative importance and preference of each criterion were compared with respect to each other using Expert Choice Software. The overall ranking of resource use criteria is shown in Figure 5-4. The highest and lowest priorities of all resource use criteria are presented in a bar graph. As shown, it is clearly observed that "locally produced" and "energy efficiency" criteria had the highest priority among all resource use criteria with a weight of 0.212. This was reflected by the results of interviews conducted with selected samples of designers and engineers who indicated that the availability of materials is the most used criterion when selecting building materials. This is followed by the "renewable resources" criterion that had a weight of 0.118. The third priority was given to the "embodied energy consumption" criterion that had a weight of 0.108. It is also observed that "using certified wood" had the lowest priority among all resource use criteria with a weight of 0.045. Figure 5-4 also shows that that the judgments of the comparison matrix of resource use criteria are consistent because the consistency ratio is less than 0.10 (CR = 0.04 < 0.10).

Table 5.4 Pairwise Matrix for Resource Use Category

	Recyclability	Embodied energy consumption	Energy efficiency	Use of natural resources	Using certified wood	Locally produced	Renewable contents	. Reusability
1. Recyclability	1	1.21	1.44	1.18	2.75	2.08	1.00	1.00
2. Embodied energy consumption		1	1.44	1.06	3.00	1.44	2.46	1.00
3. Energy efficiency			1	2.46	3.97	1.44	2.46	2.46
4. Use of natural resources				1	1.70	2.08	1.44	1.44
5. Using certified wood					1	4.71	1.44	3.97
6. Locally produced						1	3.00	2.75
7. Renewable contents							1	2.08
8. Reusability								1

Underlined values indicate the preference of the compared criteria at the head of the matrix.

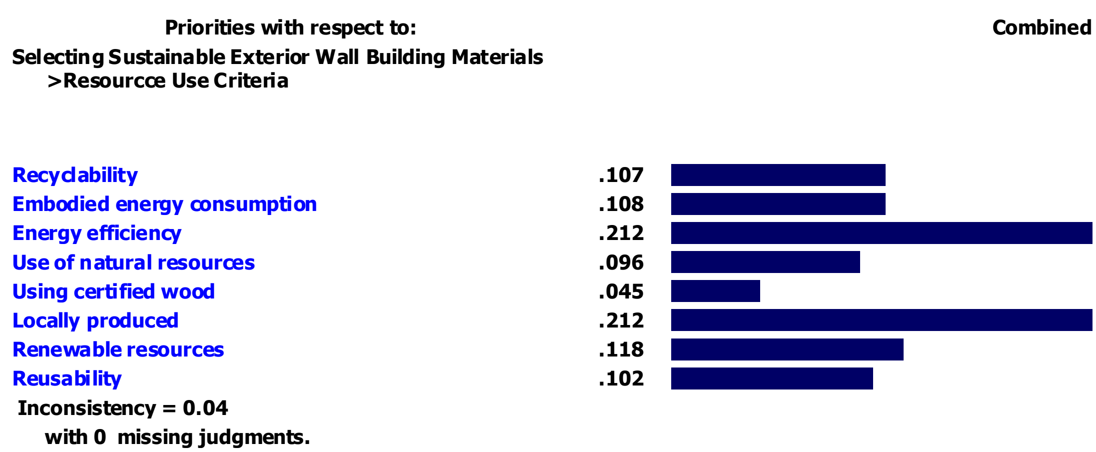


Figure 5-4 Overall Ranking with Respect to Technological Criteria

5.6 Pairwise Comparison of Socio economic Category

Pairwise comparisons for socio economic criteria are shown in Table 5-5. All resource use criteria were compared with each other with respect to the main goal. Figure 5-5 presents the overall ranking of resource use criteria. As shown, “improve indoor air quality” criterion had the highest priority among all socio economic criteria with a weight of 0.162. This indicated the importance of improving the indoor air quality to minimize the negative impacts on the health of the buildings' occupants. This was closely followed by “enhance occupant's productivity” which had a weight of 0.158. This emphasized that providing suitable workplaces that increase the level of occupant's performance is one of the main goals of selecting sustainable building materials. This was followed by “thermal comfort” which had a weight of 0.138. The third priority was given to the “thermal comfort” criterion. It is also noticed that the lowest priority was given to the “less disposal costs” criterion with a weight of 0.033. Figure 5-5 also shows the consistency ratio of the comparison matrix of socio economic criteria (CR = 0.04 < 0.10).

Table 5.5 Pairwise Matrix for Socio economic Category

	Minimum life cycle costs	Improve indoor air quality	Less labor costs	Affordability	Less disposal costs	Construction waste management	Thermal comfort	Acoustic comfort	Enhance occupants productivity	Less construction time	Low maintenance costs	Aesthetic options
1. Minimum life cycle costs	1	2.48	1.14	1.24	2.41	1.70	1.91	1.56	2.08	1.67	1.40	1.18
2.Improve indoor air quality		1	3.00	3.55	3.55	3.55	1.44	1.70	1.32	3.55	3.55	2.46
3. Less labor costs			1	1.44	1.44	2.46	3.55	1.21	1.21	1.44	2.08	1.44
4. Affordability				1	1.44	2.46	1.08	1.08	3.55	1.44	2.08	1.44
5. Less disposal costs					1	1.91	3.97	3.97	5.12	2.46	1.91	1.18
6. Construction waste management						1	3.55	1.21	4.32	1.00	1.00	1.70
7.Thermal comfort							1	1.44	1.00	1.44	2.08	2.75
8. Acoustic comfort								1	1.00	1.44	2.08	3.00
9.Enhance occupants productivity									1	3.55	3.55	4.32
10. Less construction time										1	1.00	1.18
11. Low maintenance costs											1	1.32
12. Aesthetic options												1
Underlined values indicate the preference of the compared criteria at the head of the matrix.												

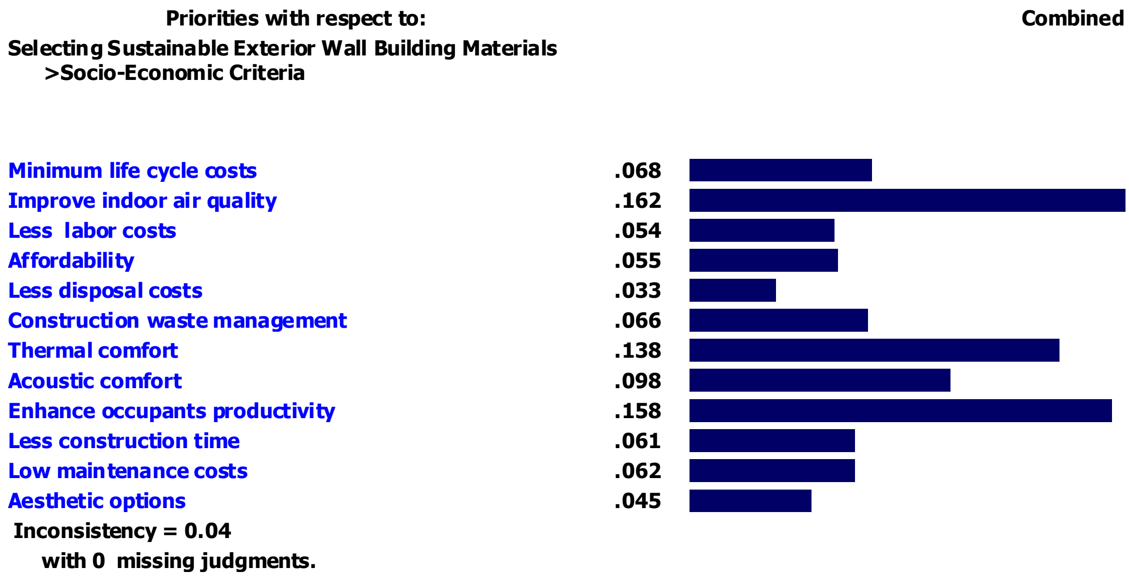


Figure 5-5 Overall Ranking with Respect to Socio economic Category

5.7 Final Weights of Main Categories and Respective Criteria

Table 5-6 shows local and global weights of all categories and sub criteria.

Table 5.6 Priority Weights of Main Categories and respective criteria

Main Category	Local weight	Sub Criteria	Local weight	Global weight
Environmental Category	0.477	Pollution prevention	0.158	0.075
		Water conservation	0.153	0.073
		Use of non-toxic or less-toxic materials	0.201	0.096
		Less ozone-depleting substances	0.70	0.033
		Healthfully maintained	0.133	0.063
		No radioactive	0.115	0.055
		Methods of extraction of raw materials	0.047	0.022
		Fire resistance	0.61	0.029
		Low-VOC assembly	0.62	0.029
Technological Category	0.158	Durability	0.316	0.050
		Biodegradability	0.102	0.016
		Service life	0.300	0.047
		Moisture resistance	0.156	0.025
		Flexibility	0.126	0.020
Resource Use Category	0.171	Recyclability	0.107	0.018
		Embodied energy consumption	0.108	0.018
		Energy efficiency	0.212	0.036
		Use of natural resources	0.096	0.016
		Using certified wood	0.045	0.008
		Locally produced	0.212	0.036
		Renewable resources	0.118	0.020
		Reusability	0.102	0.017
Socio Economic Category	0.195	Minimum life cycle costs	0.068	0.013
		Improve indoor air quality	0.162	0.032
		Less labor costs	0.054	0.010
		Affordability	0.055	0.011
		Less disposal costs	0.033	0.006
		Construction waste management	0.066	0.013
		Thermal comfort	0.138	0.027
		Acoustic comfort	0.098	0.019
		Enhance occupants productivity	0.158	0.031
		Less construction time	0.061	0.012
		Low maintenance costs	0.062	0.012
		Aesthetic options	0.045	0.009

Figure 5-6 below shows sustainable building materials local and global weights.

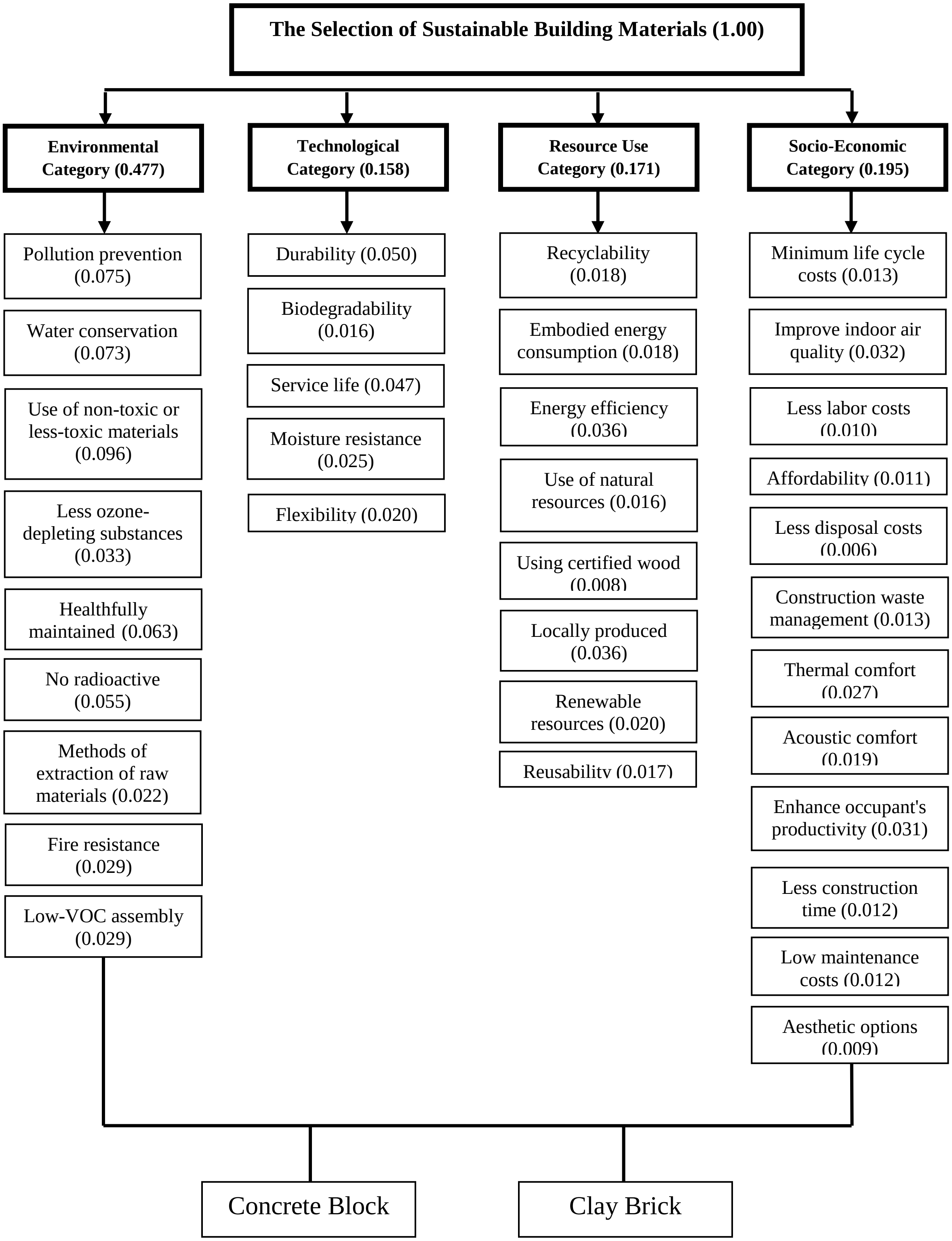


Figure 5-6 Sustainable Building Materials Local and Global Weights

5.8 Pairwise Comparison of Exterior Wall Building Materials Alternatives

After defining the problem and performing pairwise comparisons, the respondents were required to make pairwise comparisons between sustainable building materials alternatives considering all criteria identified in Chapter 2.

5.8.1 Pairwise Comparisons of Alternatives with Respect to Environmental Sub criteria

Figure 5-7 shows the priority index that had been calculated by summing all the values of all environmental criteria. As shown, it is observed that clay brick had the highest priority of 0.656 with only 0.344 for concrete block. One possible reason for this result is that concrete has many negative environmental impacts. 1.6 billion tons of cement is used annually worldwide to produce concrete. Every ton needs 1.5 tons of fossil fuel energy. Also, large amounts of carbon dioxide (CO2) are released during Portland cement production causing negative environmental impacts. In addition, the natural gas which is used as a primary fuel source to produce clay brick has less environmental impact than coal which is considered as the primary fuel source for producing concrete. Tables (5-7)-(5-15) show pairwise comparisons of alternatives with respect to environmental criteria.

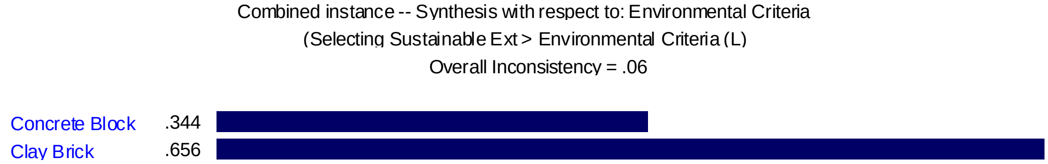


Figure 5-7 Overall Priorities of Alternatives with Respect to Environmental Category

Table 5.7 Pairwise Comparisons of Alternatives with Respect to Pollution Prevention

SDC#1	Pollution prevention	
	Concrete block	Clay brick
Concrete block	1	0.33
Clay brick	3	1
CR = 0.00		

Table 5.8 Pairwise Comparisons of Alternatives with Respect to Water Conservation

SDC#1	Water conservation	
	Concrete block	Clay brick
Concrete block	1	0.20
Clay brick	5	1
CR = 0.00		

Table 5.9 Pairwise Comparisons of Alternatives with Respect to Use of Non-toxic or Less-toxic Materials

SDC#1	Use of non-toxic or less-toxic materials	
	Concrete block	Clay brick
Concrete block	1	0.33
Clay brick	3	1
CR = 0.00		

Table 5.10 Pairwise Comparisons of Alternatives with Respect to Less Ozone-depleting

SDC#1	Less ozone-depleting	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

Table 5.11 Pairwise Comparisons of Alternatives with Respect to Healthfully Maintained

SDC#1	Healthfully maintained	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

Table 5.12 Pairwise Comparisons of Alternatives with Respect to No Radioactive

SDC#1	No radioactive	
	Concrete block	Clay brick
Concrete block	1	0.20
Clay brick	5	1
CR = 0.00		

Table 5.13 Pairwise Comparisons of Alternatives with Respect to Methods of extraction of raw materials

SDC#1	Methods of extraction of raw materials	
	Concrete block	Clay brick
Concrete block	1	0.20
Clay brick	5	1
CR = 0.00		

Table 5.14 Pairwise Comparisons of Alternatives with Respect to Fire Resistance

SDC#1	Fire resistance	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

Table 5.15 Pairwise Comparisons of Alternatives with Respect to Low-VOC Assembly

SDC#1	Low-VOC assembly	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

5.8.2 Pairwise Comparisons of Alternatives with Respect to Technological Sub criteria

Figure 5-8 shows the priority index obtained by summing all the values of technological criteria. As shown, concrete block had the highest weight of 0.598, while clay brick had a weight of 0.402. An explanation for this is that concrete is a durable material, locally available and has high strength and good resistance to weathering. Tables (5-16)-(5-20) show pairwise comparisons of alternatives with respect to all technological criteria.

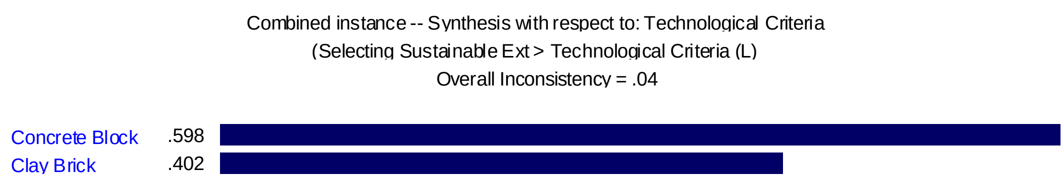


Figure 5-8 Overall Priorities of Alternatives with Respect to Technological Category

Table 5.16 Pairwise Comparisons of Alternatives with Respect to Durability

SDC#1	Durability	
	Concrete block	Clay brick
Concrete block	1	3
Clay brick	0.33	1
CR = 0.00		

Table 5.17 Pairwise Comparisons of Alternatives with Respect to Biodegradability

SDC#1	Biodegradability	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

Table 5.18 Pairwise Comparisons of Alternatives with Respect to Service Life

SDC#1	Service Life	
	Concrete block	Clay brick
Concrete block	1	3
Clay brick	0.33	1
CR = 0.00		

Table 5.19 Pairwise Comparisons of Alternatives with Respect to Moisture resistance

SDC#1	Moisture resistance	
	Concrete block	Clay brick
Concrete block	1	5
Clay brick	0.20	1
CR = 0.00		

Table 5.20 Pairwise Comparisons of Alternatives with Respect to Flexibility

SDC#1	Flexibility	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

5.8.3 Pairwise Comparisons of Alternatives with Respect to Resource Use Sub criteria

Figure 5-9 shows priorities of importance of resource use criteria which were obtained by adding all values of the sub criteria. As shown, concrete block had a weight of 0.690 and clay brick had a weight of 0.310. Tables (5-21)-(5-28) show pairwise comparisons of alternatives with respect to resource use criteria.

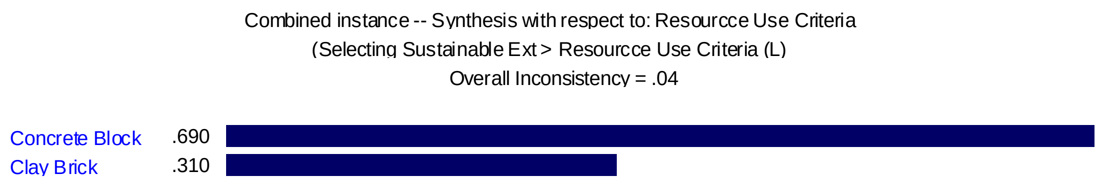


Figure 5-9 Overall Priorities of Alternatives with Respect to Resource Use Category

Table 5.21 Pairwise Comparisons of Alternatives with Respect to Recyclability

SDC#1	Recyclability	
	Concrete block	Clay brick
Concrete block	1	5
Clay brick	0.20	1
CR = 0.00		

Table 5.22 Pairwise Comparisons of Alternatives with Respect to Embodied Energy Consumption

SDC#1	Embodied energy consumption	
	Concrete block	Clay brick
Concrete block	1	3
Clay brick	0.33	1
CR = 0.00		

Table 5.23 Pairwise Comparisons of Alternatives with Respect to Energy Efficiency

SDC#1	Energy efficiency	
	Concrete block	Clay brick
Concrete block	1	5
Clay brick	0.20	1
CR = 0.00		

Table 5.24 Pairwise Comparisons of Alternatives with Respect to Use of Natural Resources

SDC#1	Use of natural resources	
	Concrete block	Clay brick
Concrete block	1	5
Clay brick	0.20	1
CR = 0.00		

Table 5.25 Pairwise Comparisons of Alternatives with Respect to Using Certified Wood

SDC#1	Using certified wood	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

Table 5.26 Pairwise Comparisons of Alternatives with Respect to Locally Produced

SDC#1	Locally produced	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

Table 5.27 Pairwise Comparisons of Alternatives with Respect to Renewable Contents

SDC#1	Renewable contents	
	Concrete block	Clay brick
Concrete block	1	3
Clay brick	0.33	1
CR = 0.00		

Table 5.28 Pairwise Comparisons of Alternatives with Respect to Reusability

SDC#1	Reusability	
	Concrete block	Clay brick
Concrete block	1	5
Clay brick	0.20	1
CR = 0.00		

5.8.4 Pairwise Comparisons of Alternatives with Respect to Socio economic Sub criteria

Figure 5-10 shows priorities of overall alternatives with respect to socio economic criteria. As shown, concrete block had a weight of 0.547 and clay brick had a weight of 0.453. Tables (5-29)-(5-40) show pairwise comparisons of alternatives with respect to socio economic criteria.

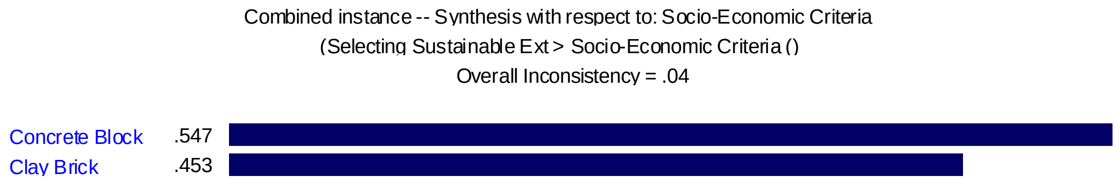


Figure 5-10 Overall Priorities of Alternatives with Respect to Socio economic Category

Table 5.29 Pairwise Comparisons of Alternatives with Respect to Minimum life cycle costs

SDC#1	Minimum life cycle costs	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

Table 5.30 Pairwise Comparisons of Alternatives with Respect to Improve Indoor Air Quality

SDC#1	Improve indoor air quality	
	Concrete block	Clay brick
Concrete block	1	3
Clay brick	0.33	1
CR = 0.00		

Table 5.31 Pairwise Comparisons of Alternatives with Respect to Less Labor Costs

SDC#1	Less labor costs	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

Table 5.32 Pairwise Comparisons of Alternatives with Respect to Affordability

SDC#1	Affordability	
	Concrete block	Clay brick
Concrete block	1	5
Clay brick	0.20	1
CR = 0.00		

Table 5.33 Pairwise Comparisons of Alternatives with Respect to Less Disposal Costs

SDC#1	Less disposal costs	
	Concrete block	Clay brick
Concrete block	1	3
Clay brick	0.33	1
CR = 0.00		

Table 5.34 Pairwise Comparisons of Alternatives with Respect to Construction Waste Management

SDC#1	Construction waste management	
	Concrete block	Clay brick
Concrete block	1	1
Clay brick	1	1
CR = 0.00		

Table 5.35 Pairwise Comparisons of Alternatives with Respect to Thermal Comfort

SDC#1	Thermal comfort	
	Concrete block	Clay brick
Concrete block	1	0.33
Clay brick	3	1
CR = 0.00		

Table 5.36 Pairwise Comparisons of Alternatives with Respect to Acoustic Comfort

SDC#1	Acoustic comfort	
	Concrete block	Clay brick
Concrete block	1	3
Clay brick	0.33	1
CR = 0.00		

Table 5.37 Pairwise Comparisons of Alternatives with Respect to Enhance Occupants Productivity

SDC#1	Enhance occupants productivity	
	Concrete block	Clay brick
Concrete block	1	5
Clay brick	0.20	1
CR = 0.00		

Table 5.38 Pairwise Comparisons of Alternatives with Respect to Less Construction Time

SDC#1	Less construction time	
	Concrete block	Clay brick
Concrete block	1	0.14
Clay brick	7	1
CR = 0.00		

Table 5.39 pairwise Comparisons of Alternatives with Respect to Maintenance Costs

SDC#1	Maintenance costs	
	Concrete block	Clay brick
Concrete block	1	0.7
Clay brick	0.14	1
CR = 0.00		

Table 5.40 pairwise Comparisons of Alternatives with Respect to Aesthetic Options

SDC#1	Aesthetic options	
	Concrete block	Clay brick
Concrete block	1	0.20
Clay brick	5	1
CR = 0.00		

5.9 Sustainable Building Materials Alternatives Overall Rating Using AHP

The overall priorities of sustainable building materials alternatives are shown in Table 5-41.

Table 5.41 Alternatives Overall Rating Using AHP

Main Categories	Local Weight	Sub criteria	Local Weight	Alternatives Local Weight		Alternatives Global Weight	
				Concrete Block(LW)	Clay Brick (LW)	Concrete Block (GW)	Clay Brick (GW)
Environmental	0.477	Pollution prevention	0.158	0.25	0.75	0.0188	0.0565
		Water conservation	0.153	0.167	0.833	0.0121	0.0607
		Use of non-toxic or less-toxic materials	0.201	0.25	0.75	0.0239	0.0719
		Less ozone-depleting substances	0.70	0.5	0.5	0.1669	0.1669
		Healthfully maintained	0.133	0.5	0.5	0.0317	0.0317
		No radioactive	0.115	0.25	0.75	0.0137	0.0411
		Methods of extraction of raw materials	0.047	0.167	0.833	0.0037	0.0186
		Fire resistance	0.61	0.5	0.5	0.1454	0.1454
		Low-VOC assembly	0.62	0.5	0.5	0.1478	0.1478
Technological	0.158	Durability	0.316	0.75	0.25	0.0374	0.0124
		Biodegradability	0.102	0.5	0.5	0.0080	0.0080
		Service life	0.3	0.75	0.25	0.0355	0.0118
		Moisture resistance	0.156	0.167	0.833	0.0041	0.0205
		Flexibility	0.126	0.5	0.5	0.0099	0.0099

Resource use	0.171	Recyclability	0.107	0.833	0.167	0.0152	0.0030
		Embodied energy consumption	0.108	0.75	0.25	0.0138	0.0046
		Energy efficiency	0.212	0.833	0.167	0.0301	0.0060
		Use of natural resources	0.096	0.833	0.167	0.0136	0.0027
		Using certified wood	0.045	0.5	0.5	0.0030	0.0038
		Locally produced	0.212	0.5	0.5	0.0181	0.0181
		Renewable resources	0.118	0.75	0.25	0.0151	0.0050
		Reusability	0.102	0.75	0.25	0.0130	0.0043
Socioeconomic	0.195	Minimum life cycle costs	0.068	0.5	0.5	0.0066	0.0066
		Improve indoor air quality	0.162	0.75	0.25	0.0236	0.0078
		Less labor costs	0.054	0.5	0.5	0.0052	0.0052
		Affordability	0.055	0.833	0.167	0.0089	0.0017
		Less disposal costs	0.033	0.75	0.25	0.0048	0.0016
		Construction waste management	0.066	0.5	0.5	0.0064	0.0064
		Thermal comfort	0.138	0.25	0.75	0.0067	0.0201
		Acoustic comfort	0.098	0.75	0.25	0.0143	0.0047
		Enhance occupants productivity	0.158	0.833	0.167	0.0256	0.0051
		Less construction time	0.061	0.125	0.875	0.0014	0.0104
		Low maintenance costs	0.062	0.125	0.875	0.0015	0.0105
		Aesthetic options	0.045	0.167	0.833	0.0014	0.0073
Total	**1.00**					**0.479**	**0.521**
		Alternatives Overall Priority				**2**	**1**

5.10 Sensitivity Analysis

After obtaining priorities of sustainable building materials alternatives, the next step is to perform a sensitivity analysis. Expert Choice Software provides four types of sensitivity analysis, namely dynamic, gradient, head to head and performance sensitivity analysis. Figures 5-11 and 5-12 show performance and head to head sensitivity analysis of main categories respectively.

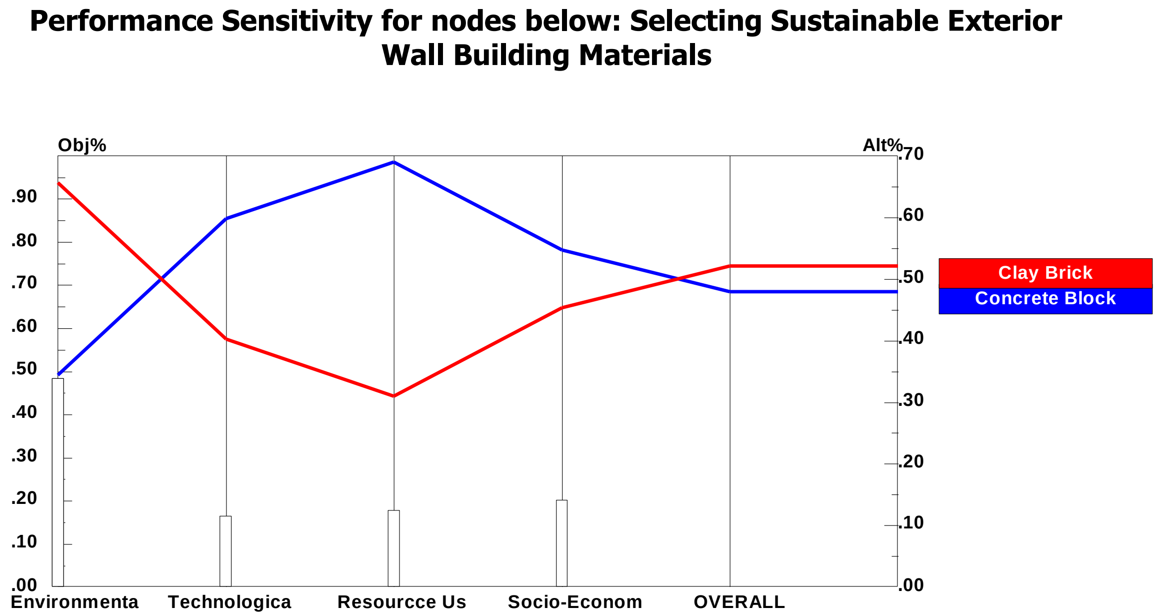


Figure 5-11 Performance Sensitivity for the Selection of Sustainable Building Materials

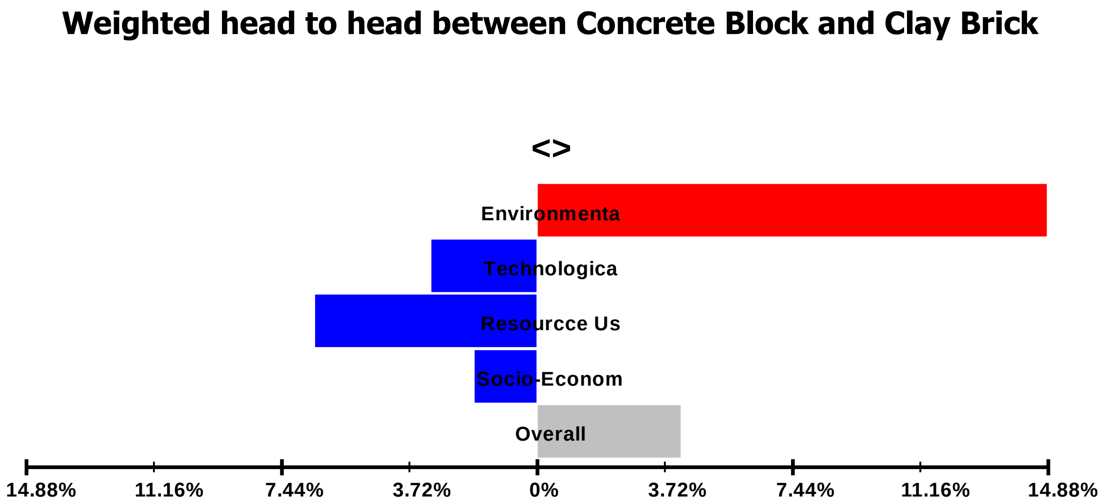


Figure 5-12 Head to Head Sensitivity for the Selection of Sustainable Building Materials

Figure 5-13 shows AHP model of selecting sustainable building materials with alternatives priority. It shows that clay brick had the highest accumulated weight of 0.521 with 0.479 for concrete block.

- Selecting Sustainable Exterior Wall Building Materials
  - Environmental Criteria (L: .477 G: .477)
    - Pollution prevention (L: .158 G: .075)
    - Water conservation (L: .153 G: .073)
    - Use of non-toxic or less-toxic materials (L: .201 G: .096)
    - Less ozone-depleting substances (L: .070 G: .033)
    - Healthfully maintained (L: .133 G: .063)
    - No radioactive (L: .116 G: .055)
    - Methods of extraction of raw materials (L: .047 G: .022)
    - Fire resistance (L: .061 G: .029)
    - Low-VOC assembly (L: .062 G: .029)
  - Technological Criteria (L: .158 G: .158)
    - Durability (L: .316 G: .050)
    - Biodegradability (L: .102 G: .016)
    - Service life (L: .300 G: .047)
    - Moisture resistence (L: .156 G: .025)
    - Flexibility (L: .126 G: .020)
  - Resourcce Use Criteria (L: .171 G: .171)
    - Recyclability (L: .107 G: .018)
    - Embodied energy consumption (L: .108 G: .018)
    - Energy efficiency (L: .212 G: .036)
    - Use of natural resources (L: .096 G: .016)
    - Using certified wood (L: .045 G: .008)
    - Locally produced (L: .212 G: .036)
    - Renewable resources (L: .118 G: .020)
    - Reusability (L: .102 G: .017)
  - Socio-Economic Criteria (L: .195 G: .195)
    - Minimum life cycle costs (L: .068 G: .013)
    - Improve indoor air quality (L: .162 G: .032)
    - Less labor costs (L: .054 G: .010)
    - Affordability (L: .055 G: .011)
    - Less disposal costs (L: .033 G: .006)
    - Construction waste management (L: .066 G: .013)
    - Thermal comfort (L: .138 G: .027)
    - Acoustic comfort (L: .098 G: .019)
    - Enhance occupants productivity (L: .158 G: .031)
    - Less construction time (L: .061 G: .012)
    - Low maintenance costs (L: .062 G: .012)
    - Aesthetic options (L: .045 G: .009)

Alternatives

Concrete Block	.479
Clay Brick	.521

Figure 5-13 Hierarchy Model with Overall Alternatives Priorities

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter contains a summary of the study. It contains the findings obtained from the literature review, and the investigations of sustainability awareness in Saudi design/consulting offices. A summary of the research will be discussed followed by conclusions and recommendations. The conclusion provides links between the research and the derived findings. The recommendations provide proposals for future elaboration in the field of the study.

6.2 Summary of the Study

The main objectives of this research were to survey criteria affecting the evaluation and selection of sustainable building materials, and to investigate the practices of Saudi design/consulting offices in selecting sustainable building materials and to develop a model, using available decision making techniques to help architects /engineers select sustainable exterior wall building materials in hot humid climate (Saudi Arabia as a case study).

The methodology consists of three main stages. **First**, the research focused on acquiring a large body of knowledge about criteria affecting the selection of sustainable building materials. Several interviews were conducted with experienced people to establish the relative importance of these criteria and to allow participants to add any other criteria. This stage resulted in identifying a holistic list of criteria affecting the selection of selecting sustainable building materials with their definition and measurement under four main categories.

Second, the current practice of Saudi design/consultant firms in the Eastern Province was investigated. This phase was carried out through developing and distributing questionnaire survey to representative samples of design firms to assess their sustainability awareness in selecting building materials and what were the barriers they normally face. This phase resulted in identifying the current local practice of Saudi design firms on how to select building materials and to identify the barriers they faced when selecting them.

Third, an analytic hierarchy process model was developed to help architects/engineers select sustainable building materials. The model was developed using the sustainable building materials criteria identified in Chapter 2. It was implemented by conducting a case study using two exterior wall building materials alternatives, namely concrete block and clay brick. A questionnaire survey was distributed to three experts to make pair wise comparisons between these alternatives. The responses of the questionnaire survey were analyzed using Expert Choice Software. The analysis resulted in determining the most sustainable exterior wall building materials from the two alternatives.

6.3 Conclusions

The following conclusion was drawn from summarizing the study:

1- Synthesizing and surveying the literature review in the field of selecting sustainable building materials resulted in identifying thirty four criteria classified under four main categories, namely environmental, technological, resource use and socio economic category.

2- A set of criteria was listed under each respective category synthesizing their respective terminologies, definitions and measurements.

3- A questionnaire survey was distributed to 69 designers/engineers in consultant offices in the Eastern Province of Saudi Arabia. The sample size was calculated to be 21 and the number of received survey was 42 with a response rate of 61 %.

4- The results revealed that all the surveyed sustainable building materials criteria were rated with an importance index of "very important" or above.

5- The "resource use" category was rated first among all categories followed by "socio economic" category with an importance index of 81.61% and 79.29% respectively.

6- The results showed that "locally produced" and "durability" criteria in the resource use and the technological categories respectively were rated as the highest priority with the same importance index of 92.26%.

7- The results of the study indicated that 66 % of the respondents were moderately aware of sustainability issues in selecting building materials, 16% were strongly aware, 9 % were slightly aware and 7 % were not aware at all.

8- It was also found that 40 % of the respondents had heard about it by reading journals and magazines, 9 % by reading building materials brochures, 26 % by surfing the Internet, 14 % through the media or by studying at universities, while 5 % of the respondents had not heard about the term “sustainability”.

9- The results revealed that 66 % of respondents select building materials based on the information they have found in brochures, 21 % of them select building materials depending on gaining knowledge from websites, and only 17 % select building materials based on meeting LEED requirements.

10- It was also found that 76 % of respondents select building materials based on their clients' wishes, 11 % of them select building materials based on their own decision, 11 % select building materials based on the contractors' decision and 4 % select building materials based on meeting building codes.

11- The results revealed that only three respondents out of 42 have been involved in selecting building materials in building projects. All of the three respondents were using LEED rating system in the selection of sustainable building materials.

12- The results showed that the most agreed sustainability consideration issue is to increase the contractors' and client's awareness of the importance of selecting sustainable building materials, with agreement index of 97%.

13- It was also found that the most agreed barrier facing designers and engineers is that clients do not care about selecting and demanding sustainable building materials with an importance index of 94 %.

14- The proposed model was developed based on the analytic hierarchy process (AHP) because it is flexible, easy to use, and has the ability to provide precise results.

15- The derived criteria were used when developing the AHP model.

16- The conducted case study emphasized the high priority of selecting clay brick which had an accumulated weight of 0.521 with 0.479 for concrete block.

6.4 Recommendations

The recommendation of this research can be summarized as follows:

- The identified criteria can be used to evaluate and select sustainable building materials not only in Saudi Arabia, but also outside Saudi Arabia.
- More awareness needed to be raised on the significance of selecting sustainable building materials. Also, government should provide academic programs and initiatives to encourage people to select sustainable building materials.
- The developed Analytic Hierarchy Process selection model will provide a significant help to designers/engineers in selecting sustainable building materials.

6.5 Directions for Future Research

Future research in the area of the study may consider the following

- The scope of this research was limited to design/consultant offices in the Eastern Province of Saudi Arabia. Further studies might include all private and public sectors in the Kingdom of Saudi Arabia.

- The research only considered the opinions of designers and engineers. Future studies may also take into considerations opinions of clients and owners to investigate the main criteria they use when selecting building materials.

- The developed model was implemented to select sustainable exterior wall building materials. Future studies may implement it to select other building materials such as roofing, waterproofing and finishing materials.

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APPENDIX I

Subject : A Study on developing A Model for Selecting Sustainable Exterior Wall Building Materials /Products in Hot Humid Climate**.**

Dear Respondent:

A study is being conducted on decision making for selecting sustainable building materials in hot humid climate. The purpose of this study is to identify criteria affecting evaluation and selection of sustainable building materials and develop a decision making model that helps architects/engineers selecting sustainable building materials in Saudi Arabia

The objective of this questionnaire is to seek your opinion about the criteria that is essential for the selection decision of sustainable building materials.

Your input is required to determine the importance of each criterion and if there are any other criteria needed to be added.

Saleh Mubarak Baharetha
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Part 1 : General Information:

1- Organization name (optional): ……………………………………………….

2- Department name (optional):………………………………………………..

3- Respondent name (optional): ……………………………………………….

4- **What is the position of the respondent in the organization**?

☐ Engineer/Architect ☐ Manager

☐ Supervisor ☐ Other (please specify) ……………………

5- How many years of experience do you have?

- ☐ 1-5 years
- ☐ 6-10 years
- ☐ 11-15 years
- ☐ More than 15 years

6- What is the nature of your organization?

- ☐ Private
- ☐ Governmental

7- What type of building project do your organization specialize in?

- ☐ Commercial
- ☐ Residential
- ☐ Institutional
- ☐ Other (please specify)…… …….
- ☐ Industrial

8- What is the number of employees in your organization?

- ☐ 1-100
- ☐ 101-200
- ☐ 201-300
- ☐ 301-400
- ☐ 401-500
- ☐ More than 500

<u>Part 2 : Sustainability awareness</u> :

9- Please indicate your level of awareness of sustainability issues in selecting building materials.

- ☐ Extremely aware
- ☐ Moderately aware
- ☐ Slightly aware
- ☐ Not at all aware

10- Kindly, indicate the way by which you heard about sustainability:

- ☐ Journals and Magazines
- ☐ Brochures
- ☐ Internet
- ☐ Other (please specify)……
- ☐ Never heard about sustainability

11- In your current practice, how do you collect information when selecting building materials?

- ☐ Manufacturing brochures
- ☐ Internet
- ☐ LEED rating system
- ☐ Other (specify)……………………

12- **From your daily practice, how do you make your decisions in selecting building materials?**

- ☐ Based on clients desire
- ☐ Based on contractors decision
- ☐ Based on meeting building codes
- ☐ Based on your own decision
- ☐ Other (please specify)……………………

13- **Have you been involved in selecting sustainable building materials in building projects?**

- ☐ Yes
- ☐ No

If yes, please continue answering the questions, if no please complete answering the questions from number (19) forward:

14- **How long have you been involved in selecting sustainable building materials:**

- ☐ Less than three years
- ☐ Between (3-5) years.
- ☐ More than 5 years

15- **What is the percentage of these projects you involved in from your all building projects?**

- ☐ Less than 30%
- ☐ Between (30 % - 50 %)
- ☐ More than 50 %.

16- **Which of the following sustainable buildings rating systems you are following when selecting sustainable building materials?**

- ☐ LEED
- ☐ BREEAM
- ☐ Greene Globes
- ☐ Other (please specify)…….

17- **Have you been contributed in selecting sustainable building materials for a building certified by LEED rating system?**

- ☐ Yes
- ☐ No

18- If yes, how many certified buildings you have been involved in?

- ☐ Less than 3
- ☐ Between (3-5)
- ☐ More than 5

19- Kindly, rate your level of agreement or disagreement in terms of the following issues?

Statement	Strongly agree 4	Agree 3	Disagree 2	Strongly disagree 1
Selecting sustainable building materials is very important to construct more efficient buildings				
Some building materials have negative impacts to the environment and human health				
Buildings contractors and owners should be aware of the importance of selecting building materials				
Building materials initial cost is more preferred to life cycle costs.				
Sustainable building materials criteria should be incorporated in building codes?				

20- What barriers prevent you from selecting sustainable materials in building projects?

Barriers	Extremely Important 4	Very Important 3	Not Important 2	Extremely Not Important 1
Lack of Information of sustainable materials specification?				
Financial cost				
The clients do not care about selecting and demanding sustainable building materials				
Unawareness of the requirements of selecting sustainable building materials				
No governed or municipal code requires selecting sustainable building materials				
Culture (accustomed to use materials)				
Construction techniques are limited				
It is difficult to use unconventional materials				
Others (please specify)…………..				
Others (please specify) …………..				
Others (please specify)…..………..				

Part 3 : Development of Sustainable Building Materials Selection Criteria

Kindly, rate the following criteria in terms of their importance in selecting sustainable building materials (use the scale 1 to 4 as the following):

Scale Points	Description
4	Extremely Important
3	Very Important
2	Not Important
1	Extremely not Important

Sustainable Building Materials Criteria	Sustainable Building Materials Criteria Evaluation Outcomes			
	Extremely Important 4	**Very Important 3**	**Not Important 2**	**Extremely Not Important 1**
Environmental Category				
1. Pollution prevention *(To check if the material is not a source of releasing contaminants itself or by its treatment after installation)*				
2. Water conservation *(reduce water consumption in buildings and conserve water in landscaped areas).*				
3. Use of non-toxic or less-toxic materials *(emit few reproductive toxicants)***.**				
4. Less ozone-depleting substances *(manufactured by using non-ozone depleting substances)***.**				
5. Healthfully maintained *(cleaned by using non-toxic or low-VOC methods)***.**				
6. No radioactive *(release less amount of radium).*				
7. Methods of extraction of raw materials				

Sustainable Building Materials Criteria	Extremely Important 4	Very Important 3	Not Important 2	Extremely Not Important 1
8. Fire resistance				
9. Low-VOC assembly: *(VOCs: Volatile Organic Compounds are emitted after installing materials causing many healthy risks to building occupants).*				
Others ………………………………				
Others ………………………………				
Others ………………………………				
Technological Category	**4**	**3**	**2**	**1**
1. Durability				
2. Biodegradability *(can be naturally returned to the earth with no waste generation damage).*				
3. Service life				
4. Moisture resistance				
5. Flexibility *(Can be used for different purposes).*				
Others (please specify)……………………………………………..				
Others (please specify)……………………………………………..				
Others (please specify)……………………………………………..				
Resource Use Category	**4**	**3**	**2**	**1**
1. Recyclability				
2. Embodied energy consumption (*energy consumed in materials extraction, processing and delivering)*				
3. Energy efficiency				
4. Use of natural resources				
5. Using certified wood *(it should be harvested in a sustainable way)*				
6. Locally produced				
7. Renewable resources				
8. Reusability *(can be reinstalled again in their original form).*				
Others (please specify)……………………………………………..				
Others (please specify)……………………………………………..				
Others (please specify)……………………………………………..				
Socio-Economic Category	**4**	**3**	**2**	**1**
1. Minimum life cycle costs				
2.Improve indoor air quality				

Sustainable Building Materials Criteria	Extremely Important 4	Very Important 3	Not Important 2	Extremely Not Important 1
3. Less labor costs				
4. Affordability *(within building budget).*				
5. Less disposal costs				
6. Construction waste management *(Recycle nonhazardous waste resulting from construction and demolition and reuse it in manufacturing process).*				
7.Thermal comfort				
8. Acoustic comfort				
9.Enhance occupants productivity				
10. Less construction time				
11. Low maintenance costs				
12. Aesthetic options				
Others (please specify)……………………………………………..				
Others (please specify)……………………………………………..				
Others (please specify)……………………………………………..				

Part 4 : Pairwise Comparison of Criteria Affecting Selecting Sustainable Exterior Wall Building Materials:

Kindly, rate on a scale of (1 to 9) the relative importance of each criterion.

Intensity of Importance	Definition
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred
2,4,6,8	Intermediate values between two adjacent judgments

Pairwise Comparison of Main Categories

Comparing (Environmental) category with respect to other main categories										
	9	7	5	3	1	3	5	7	9	
Environmental Category										Technological Category
										Resource Use Category
										Socio-Economic Category
Comparing (Technological) category with respect to other main categories										
Technological Category										Resource Use Category
										Socio-Economic Category
Comparing (Resource Use) category with respect to other main categories										
Resource Use Category										Socio-Economic Category

1- Comparing (Sub-Environmental) Criteria With Respect to Each Other

Comparing (pollution Prevention) criterion with respect to other environmental criteria										
	9	7	5	3	1	3	5	7	9	
Pollution prevention										Water conservation
										Use of non-toxic or less-toxic materials
										Less ozone-depleting
										Healthfully maintained
										No radioactive
										Methods of extraction of raw materials
										Fire resistance
										Low-VOC assembly
Comparing (Water conservation) criterion with respect to other environmental criteria										
Water conservation										Use of non-toxic or less-toxic materials
										Less ozone-depleting
										Healthfully maintained
										No radioactive
										Methods of extraction of raw materials
										Fire resistance
										Low-VOC assembly
Comparing (Use of non-toxic or less-toxic materials) criterion with respect to other environmental criteria										
	9	7	5	3	1	3	5	7	9	
Use of non-toxic or less-toxic materials										Less ozone-depleting
										Healthfully maintained
										No radioactive

	9	7	5	3	1	3	5	7	9	
Use of non-toxic or less-toxic materials										**Methods of extraction of raw materials**
										Fire resistance
										Low-VOC assembly
Comparing (Less ozone-depleting) criterion with respect to other environmental criteria										
Less ozone-depleting										**Healthfully maintained**
										No radioactive
										Methods of extraction of raw materials
										Fire resistance
										Low-VOC assembly
Comparing (Healthfully maintained) criterion with respect to other environmental criteria										
Healthfully maintained										**No radioactive**
										Methods of extraction of raw materials
										Fire resistance
										Low-VOC assembly
Comparing (No radioactive) criterion with respect to other environmental criteria										
	9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	
No radioactive										**Methods of extraction of raw materials**
										Fire resistance
										Low-VOC assembly
Comparing (Methods of extraction of raw materials) criterion with respect to other environmental criteria										
Methods of extraction of raw materials										**Fire resistance**

	9	7	5	3	1	3	5	7	9	
Methods of extraction of raw materials										**Low-VOC assembly**
Comparing (<u>Fire resistance</u>) criterion with respect to other environmental criteria										
Fire resistance										**Low-VOC assembly**

2- Comparing (Sub-technological) Criteria With Respect to Each Other

Comparing (<u>durability</u>) criterion with respect to other technological criteria										
	9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	
Durability										**Biodegradability**
										Service life
										Moisture resistance
										Flexibility
Comparing (<u>Biodegradability</u>) criterion with respect to other technological criteria										
Biodegradability										**Service life**
										Moisture resistance
										Flexibility
Comparing (<u>Service life</u>) criterion with respect to other technological criteria										
Service life										**Moisture resistance**
										Flexibility
Comparing (<u>Moisture resistant</u>) criterion with respect to other technological criteria										
Moisture resistant										**Flexibility**

3- Comparing (Sub-Resource Use) Criteria With Respect to each Other

Comparing (Recyclability) criterion with respect to other resource use criteria										
	9	7	5	3	1	3	5	7	9	
Recyclability										Embodied energy consumption
										Energy efficiency
										Use of natural resources
										Using certified wood
										Locally produced
										Renewable resources
										Reusability
Comparing (Embodied energy consumption) criterion with respect to other resource use criteria										
Embodied energy consumption										Energy efficiency
										Use of natural resources
										Using certified wood
										Locally produced
										Renewable resources
										Reusability
Comparing (Energy efficiency) criterion with respect to other resource use criteria										
	9	7	5	3	1	3	5	7	9	
Energy efficiency										Use of natural resources
										Using certified wood
Energy efficiency										Locally produced
										Renewable resources
										Reusability

Comparing (<u>Use of natural resources</u>) criterion with respect to other resource use criteria										
Use of natural resources										**Using certified wood**
										Locally produced
										Renewable resources
										Reusability
Comparing (<u>Using certified wood</u> criterion with respect to other resource use criteria										
Using certified wood										**Locally produced**
										Renewable resources
										Reusability
Comparing (<u>Locally produced</u>) criterion with respect to other resource use criteria										
Locally produced										**Renewable resources**
										Reusability
Comparing (<u>Renewable resources</u>) criterion with respect to other resource use criteria										
Renewable resources										**Reusability**

4- Comparing (Sub-Socio-Economic) Criteria With Respect to Each Other

Comparing (Minimum life cycle costs) criterion with respect to other socio-economic criteria										
	9	7	5	3	1	3	5	7	9	
Minimum life cycle costs										Improve indoor air quality
										Less labor costs
										Affordability
										Less disposal costs
										Construction waste management
										Thermal comfort
										Acoustic comfort
										Enhance occupants productivity
										Less construction time
										Low maintenance costs
										Aesthetic options
Comparing (Improve indoor air quality) criterion with respect to other socio economic criteria										
Improve indoor air quality										Less labor costs
										Affordability
										Less disposal costs
										Construction waste management
										Thermal comfort
	9	7	5	3	1	3	5	7	9	
Improve indoor air quality										Acoustic comfort
										Enhance occupants productivity
										Less construction time
										Low maintenance costs
										Aesthetic options

Comparing (Less labor costs) criterion with respect to other socio-economic criteria										
Less labor costs										**Affordability**
										Less disposal costs
										Construction waste management
										Thermal comfort
										Acoustic comfort
										Enhance occupants productivity
										Less construction time
										Low maintenance costs
										Aesthetic options
Comparing (Affordability) criterion with respect to other socio-economic criteria										
Affordability										**Less disposal costs**
										Construction waste management
										Thermal comfort
										Acoustic comfort
	9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	
										Enhance occupants productivity
Affordability										**Less construction time**
										Low maintenance costs
Comparing (Less disposal costs) criterion with respect to other socio-economic criteria										
Less disposal costs										**Construction waste management**
										Thermal comfort
										Acoustic comfort
										Enhance occupants productivity
										Less construction time
										Low maintenance costs
										Aesthetic options

Comparing (Construction waste management) criterion with respect to other socio-economic criteria										
Construction waste management										**Thermal comfort**
										Acoustic comfort
										Enhance occupants productivity
										Less construction time
										Low maintenance costs
										Aesthetic options
Comparing (Thermal comfort) criterion with respect to other socio-economic criteria										
	9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	
Thermal comfort										**Acoustic comfort**
										Enhance occupants productivity
										Less construction time
										Low maintenance costs
										Aesthetic option
Comparing (Acoustic comfort) criterion with respect to other socio-economic criteria										
Acoustic comfort										**Enhance occupants productivity**
										Less construction time
										Low maintenance costs
										Aesthetic option
Comparing (Enhance occupants productivity) criterion with respect to other socio-economic criteria										
Enhance occupants productivity										**Less construction time**
										Low maintenance costs
										Aesthetic option
Comparing (Less construction time) criterion with respect to other socio-economic criteria										

	9	7	5	3	1	3	5	7	9	
Less construction time										**Low maintenance costs**
										Aesthetic option
Low maintenance costs										**Aesthetic option**

Part 5 : Pairwise Comparison of Exterior Wall Building Materials Alternatives :

	Concrete Blocks	9	7	5	3	1	3	5	7	9	Clay Bricks
Environmental Category											
1.Pollution prevention											
2.Water conservation											
3.Use of non-toxic or less-toxic materials											
4.Less ozone-depleting											
5.Hazardous demolition											
6.No radioactive											
7.Methods of extraction of raw materials											
8.Fire resistance											
9.Low-VOC assembly											
Technological Category		9	7	5	3	1	3	5	7	9	
1. Durability											
2. Biodegradability											
3. Service life											
4. Moisture resistance											
5. Flexibility											

Resource Use Category		9	7	5	3	1	3	5	7	9	
1. Recyclability											
2. Embodied energy consumption											
3. Energy efficiency											
4. Use of natural resources											
5. Using certified wood											
6. Locally produced											
7. Renewable resources											
8.Reusability											
Socio economic Category		**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	
1. Minimum life cycle costs											
2.Improve indoor air quality											
3. Less labor costs											
4. Affordability											
5. Less disposal costs											
6. Construction waste management											
7.Thermal comfort											
8. Acoustic comfort											
9.Enhance occupants productivity											
10. Less construction time											
11. Low maintenance costs											
12. Aesthetic options											

APPENDIX II

جامعة الملك فهد للبترول والمعادن

كلية تصاميم البيئة

قسم الهندسة المعمارية

<u>الموضوع : دراسة العوامل المؤثرة على عملية اختيار مواد بناء (مستدامة) لبناء الجدران الخارجيه فى المناخ الحار الرطب</u>

تهدف هذه الدراسة الى تعريف وتقييم العوامل المؤثرة في اختيار مواد بناء مستدامه لبناء الجدران الخارجية في المناخ الحار الرطب.

ويهدف الاستبيان المرفق الى معرفة رايكم حول تلك العوامل وتحديد درجة الاهمية لكل عامل على قرار اختيار مواد بناء مستدامه لبناء الجدران الخارجية.

مساهمتك في تعبئة هذا الاستبيان ستؤدي الى تعريف المهندسين المعماريين والمدنيين بالعوامل المؤثرة في اختيار مواد بناء مستدامه لبناء الجدران الخارجية والذي من شانه سيؤدي الى تعزيز مفهوم المباني الصديقة للبيئة و تقليل الطاقة المستهلكة في تركيب وتشغيل وصيانه المباني .كما نؤكد لكم ان المعلومات لن تستخدم الا لغرض البحث فقط.

بعد الانتهاء من تعبئة الاستبيان الرجاء إرساله الى العنوان التالي :

صالح مبارك باحارثه.
قسم الهندسة المعمارية.
جامعة الملك فهد للبترول والمعادن.
الظهران 31261.
المملكه العربيه السعوديه.
E-mail:saleh1882@yahoo.com

فاكس 03-860-3785

جوال 0535101978

الاستبيان

الجزء الاول : معلومات عامه

1- معلومات عن المستجيب:

الاسم (اختياري)	
اسم الشركة او المكتب (اختياري)	
التلفون (اختياري)	
الفاكس (اختياري)	
البريد الالكتروني (اختياري)	

2- كم عدد سنوات الخبرة لديك :

أقل من 5 سنوات		من 5 الى عشر سنوات	
من 10 الى 20 سنة		اكثر من 20 سنة	

3- ما هو موقعك الوظيفي في الشركة :

مدير مشاريع	
مهندس معماري	
مهندس مدني	
مشرف	
مسمى اخر (حدد)	

4- ما نوع الشركة او المكتب الذي تعمل فيه :

خاص	
حكومي	

5- ما نوعية المشاريع المتخصصة فيها شركتك ؟

مباني تجارية		مباني سكنية	
مباني مؤسسية		مسمى اخر (حدد)	
مباني صناعية			

6- كم عدد الموظفين في شركتك ؟

من 1 الى 100		من 101 الى 200		من 201 الى 300	
من 301 الى 400		من 401 الى 500		أكثر من 500	

الجزء الثاني : التعرف على مدى تطبيق معايير التنمية المستدامة فى عملية اختيار مواد البناء :

7- حدد مستوى الوعي لديك في مراعاة تطبيق أسس (التنمية المستدامة) في عملية اختيار مواد البناء:

واعي بدرجه عالية		واعي بدرجه متوسطة		واعي بدرجة قليلة	
لا اراعي معايير التنمية المستدامة					

8- حدد الوسيلة التي سمعت بها عن مصطلح (التنمية المستدامة) :

الصحف والمجلات		البروشورات (الكتيبات)	
الانترنت		اخر (حـــدد)	
لم اسمع مطلقاً بمصطلح (التنمية المستدامة)			

9- من خلال ممارساتك اليومية، كيف تجمع المعلومات اللازمة عند اختيار مواد البناء ؟

من بروشورات المصنع		الانترنت	
طبقا وقوانين ال - LEED		اخر (حدد)	

10-من خلال ممارساتك اليومية، على ماذا تبني قراراتك في عملية اختيار مواد البناء ؟

بناءاً على رغبة الزبون		بناءاً على رغبة المقاول	
طبقاً وقانون البناء		بناء على قرارك الشخصي	
اخر (حـــدد)			

11-هل سبق وان قمت بعملية اختيار مواد بناء مستدامة في مشاريع سابقة ؟

نعم		لا	

أذا كانت الاجـــــابة (نعم)، أجب عن الاسئلة التالية، وإذا كانت الاجـــــــابة (لا) اجب عن الاسئلة إبتداءاً من سؤال رقم (17) :

12- كم الفترة التي قمت فيها باختيار مواد بناء مستدامة ؟

3 سنوات		من (3-5) سنوات	
أكثر من 5 سنوات			

13-وكم تبلغ النسبة الكلية للمشاريع التي قمت فيها باختيار مواد بناء مستدامة بالنسبة الى جميع المشاريع ؟

30 %		من (30-50) %	
أكثر من 50 %			

14- أي من انظمة تقييم المباني المستدامة التالية تعتمد عليه في عملية اختيار مواد البناء ؟

LEED		BREEAM	
Green Globe		اخر (حدد)	

15- هل قد ساهمت في اختيار مواد بناء مستدامة لمبنى حائز على شهادة ال (LEED) للأبنية المستدامة ؟

نعم		لا	

16-اذا كانت الاجابة نعم، كم عدد المشاريع المعتمدة من ال (LEED) والتي ساهمت فيها في اختيار مواد بناء مستدامة ؟

اقل من 3 مشاريع		من (3-5) مشاريع	
أكثر من 5 مشاريع			

17- عبر عن موافقتك او عدم موافقتك في الاتي :

الجمله	موافق بشده 4	موافق 3	غير موافق 2	غير موافق بشده 1
اختيار مواد بناء مستدامة مهم جدا للحصول على مباني ذات كفاءه عاليه وكلفة منخفضه				
بعض مواد البناء لها اثار سلبيه على البيئة والسكان				
يجب توعية كل من المالك والمقاول باهمية اختيار مواد بناء مستدامه				
عند اختيار مواد البناء، يفضل مراعاة الكلفة الاوليه للمواد على الكلفة التشغيليه .				
ينبغي إدراج معايير مواد البناء المستدامه ضمن قوانين البناء في المملكه				

18-ما هي الصعوبات التي تواجهك في عملية اختيار مواد بناء مستدامه ؟

الصعوبات	موافق بشده 4	موافق 3	غير موافق 2	غير موافق بشده 1
قلة المعلومات المتوفرة عن مواصفات مواد البناء المستدامه				
الكلفة الماليه				
العملاء لا يهتمون ولا يطلبون مواد بناء مستدامه				
عدم انتشار الوعي الكافي حول الافضليه لمواد البناء المستدامه عن مواد البناء الاخرى				
عدم وجود اشتراطات او قوانين من البلديه بضرورة اختيار مواد بناء مستدامه				
العادات والتقاليد				
تقنيات البناء الموجوده محدودة جداً				
هناك صعوبات في عدم استخدام مواد البناء العاديه واستبدالها بمواد اخرى				
اخرى				
اخرى				
اخرى				

الجزء الثالث : تقييم الاهمية لكل عامل من العوامل المؤثرة فى عملية اختيار مواد بناء مستدامة للجدران الخارجية

يرجى منكم تقدير أهمية كل عامل يؤثر على قرار اختيار مواد بناء مستدامة، وإضافة أي عوامل أخرى ترونها مناسبة.

العوامل المؤثرة في عملية اختيار مواد بناء مستدامه	مقدار الاهمية			
	مهم جــــــداً 4	مهـــم 3	غير مهم 2	غير مهم جـــــــداً 1
العوامل البيئـــــــية				
1- مقاومة التلوث.				
2- تقليل كمية المياة المستهلكة.				
3- اختيار مواد غير سامه او اقل سميه.				
4- اختيار مواد اقل ضررا على طبقة الاوزون.				
5- اختيار مواد قابلة للصيانة والتنظيف باستخدام تقنيات غير ضارة بالبيئة والانسان				
6- اختيار مواد قليلة الاشعاع.				
7- طريقة استخلاص المواد الخام (استخلاص المواد بطريقة مستدامه او غير مستدامه).				
8- مقاومة الحرائق.				
9- اختيار مواد ذات كميات قليله من (المركبات العضوية المتطايرة - VOC وهي عبارة عن مركبات ضارة بالبيئة والانسان تنبعث اثناء تركيب بعض المواد مثل السجاد.				
- عوامل اخرى				
- عوامل اخرى				
العوامل التقنيــــــــة				
1- المتانة.				
2- فترة التحلل البيولوجي.				
3- اختيار مواد ذات عمر اطول.				
4- مقاومة الرطوبة.				
5- المرونة (قابلية المادة للاستخدام في اكثر من غرض).				
- عوامل اخرى				
- عوامل اخرى				
- عوامل اخرى				

العوامل المتعلقة بخواص المواد ومصادرها	4	3	2	1
1- اختيار مواد قابلة لإعادة التدوير.				
2- مقدار الطاقة الكامنة (الطاقة المستنفذة في استخلاص و معالجة ونقل المواد الى المبنى)				
3- الكفاءة في استهلاك الطاقة.				
4- اختيار مواد طبيعية (مواد البناء اما طبيعية لا تحتاج الى المزيد من المعالجة مثل الخشب – او تحتاج الى عملية تصنيع مثل البلاستيك)				
5- اختيار خشب مصدق عليه من (مجلس الاشراف على الغابات).				
6- استخدام مواد متوفرة ومصنعة محلياً.				
7- استخدام موارد متجددة .				
8- اختيار مواد قابلة للاستخدام مرة اخرى.				
- عوامل اخرى				
- عوامل اخرى				
- عوامل اخرى				
العوامل الاقتصادية والاجتماعية				
1- اختيار مواد ذات كلفة اقتصاديه اقل في كامل عمرها الافتراضي				
2- تحسين جودة الهواء الجوي				
3- تقليل كلفة العمالة.				
4- ان تتلاءم كلفة المادة مع كلفة وميزانية المبنى .				
5- تقليل كلفة التخلص من المادة بعد انتهاء عمرها الافتراضي.				
6- ادارة التخلص من النفايات .				
7- الراحة الحرارية (العزل الحراري).				
8- العزل الصوتي.				
9- تحسين اداء وانتاج شاغلي المبنى.				
10- تقليل كلفة التركيب والبناء.				
11- تقليل كلفة الصيانة.				
12- المظهر الجمالي.				
- عوامل اخرى				
- عوامل اخرى				
- عوامل اخرى				

Vitae

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