DEVELOPMENT OF A MULTI-CRITERIA APPROACH FOR THE SELECTION OF SUSTAINABLE MATERIALS FOR BUILDING PROJECTS

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Declaration

This work or any part thereof has not previously been presented in any form to the University or to any other body whether for the purposes of assessment, publication or for any other purpose. Save for any express acknowledgment references and/or bibliographies cited in the work, I confirm that the intellectual contents of the work are the result of my own efforts and no other person.

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ABSTRACT

Construction activity is known to have a major impact on the environment and is a major consumer of a wide range of naturally occurring and synthesized resources. Despite the recognition that environmental issues are important to the survival of the construction industry, the industry continues to degrade the environment, exploiting resources and generating waste, and is slow to change its conventional practices to incorporate environmental matters as part of its decision making process. With increased awareness and knowledge of these impacts, efforts are being made to avoid these adverse effects and to work towards impact mitigation. Among these is sustainable building material selection. Building material selection is an important issue in building design and construction decision-making and environmental issues need to be incorporated into the evaluation process. The research reported in this thesis was initiated to address these issues in the UK, towards developing an assessment model for incorporating sustainability into building material selection process. A questionnaire survey was conducted to investigate the level of awareness, knowledge and implementation of sustainable practices among architects and designers and how this impacts on their design decisions. To facilitate the implementation of sustainable practices into building material selection, a set of sustainable assessment criteria (SAC) for modeling and evaluating sustainability performance of building materials was developed. Building material can be assessed using an index system that combines the principal criteria of sustainable development. The derived criteria were assessed and aggregated into a composite sustainability index using the Analytical Hierarchy Process (AHP) technique which has been praised for its ability to incorporate both objective and subjective considerations in the decision process. The development of a sustainability index is a way of supporting decision makers faced with making numerous and sometimes conflicting evaluation as with building material selection. The methodology adopted in undertaking this research was the mixed method approach involving a detailed review of the relevant literature, followed by an industry-wide survey of UK architects and designers. Following this, case study was conducted to collect data for sustainability criteria used in the assessment model. The data collected were analyzed, with the aid of SPSS, Excel and expert choice software using a variety of statistical methods including descriptive statistics analysis, relative index analysis, Kendall's concordance and factor analysis. The key finding was the existing gap between awareness and implementation of sustainable construction practices, which has led to failure of realizing the benefits of a sustainable approach to construction. The study showed a discrepancy between what architects and designers claim to be convinced about, and knowledgeable in, and their commitment and practices; they seem to be unable to translate their environmental awareness and knowledge into appropriate design decisions and are in need of a decision support system that can aid the incorporation of sustainability into building design. The model developed satisfy this gap and was validated by application to a roof covering material selection decision process for a case study building project by means of experts' review via a survey and the findings obtained suggest that the model is valuable and suitable for use in practice. Finally, areas for further research were identified.

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BRE	Building Research Establishment
BSRIA	Building Services Research and Information Association
CIB	International Council for Building
CIRIA	Construction Industry Research and Information Association
CRISP	Construction Research and Innovation Strategy Panel
DEFRA	Department for Environment, Food and Rural Affairs
DETR	Department of the Environment, Transport and the Regions
DTI	Department of Trade and Industry
FIEC	European Construction Industry Federation
EU	European Union
GBC	Green Building Council
GDP	Gross Domestic Product
HK-BEAM	Hong Kong Building Environmental Assessment Method
HM Treasury	Her Majesty's Treasury
IPCC	Intergovernmental Panel on Climate change
KMO	Kaiser-Meyer-Olkin
LCA	Life Cycle Analysis
LCCA	Life Cycle Cost Analysis
MCA	Multi Criteria analysis
NAO	National Audit Office
NAO	National Audit Office
NS	National standard
ODPM	Office of the Deputy Prime Minister
OECD	Organisation for Economic Coperation and Development
OGC	Office of Government Commerce
ONS	Office for National Statistics
Q	Quater
RICS	Royal Institution of Chartered Surveyors
SPSS	Statistical Package for the Social Sciences
TRL	Transport Research Laboratory
UK	United Kingdom
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
US	United States
W	*Kendall's coefficient of concordance*
WHO	World Health organisation
WRAP	Waste and Resources Action Programme

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DEDICATION

This research is dedicated to my Father, Akadiri Babajide, Mother, Mrs. Akadiri Olusola, Brothers and Sisters and my entire family

CHAPTER 1: GENERAL INTRODUCTION

1.1 Introduction

Sustainability is a broad and complex concept, which has grown to be one of the major issues in the construction industry. Consequently, there are proliferations of research in the field. This research is based on the premise that to achieve sustainability in the industry, there is need for a holistic approach for integrating sustainability principles into material selection decision making at the design stage of building project. Whilst there are hosts of related research in this domain, major barriers still persist in integrating sustainability issues in building project. This research therefore attempts to redress this imbalance. This chapter describes the research background, aim and objectives, research method and hypotheses, as well as the structure of the thesis.

1.2 Research Background

Rapid population growth and the continuous growth of industrialization throughout the world together with increasing living standards have turned the creation of the built environment into a rising threat to the natural environment (Emmanuel, 2004).Building and the environment are inextricably linked. The relationship between the built and the natural environments has received an unprecedented level of coverage in the media in recent years as well as driving much new scientific research (Anderson *et al.* 2009). The construction, fit-out, operation and ultimate demolition of buildings is a huge factor of human impact on the environment both directly (through material and energy consumption and the consequent pollution and waste) and indirectly (through the pressures on often inadequate infrastructure). The built environment also has a crucial impact on the physical and economic health and well-being of individuals, communities and organisations. A good building is a delight, will enhance a community or organisation, and our ability to learn or increase our productivity (Halliday, 2008). Where buildings contribute to ill-health and alienation, undermine community and create excessive financial liability, they are undesirable and unsustainable.

As awareness of the potential environmental impacts of building construction has grown, efforts are being made to avoid these adverse effects and to work towards impact mitigation (BRE, 2004). There is a growing consensus that appropriate strategies and actions are needed to make buildings and construction activities more sustainable (BSRIA, 1998; DETR, 1998; CIB, 1998; CRISP, 1998; Barrett *et al.,* 1999; Halliday, 2008). With respect to such significant influence of the construction industry, the sustainable construction approach has a high potential to make a valuable contribution to sustainable development.

The sustainability of a building depends on the decisions taken by a number of actors in the construction process: owners, managers, designers, firms, etc. The pace of actions towards sustainable application depends on the awareness, knowledge as well as an understanding of the consequences of individual actions (Braganca *et al.,* 2005; Abidin, 2009). Among these is the environmentally responsible approach to the selection of building materials (Anderson *et al.,* 2009). The selection of building materials is one of several factors that can impact the sustainability of a project (Nassar *et al.,* 2003). An appropriate choice of materials for a design process plays an important role during the life cycle of a building (Treloar *et al.,* 2001; Zhou *et al.,* 2008). Understanding the environmental issues surrounding the extraction of raw materials, the manufacture of construction materials, and their effects in use, is important to ensure sustainability (Ofori *et al.,* 2002; BRE, 2004).

1.2.1 Sustainable Construction Agenda in the UK

The UK Government commitment to sustainable construction is set out in *'Building a better quality of life- a strategy for more sustainable construction'* (DETR, 2000). Following this, the first progress review was published that highlighted areas for future focus (DEFRA, 2002). Although the 2002 progress review made some changes in emphasis the core of the UK Government's strategy remained the same, based around four key themes. These themes all interact and all have implications for construction development. In turn, construction development can impact on each of the themes as outlined below (Hall and Purchase, 2006).

1. Maintain stable economic growth and employment – the UK construction industry accounts for approximately 8.5% of GDP (ONS, 2009). Compared with other industries, construction has relatively small profit margins and hence is more vulnerable to an unstable economy (NAO, 2001). Consequently, there have been many government initiatives aimed at improving the industry and making it more financially robust, dating back to the start of the last century (NAO, 2001). Recent examples include the government funded Strategic Forum for Construction and the use of the Private Finance Initiative set up to provide input into developing the main agendas for change set out in the Rethinking Construction report.

2. Provide effective protection of the environment – construction activity affects the environment in two ways. First, the erection of a new development obviously has a direct physical impact on the immediate area. There is also often a knock-on effect as new developments can increase traffic, water usage, electricity requirements etc. Second, many materials used in construction are quarried or mined, which again makes a direct physical impact on the environment. Many of the materials also involve manufacturing processes that contribute to pollution.

3. *Ensure prudent use of natural resources* – the construction process consumes natural resources such as wood, stone and water in concrete. However, the design of buildings can affect the use of natural resources over the whole life of the facility. For example, poor insulation and poor layout can significantly affect the consumption of electricity for heating.

4. *Encourage social progress that meets the needs of everyone* – the £3 billion allocated for the development of social housing is a prime example of the role that construction plays in encouraging social progress. Additionally, the construction of schools, hospitals, transport systems and other public facilities all contributes to increasing the quality of life.

Construction is an interesting area to test the government's ability to implement its strategy, as there is a clear potential for conflict between the four themes (Hall and Purchase, 2006). At the risk of over-simplifying the argument, to grow the economy, provide jobs and encourage social progress would seem to require more construction activity. However, to protect the environment and reduce the consumption of natural resources might require less construction. The task then, for a sustainable construction strategy, is to find ways for the four themes to complement each other. Ever since its publication, the sustainable construction agenda has been taken forward through a dynamic partnership between the government and industry. As a result, there have been several developments as summarised below.

- There has been an increase in the number of voluntary policies, legislations, regulations, economic measures and fiscal incentives such as Landfill Tax, Climate Change Levy, Aggregates Levy, Renewable Grant Schemes, Land Use Incentives and changes to the Building Regulations.
- The Building Regulations, the Planning White Paper, the Communities Plan and the Energy White Paper have been amended to reflect sustainable construction agenda.
- There are several joint initiatives to promote awareness, capacity building and reporting mechanisms such as Global Reporting Initiatives, CIRIA's industry sustainability indicators, sustainable construction task force and the sustainable building task force etc.
- Sectors within the industry (e.g. steel, concrete, brick, civil engineering, etc.) have developed their own sustainability strategy and action plans and have started reporting on progress; these are highlighted further in the literature review.
- A host of demonstration projects on sustainable construction initiatives providing tangible evidence of positive outcome such as the Rethinking Construction, WRAP, Sustainable Construction Road Show and so on.
- Research centres on sustainable construction funded by the government have been organised nationwide, numerous conferences, books, journals and publications are available, and universities are offering various courses and degrees in the fields.

- There are plethora of research on sustainable construction concepts, tools, frameworks, technologies, materials, energy systems, water conservation systems and other related issues, such as waste minimisation, recycling techniques, alternative materials and environmental management. The results are available as publications (e.g. CIRIA and TRL Reports), digests (e.g. BRE), guidance notes (e.g. Environment Agency Pollution Prevention Guidance (PPG), videos and training packs.

On the surface, at least, it would appear that these efforts are a significant success story and the industry movement toward more sustainable construction has gained significant momentum. However, the actual situation may not be so upbeat as the industry is still faced with major challenges (CIRIA, 2001; Kilbert, 2004; Abidin, 2009).

1.3 Problem definition

There is a growing political imperative to build sustainably in UK. For the last decade the Government has seen planning and construction practices as the main mechanisms by which to promote and deliver a sustainable built environment (DETR, 1998, 2000). To this end it has instigated a number of initiatives to ensure that sustainable development schemes are produced. Different government offices are leading programmes to create sustainable communities, reduce energy use in buildings, ensure sustainable building materials and methods are used and promote private sector interest in sustainable construction (Sustainable Buildings Task Group, 2004). However, it appears that the majority of new developments in UK still incorporate few sustainability features despite the high level of awareness exhibited by building designers (Williams and Dair, 2007). In a recent review of sustainable building activity, Williams and Lindsay (2005) found that a very small proportion of UK's building stock can claim to be sustainable in any way, whether judged on sustainable construction, design or performance in use. The question then arises of why is this so? Given such a strong policy drive, what is stopping sustainable developments from being realized in practice?

According to Ugwu *et al.,* (2006) the process of translating national strategic sustainability objectives into concrete action at micro (i.e., project specific) levels is a difficult task. While current sustainability initiatives, strategies, framework and processes focus on wider national aspirations and strategic objectives, they are noticeably weak in addressing micro-level integrated decision-making. Paradoxically, it is precisely at the micro-levels that national strategic objectives have to be translated into concrete practical actions, by using a holistic approach to facilitate decision making. Although there is increasing realisation of the need to design and construct for sustainability, the real challenge is on achieving these objectives at the project-level. An important task in the implementation of sustainability objectives at the design development stage of a building project is the sustainable selection of building materials to be used in building project. Careful selection of sustainable building materials has been identified as the easiest way for designers to begin incorporating sustainable principles in building project (Godfaurd *et al.,* 2005).

1.3.1 The Material Selection Issue

Traditionally, the focus in construction is on minimising the initial building cost. It has, however, since the 1930s become obvious that it is unfavourable to base the choice between material alternatives solely on the initial cost alone (Kishk *et al.,* 2003). An inefficient building imposes a cost penalty on the client throughout its lifetime. While the client has an incentive to minimise whole life costs, the contractors and consultants do not, as they have no long-term interest in the building and are not accountable for performance in use (Sorrell, 2003). Increasingly, public sector guidance on construction procurement and best practice literature is emphasising the importance of whole life costs (Her Majesty's Treasury, 2000c; Sorrell, 2003). The conventional material assessment methodology employs life cycle cost analysis (LCCA) as the main tool in the decision-making process, particularly in the public sector (Perkins, 1994; van Pelt, 1994; Durairaj *et al.,* 2002). Life Cycle Costing is an economic evaluation technique that concerns the assessment of the total cost of an asset over its operating life, including initial capital costs, maintenance costs, operating costs and the cost or benefit of the eventual disposal of the asset at the end of its life (Utne, 2009). Life Cycle Costing is a decision-making tool that could be used to select among alternative building components (Arpke and strong, 2006).

Although LCCA may appear reasonable and practical, there are growing concerns that this approach often ignores or underestimates environmental issues, leading to overuse and depletion of environmental assets (Tisdell, 1993; Hobbs and Meier, 2000). Literature on LCCA and environmental protection indicates that using a single objective in the evaluation process is insufficient when taking environmental issues into account (Spash, 1997; Glucha and Baumann, 2004; Thabrew *et al.,* 2009). The environment's complexity means its relationship with human activities remains largely unknown (van de Burgh, 1996; Harding, 1998; Garrette, 2006; Parker *et al.* 2008).

Research on non-monetary techniques has been undertaken to search for alternative methods so that environmental values can be identified and evaluated in a proper manner. One such method is multi-criteria analysis which uses a weighted score approach to evaluate environmental issues. This has gained significant attention in operational research (Hobbs and Meier, 2000; Ding, 2008; Anada and Herath, 2009). Completely replacing a monetary market approach with non-monetary techniques has limitations; however both methods are regarded as complementary tools by many researchers (Gregory *et al.,* 1993; van Pelt, 1993; Powell, 1996; Joubert *et al.,* 1997; Mirasgedis and Diakoulaki, 1997; RICS, 2001). There is no strategic model for material assessment that embraces significant sustainability criteria where these are assessed using methods that suit their nature (Ugwu *et al.,* 2005; Ding, 2008).

A gap therefore exists between conventional material assessment techniques and the incorporation of sustainability principles in the decision-making process. In order to bridge the gap, current assessment methodologies require thorough updating leading to a new model that incorporates the principal determinants of sustainable development into the decision-making process using a multi-criteria approach as opposed to the current single dimensional approach.

1.3.2 The Research

This research studied UK architect's and building designer's strategic approach to sustainability implementation in building projects, and how it influences their design. It focuses on decision-making in the selection of materials and also seeks to identify significant criteria for selecting sustainable building materials. This requires a comprehensive examination of the existing decision-making method and approach used in the construction industry. The use of LCCA and environmental assessment techniques was investigated and an examination of the current literature also identified significant sustainability criteria used for decision-making in material selection.

A multi criteria decision-making model was developed which embraced the broader sense of environmental protection at the conceptual stage of building project, thereby increasing the efficiency of the construction industry. The developed model was used to aggregate the set of criteria into a composite index for ranking the sustainability of building materials. The investigation is in three main areas:-

1) An environmental impact review of construction activities and identification of sustainable material selection criteria.
2) Using findings from the literature as a basis for an extensive industry survey to (i) investigate awareness of environmental issues, and how it impact on design decisions (ii) investigate sustainable building material selection process and (iii) identified and determine the relative importance of sustainable material selection criteria, and
3) The formulation of a multi criteria decision-making model based on the survey results.

A review of the literature was undertaken to establish the criteria and a pilot study with selected and well experienced practising architects and designers was undertaken to determine the suitability of the criteria. The criteria were used in developing a decision making model for material selection. Data on criteria were collected and analysed on building roof covering materials to test the model robustness and validity.

The industry survey to rank significant sustainability criteria comprises an extensive questionnaire for architects and designers currently practising in the construction industry. Their opinions on the ranking of a series of decision-making criteria are examined and collated to develop a framework for decision-making. The technique of multi-criteria analysis is used to bring these criteria together into a single model. A sustainability index (SI) was then developed to calculate the level of sustainability of building roof covering materials and facilitate the choice of the best option. The principal role of the sustainability model is to incorporate environmental, economic, social and technical issues into the decision-making process at an early stage.

1.4 Research Aim and Objectives

The aim of this research is to develop a model to aid the integration and implementation of sustainability principles in building material evaluation and selection and to promote wider uptake of the concept in the construction industry. A decision-making model was developed which aid the incorporation of sustainability issues into the decision-making process at the design stage of a building project. The model was then applied to choose a sustainable roof covering material option. Specifically, it is envisaged that this research will promote environmental sustainability in the UK construction industry.

The specific objectives of this research that will realise the research aim are to:

i. Investigate through literature review development impacts on the environment.
ii. Investigate decision-making processes and suggest ways to improve the conventional decision methodology used in the construction industry for selecting construction materials.
iii. Highlight the environmental impact of construction activities with focus on the impact of construction materials throughout their life cycle and suggest strategies for sustainable construction implementation.

iv. Investigate through a questionnaire survey the environmental issues awareness and sustainable construction practices of architects and designers in the UK and barriers faced in implementing sustainability in material selection decision-making process.

v. Evaluate the principal sustainability criteria relevant to building materials for modelling decision-making in building projects through a survey of architects and designers.

vi. Develop a multi criteria assessment model for aggregating sustainability criteria into a composite index for building material selection.

vii. Test the effectiveness and usefulness of the new decision model.

viii. Suggest policy implication arising from the study and identify areas of further research.

The review of literature was extensively and critically undertaken throughout the study to build up a solid theoretical base for the research area and a foundation for addressing the problems and achieving the research objectives. The review helped to identify gaps in knowledge and formed the basis for developing the research aim and objectives. Information was sought from various sources including industrial and academic publications, institutions and university databases, the Internet, seminars, workshops and conference notes attended. Moreover, information and knowledge was also gained by attending relevant courses. In addition practioners were consulted to obtain their views and to see if and how this differed from the literature.

1.5 Reseach questions

The main research questions this research aims to address are:

1. What is the gap in current decision-making practice used in selecting building materials and how can it be improved?
2. What is the level of environmental awareness and sustainable practices of architect's and designer's in the UK and how does it affect design decisions?
3. What are the sustainable criteria used in material selection and how can they be used in modelling decision-making in building projects?
4. What should be the appropriate model for evaluating and selecting sustainable building materials?

1.6 Research method in brief

This research involves both quantitative and qualitative data. The method engaged in this research therefore, consists of a combination of both strategies. A literature search involved a thorough review of current practices and previous research in the area of environmental evaluation and material assessment; environmental impacts of architect's design decisions and the situation in UK construction industry regarding architect's environmental awareness implementation and related action. The literature search also explored the background issues in relation to the development of a sustainability index as a decision making tool. Data collection has been divided into two parts. The first part used questionnaire survey to investigate the sustainable construction practices of UK architects and designers and identify criteria for developing the model of sustainability index. The second part involved applying the decision model to a building material selection problem using a case study building project.

It was decided to use an industry questionnaire to obtain data on architect's and designer's opinions about sustainability criteria used in material selection decision making. The questionnaire was to identify criteria to be included in the decision-making model for sustainability. A mail survey was employed due to the benefits of administration, wider coverage and the speed of data collection. Following the identification of key criteria for the decision-making model, case study research was used to collect data for the criteria. The decision-making model was primarily developed to assess building materials; therefore, case study methodology is a rational approach for this process (Yin, 2003).

Data analysis for the first part of the research was undertaken using descriptive statistics at the preliminary stages to provide useful insights, with more detailed analysis done using Relative index analysis, Kendall coefficient of Concordance, Chi-square tests, Factor analysis, and other statistical tests of significance. Appropriate statistical analysis software such as Statistical Package for the Social Sciences (SPSS) are employed, where necessary, to aid analysis. The second part used a suitable modelling technique in the form of multi criteria decision analysis, in developing the model of sustainable material selection.

1.7 Thesis organization

The thesis structure is presented in Figure 1.1 and the specific chapter descriptions are as follows:

Chapter One

This chapter provides background information for this research. It explains why this research was undertaken and how this research is significant to the construction industry. Research aims and objectives, reseach questions and the method adopted were highlighted.

Chapter Two

This chapter builds a theoretical foundation for the research by reviewing literature and previous research. The chapter examines the impact of human activities and economic growth on the global environment. It provides information and argument for the importance of incorporating sustainability principles in material selection. A multi-criteria approach for material evaluation is reviewed and contrasted to the conventional market-based approach. The argument established provides a platform for further investigating the literature concerning other environmental valuation techniques such as non-monetary approaches.

Chapter Three

Whilst the previous chapter focuses on the broader discussion of environmental issues, this chapter concentrates on the relationship between environmental issues and the construction industry. This chapter examines the effects of construction activity on the natural and man-made environment and considers strategies that can help to reduce the impact and enhance sustainable goals in the construction industry.

Chapter Four

This chapter critically reviews the environmental building assessment methods currently used at national and international levels when evaluating a building material performance. A multi-dimensional approach to the sustainable evaluation of materials is discussed as opposed to the conventional single-dimensional approach. This chapter also presents the conceptual development of sustainability-based decision making for building material selection.

Chapter Five

Following the review of literature in chapters 2, 3 and 4, this chapter provides an outline of the research methodology adopted for undertaking this research. Arguments are presented justifying this choice of a conciliatory approach and the specific research methods applied to collect data. The data collection process is detailed in this chapter.

Chapter Six

This chapter presents the result of the findings regarding the environmental issues awareness and sustainable construction practices of UK architects and designers. The chapter also investigates the sustainability criteria used in developing the multi criteria decision model for material selection.

Chapter Seven

Chapter seven is devoted exclusively to the development of the multi criteria decision model for material selection. The chapter examines in detail the criteria to be incorporated in developing the model and the aggregation of the criteria into a composite sustainability index for material selection.

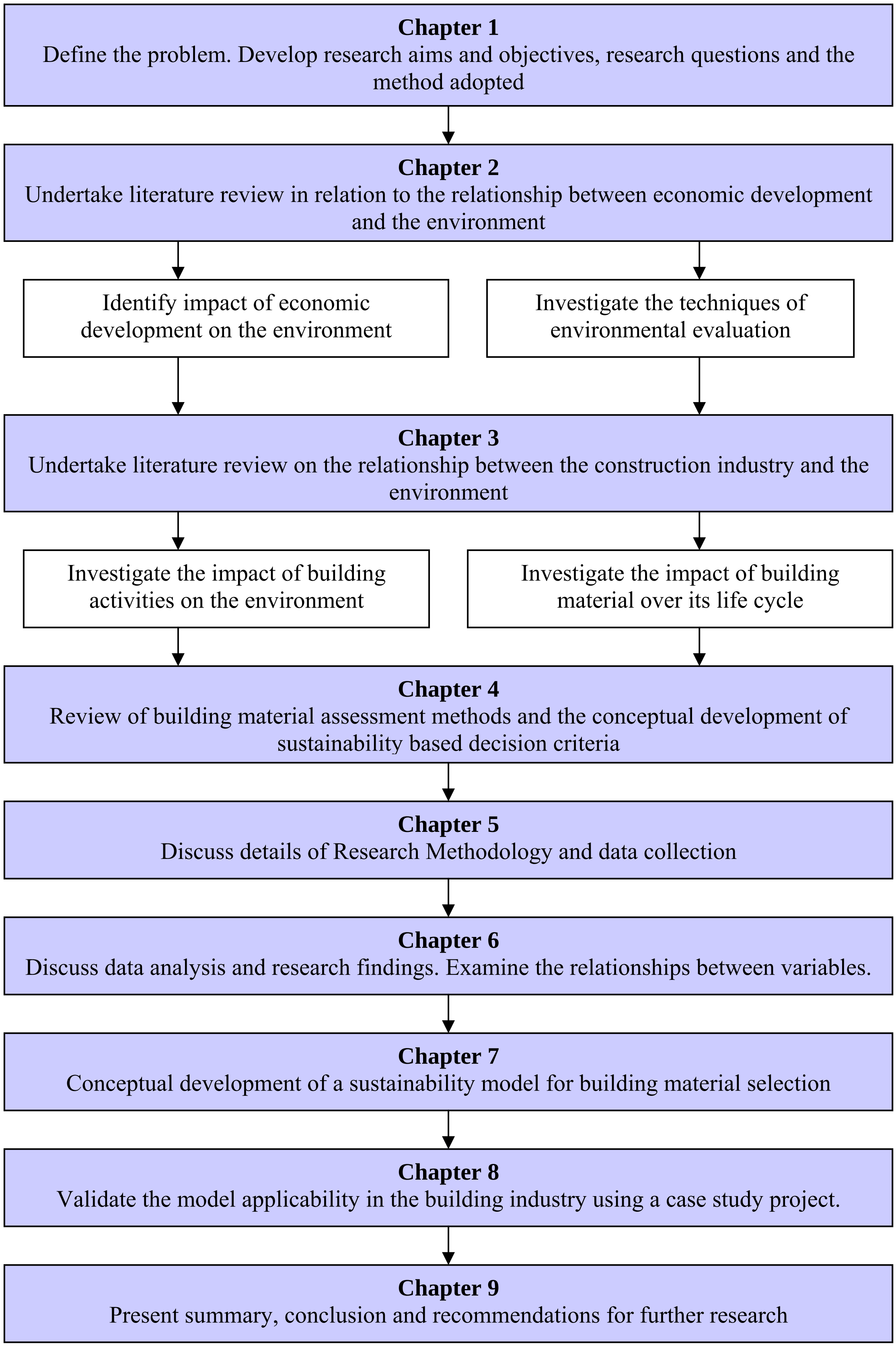
Chapter Eight

The application of multi criteria decision making analysis is reported here using a case study of a proposed building project. The chapter also describes the validation process and the methodology adopted in the validation procedure. The validation processes are discussed in terms of the literary, conceptual and substantive domains of the research.

Chapter Nine

This chapter summarises the research and states the conclusions. Conditional statements are made with respect to the application of the conceptual model in the construction industry. Limitations of the research and the possibilities of further research are made at the end of the chapter.

Figure 1.1 Thesis organizations



CHAPTER 2: ECONOMIC GROWTH AND THE ENVIRONMENT

2.1 Introduction

The nature of the relationship between economic development and the environment has been discussed since the 1960s, yet opinions remains divided. A fundamental question of economic development is to what extent increases in economic activity affect the natural environment. This chapter provides a comprehensive analysis of the impact of economic growth on the natural environment. The conventional market-based approach to decision-making is examined in detail, compared with the multi-criteria approach to evaluating environmental values.

The interaction between the society and the environment is a complex web of positive and negative feedback flows. The environment, economy and society are interconnected (Giddings *et al.,* 2000). If a simple model for the relationship between the natural and the social systems is considered we have on one side, the flow of natural resources to the system, and on the other side, the flow of waste products back to the environment. The damage done by the load of waste products upon the environment depends on its ability of regeneration and its assimilation capacity (Cordero *et al.,* 2005). Pollutants for which the environment has little or no absorptive capacity are called stock pollutants. This kind of waste accumulates over time and creates interdependency between the present and the future, since the damage imposed on the future depends on current actions. The depletable resources and the stock pollutants are different sides of the intergenerational equity problem by using up depletable resources, it is possible for current generation to create a burden for future generations thereby diminishing the remaining endowment; stock pollutants also create intergeneration problems because their damages will persist after the benefits received from incurring in these damages have been forgotten (Cordero *et al.,* 2005).

Now economic growth, particularly in the construction industry, is under threat from overuse or finite limits of supply (Rees, 1999). External effects such as air and water pollution generated from mining, manufacturing and construction processes can also seriously affect the environment's capacity to continue producing raw materials (Kein *et al.,* 1999). Economic growth and the natural environment jointly affect mankind's well-being, therefore the efficient allocation of scarce resources for building project is an important issue to both present and future generations, and decisions taken during building design are of paramount importance if the balance of our social fabric is to be maintained. The activities which precipitated this environmental crisis relate mainly to man exhausting and degrading natural resources, population growth and pollution. Research shows that non-market characteristics are the main causes and these environmental issues possibly affecting society's economic growth (Nijkamp *et al.,* 1990; Hanley and Spash, 1993; Joubert *et al.,* 1997). So it can be seen that the relationship between the environment and economic growth is vital and much depends upon its investigation and improvement.

2.2. Global environment and the economy

2.2.1. Background

It is commonly argued that we need economic growth to ensure the well-being of the economy and improve standards of living (Schwartz *et al.*, 2006). Further, the promotion of economic growth worldwide is seen as the way to lift developing countries out of poverty. But what are the effects of economic growth on the environment? Some economists argue that economic growth will eventually lead to an improvement in the environment, despite some past increases in environmental degradation correlated with economic growth (Khan, 2008). But to what extent does economic growth promote resource depletion and increase in waste production and hence increased damage to the environment? To what extent does it damage the basic ecosystems on which we all depend? To what extent does it cause reduction of biodiversity?

Economic growth and environmental protection have a two-way interaction. The environmental crisis is now of global importance. Human economic activity is the principal cause through exploitation and pollution, yet such activity relies heavily on a healthy environment for continuation and productivity (Common, 1995). There is, hence, a vital partnership upon which much depends. This section investigates the role of the environment in economic growth and the environmental problems associated with these activities.

2.2.2 Characteristics of the natural environment

Schwartz *et al.* (2006) in his global environmental change article report that human activity is bringing about significant changes in the global environment at an unprecedentedly fast pace. The changes which began since the industrial revolution, has steadily over-weighted the global environment. (Schwartz *et al.*, 2006). The conditions of the global environment have been made clear through the continuous observation and surveillance performed by the U. N. Environment Programme (UNEP), which was established according to the decision of the U. N. Conference on the Human Environment in 1972, and by the World Meteorological Organization (WMO) and the World Health Organization (WHO). Considering those developments, there is increasing global interest in environmental issues in recent years, and there is a widespread recognition that it should start to take necessary action in concert for the future generation. The economy and the environment are mutually dependent on each other's existence for survival. Common (1995) states that the linkages between economic activity and the environment are pervasive and complex. The complexity of the relationship is due to the inherent, and difficult to quantify value of the natural environment to the economy and the natural environment supporting the economy. Hill (1997) suggests that the biosphere would seem to have infinite value, since without the biosphere, nothing can survive. When considering environmental values, Shechter and Freeman (1994) argue that moral rights and interest should also be assigned to the non-human nature of the environment. Therefore, the environment has a value, no matter whether humans are around to sense, consume or experience it.

The environment serves the economy in many ways including as a resource base and providing renewable and non-renewable resources as required (Common, 1995; Ding, 2005). Renewable resources are the biotic population of flora and fauna that have potential to regenerate through natural reproduction when there are losses from economic extraction, such as timber (Ding, 2005). Non-renewable resources are minerals such as fossil fuels that cannot regenerate and so cannot be used sustainably. These stocks also require geological surveys to estimate their size and value and are used to produce goods and services consumed in the economy. As Booth (1998) says, the supply of environmental resources is critical in order to sustain our living standard.

Whilst the environment serves as a resource base, it also performs as a receptacle for wastes (Ding, 2005). Economic activities produce waste products, often described as pollutants that are discharged into the natural environment. The law of conservation of mass states that energy can neither be created nor destroyed by human activity (Common, 1995; Beggs, 2009), it is merely transformed from one state to another. The environment's ability to absorb waste products is assimilative, as it is capable of receiving waste matter, degrading it and converting it to nutrients, which then feed the occupants of an ecosystem. However, that capacity depends on the waste's biodegradability or whether the level of biodegradable material is exceeded (Pearce, 1998).

Despite the environment's direct value through providing the necessary materials for economic activities and absorbing the waste product as a result of these activities, the environment also adds an indirect value to the normal functioning of the economy by providing humans with recreational facilities and other sources of pleasure and stimulation (Thampapillai,1991; Burgan and Sansom, 2006).This function does not directly involve any consumptive material flow however its excessive use may lead to changes in its character such as soil erosion and vegetation loss. This function is important to our quality of life. Finally, the environment provides the life support system for mankind to survive, such as breathable air, range of temperatures and water (Ofori, 2002). These functions do not directly contribute to economic activities, but if its existence ceased to function there would, no doubt, be not only a serious affect on the economic growth but also on human life.

When the environment is exploited non-sustainably and rapidly polluted, there is a loss of one or more of environmental services such as health, productivity or amenity and the survival of the human race is seriously under threat. When a rare species or feature of the environment disappears, there is not only a loss to man, but also an irreversible loss of existence value. The economy often regards the adoption of environmental protection as a costly measure that jeopardises profitability (Boughey, 2000). However, there is a strong association between labour productivity and a high standard of environmental quality such as output losses due to illness and absenteeism. Clearly, the natural environment is an important component of the economic system and without it the economic system would not be able to function. Therefore, as Thampapillai (1991) states, the natural environment should be treated as an asset and a resource on the same basis as the other factors of production.

The supply of public goods in the global common is often abundant and once it is available for everyone it will not exclude anyone else from consuming it. Once it is provided it bears no extra cost to additional consumers. Environmental goods are free gifts of nature and there is no private property right of its ownership. However, up to a certain extent, the public properties of environmental assets will cease and they will become private goods. Beyond this point people may need to pay for the consumption of environmental goods. According to OECD (1995), based on an economic viewpoint, something that is abundantly available to all has no economic value. However, when the assets start to become scarce, it starts to have potential economic value. This zero price condition leading to market failure has led to these goods being excessively used, resulting in depletion, deterioration and no incentive for their protection (Datta and Mirman, 1999).

As society fails to protect the environment and destruction occurs, these goods become external to the market (Beder, 1996).The natural environment has been shown to be an important factor for economic growth. Therefore, as natural environmental resources are eroded and destroyed, the result will be jeopardised, if not limited, economic growth (Thampapillai, 1991). There are ongoing discussions about whether a constraint should be placed on economic growth as environmental degradation is so evident (Xepapadeas and Amri, 1998). Some people argue that economic growth is necessary to pay for environmental protection and reverse environmental deterioration (Booth, 1998).Daly (1992) supports a steady-state economy under which the natural resources are consumed at a fixed, sustainable rate and the quality of the environment is maintained at a level that protects the health of human individuals, species and ecosystems. Booth (1998) advocates that economic growth is contrary to any notion of sustainability. He goes on to state that even if all environmental costs were successfully internalised, economic growth could still lead to environmental deterioration. Hence, in according with his opinion, the only way to protect or preserve the environment is to cease all kinds of economic activity.

Daly's (1992) opinion is more acceptable as it is more realistic about maintaining a balance for economic growth and environmental protection. In fact, it is impossible to stop all economic activities for the sake of protecting the environment. On one hand, if economic activities are reduced in order to protect the environment, environmental degradation will also be caused as a result of increased unemployment and poverty (Thampapillai, 1991; Spence and Mulligan, 1995; Langston and Ding, 2001; Reed, 2002).Therefore, neither extreme will benefit the environment. Barbier (2003) suggests that the environmental and natural resources should be treated as important assets and described as natural capital. Better understanding of these complex environmental values may lead to more sustainable economic development. The natural environment is an important component of the economic system, which affects many aspects of mankind now and in the future. Renewable resources should not be consumed at a rate greater than their natural rate of regeneration. Even though non-renewable resources cannot be replaced, they should be conserved and used in a more efficient way. Through technological improvements, their conservation can be achieved by preventing their exhaustion by the present generation (Pearce and Turner, 1990).

2.2.3 Environmental challenges to development

Since the beginning of the Industrial Revolution, the industrialized world has engaged in a paradigm based upon material goods, in which unlimited development, mass production, and ever-increasing consumption have been the rule of the day. Accordingly, industrialized nations throughout the world have implemented comprehensive policies to promote accelerated economic growth and manufacturers have responded by shifting their focus from quality to quantity as they continually strive for increased production and the increased profits which are attendant (Kyounghoon *et al.,* 2008).

Environmental destruction is apparent everywhere, precipitating a crisis that is now of global proportions. Global warming, thinning of the ozone layer, loss of biodiversity, depletion of natural resources, widespread deforestation and the resulting deserts are examples of global environmental degradation. Human economic activity is the principal cause of the environmental crisis through exploitation and pollution, and yet such activity relies heavily on a healthy environment for its continuance and productivity. Rees (1999) says that 'empirical evidence' suggests that resource consumption already exceeds the productive capacity of critical biophysical systems on every continent. He further suggests that waste production has already violated the assimilative capacity of many ecosystems at every scale.

2.2.3.1 Climate change

Climate change has become synonymous with global warming (Loaiciga, 2009) and it is caused by the build-up of greenhouse gases, which trap energy on the Earth's surface. Significant climate change over the next century is expected. The continuing of global warming has intensified many atmospheric extremes leading to significant increase in the frequency and severity of heat waves (Glasby, 2002) and associated effect on human health as shown in table 2.1. The greenhouse gas effect is not a new problem. As early as 1896, a Swedish chemist already proposed that the changing atmospheric carbon dioxide concentration was the major cause of global temperature fluctuations (Kininmonth, 2003). In accordance with Loaiciga (2009), the carbon dioxide concentration in 1765 was about 280 parts per million by volume (ppmv) but it has increased to approximately 364 ppmv in 2009.

Table 2.1 Climate change-induced effects of contaminants on human health

Climate change-induced effect	Relationships/Interactions	References
Increased allergenicity potential	▪ Air pollution and allergen exposures linked to climate change can exacerbate allergic disease and asthma incidences ▪ Climate change enhanced allergen production coupled with POP exposures may sensitize individuals to allergic disease ▪ Low-income populations, infants, children, and the chronically ill may be more susceptible	(D'Amato *et al.,* 2002;Diaz-Sanchez *et al.,* 2003;Epstein, 2005; Janssen *et al.,* 2003)
Increased cardio-respiratory disease	▪ ↑ temperature exacerbates the adverse effects of ozone and PM ▪ The elderly and individuals with pre-existing cardio-respiratory disease may be more vulnerable to these effects	(Bell *et al.,* 2007; Confalonieri et al., 2007; Dominici *et al.,* 2006; Mauzerall et al., 2005; Ordonez *et al.,* 2005; Ren and Tong, 2006)
Altered exposure and risk	▪ Some populations may experience increases or decreases in POP exposures and health risks depending on the region and diet of exposed individuals ▪ Pesticides may impair mechanisms of temperature regulation especially during times of thermal stress	(Bard, 1999; Gordon, 1997; McKone et al., 1996; Watkinson et al., 2003)
Increased susceptibility to pathogens	▪ Toxicants can suppress immune function, and climate-induced shifts in disease vector range will result in novel pathogen exposure ▪ Immune system impairment linked to toxicants may increase human vulnerability to climate shifts in pathogens ▪ Low-income populations, infants, children, and the chronically ill may be more susceptible	(Abadin *et al.,* 2007; Haines *et al.,* 2006; Lipp *et al.,* 2002; Nagayama *et al.,* 2007; Patz *et al*., 2005; Rogers and Randolph, 2000; Smialowicz *et al.,* 2001)

The concentration of carbon dioxide was due to the burning of fossil fuels leading to global warming. In 1985, researchers claimed that global warming was caused by human activities (Kininmonth, 2003) and the first Intergovernmental Panel on

Climate Change (IPCC) confirmed this claim in 1988. The subsequent report, published in 1990, confirmed that there is a greenhouse effect and the increased atmospheric concentration of carbon dioxide was caused by human activities. A second IPCC followed in 1995 and a third in 2001 both expressed increasing confidence that greenhouse gases will cause dangerous future climate change (Bala, 1998; Kininmonth, 2003; Meadows and Hoffman, 2003). Figure 2.1 provides a projection of future greenhouse gas emissions of developed and developing countries. Total emissions from the developing world are expected to exceed those from the developed world by 2015.

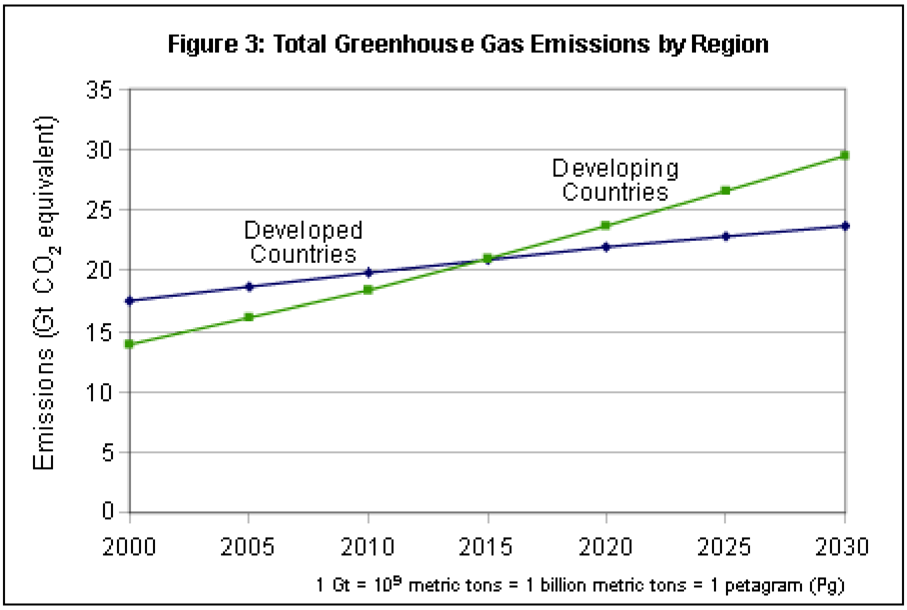


Figure 2.1 World Greenhouse Gas Emissions by region

Source: United States Environmental Protection Agency (EPA).

Apart from the increased atmospheric concentration of carbon dioxide, atmospheric concentrations of other greenhouse gases such as methane, nitrous oxide and chlorofluorocarbons are also increasing as a result of human activities (Loaiciga, 2003). According to the third IPCC in 2001, the Earth's surface temperature has increased between 0.3°C and 0.6°C during the last 150 years (Loaiciga, 2003), and if no environmental pressure or controls are introduced, an increase in global mean temperature of about 2.5°C can be expected by the year 2100 (Houghton, 1997).

The warming of the Earth's surface has a significant effect on the living creatures on Earth and as well as the structure of the atmosphere. Human health will be affected by the increased heat stress and widespread vector-borne diseases such as malaria (Houghton, 1997). Increasing global temperature warms and expands the oceans, melts polar ice caps and, in turn, raises sea levels. It is estimated that there will be an average increase in sea level of about 6cm per decade for a temperature rise of between 1.5 to 5.5°C (Falk and Brownlow, 1989). The sea levels are expected to rise by about 0.5m by 2100 (Houghton, 1997; Bala, 1998). The potential impacts of climate change on anthropogenic (man made activities) systems, of anthropogenic systems on natural systems, and their subsequent influences on natural and human-induced disasters are illustrated in figure 2.2. As sea levels rise, soil erosion, flooding and storm damage to some coastal regions will follow. Ecosystems at river mouths and the quality of fresh water are also affected. Reduced snow and ice will reflect less light back into space and produce even greater warming (Langston and Ding, 2001). High concentration of carbon dioxide in the atmosphere will also affect coastal ecosystem productivity (Bala, 1998). The high concentration of carbon dioxide in the atmosphere also increases the rate of plant loss, that is, loss of biodiversity, another environmental problem that threatens human existence.

2.2.3.2 Biodiversity

Biodiversity refers to the variety of life of Earth. It is an important global resource and its existence has a close relationship with every aspect of human society. Its conservation must be treated as a matter of urgency as human populations are degrading the environment at an accelerating rate, destroying natural habitats and reducing it. According to Glasby (2002) the rate at which species are disappearing is about 1,000 to 10,000 times the normal rate and more than 25 percent of all species could disappear within the next two decades.

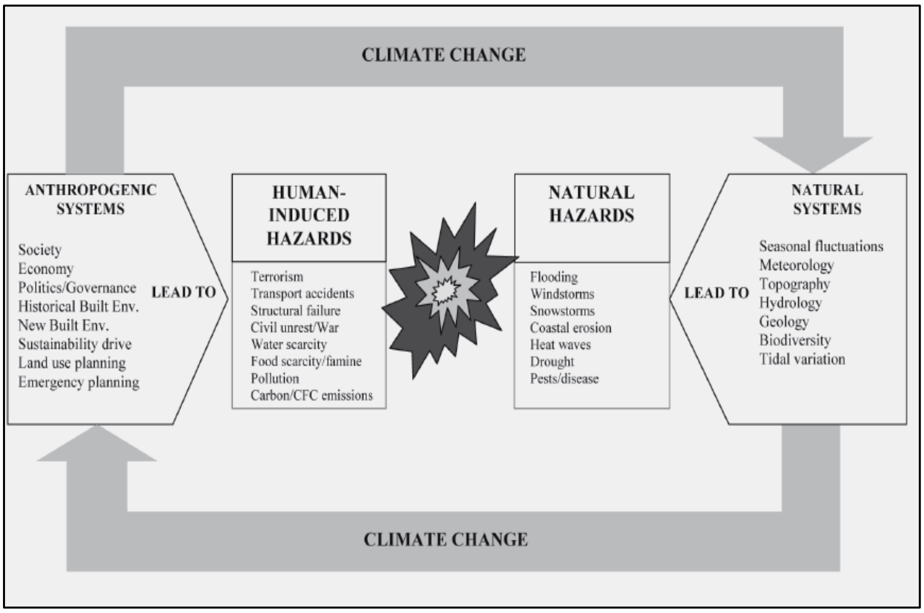


Figure 2.2 Potential relationships between climate change and natural and human induced hazards

Source: adapted from (Bosher *et al.,* 2007)

Biodiversity is important in many ways. First, it sustains food production. With an increasing rate of growth in world population, the demand for food becomes critical (Gilland, 2002). Second, species are the source of medicines to cure a range of known diseases, as well as for medical research and development (Bates, 1990; Wills, 1997; de Mendonca *et al.,* 2003). Third, rainforests play an important role in the terrestrial recycling of carbon, nitrogen and oxygen by helping to regulate the greenhouse effect through absorbing carbon dioxide from the air, returning oxygen (Common, 1995; Pearce, 1998). Fourth, the planet is an interwoven ecosystem. The existence of one species is important to the existence of another. The extinction of one species may eventually lead to the loss of many others dependant upon it, which may result in an accelerated loss of important genetic information (Bates, 1990; Wills, 1997).

The loss of biodiversity may be caused by the expansion of human population and activities (Wills, 1997; Bala, 1998). The construction of facilities and extraction of resources can disturb natural land areas and thereby endanger sensitive ecosystems Flora and fauna destroyed through human activities may not fully regenerate.

2.2.3.3 Population growth

Population growth is clearly a major threat to the environment (Munda *et al.,* 1998; Chew, 2001; Glasby, 2002) and there is no doubt that the human population has been putting increasing pressure on the ecosystem of the Earth for food, clean water and resources. It increases the pressure on renewable and non-renewable resources, reduces the amount of capital and productivity per worker, and increases the inequality of income.

According to a 1998 United Nations (UN) report, the global population will increase to eight billion in 2025 and nine billion in 2050 as shown in fig. 2.3 (Young, 1999; Reuveny, 2002). The annual increase in world population is approaching 80 million per year, approximately 90 percent of which is in the poorest countries. The fundamental reason for this increase is that life expectancy is extended as a result of the improvement and advancement of medicine.

Population increases at an exponential rate, placing more demand on food production (Young, 1999; Chew, 2001). However, as Hopfenberg and Pimental (2001) state, the world human food availability continues to grow, but slower than the population rate. The shortage became more evident after the world food summit in 1996 where plans were prepared to reduce the number of under-nourished, estimated as 920 million, to half this level by 2015 (Young, 1999).

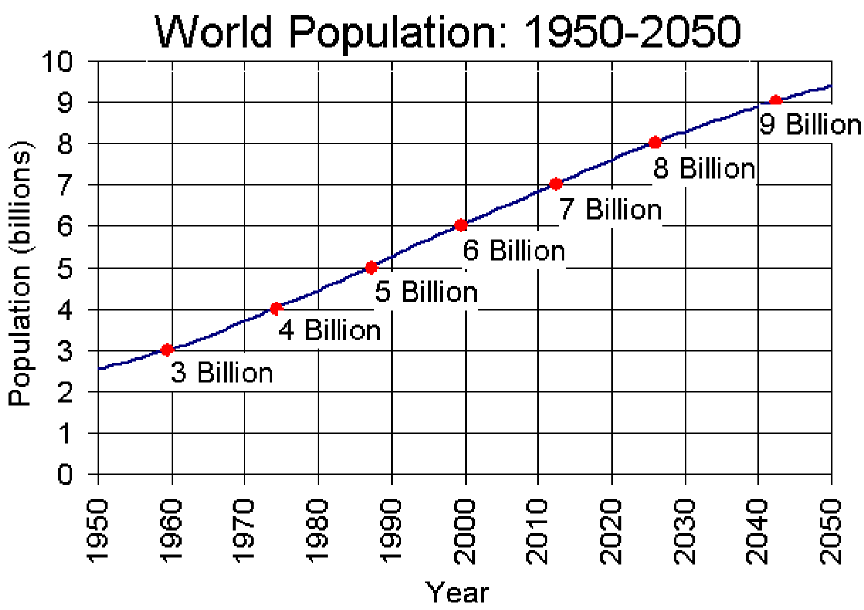


Figure 2.3 World Population Growth, actual and projected, 1950-2050

Source: WRI and Population Reference Bureau 2006 revision

Population growth may also be associated with the world poverty level. Population growth may be a cause of poverty, particularly in the developing countries. In accordance to the World Development Report 2000/2001, 2.8 billion people are earning less than US$2 per day (Glasby, 2002) and the 1998 UN report states that about 25 percent of the world's population live in absolute poverty (Young, 1999). By the end of this century, approximately eight out of nine people will live in poor developing countries compared with approximately one out of two in 1950 (Plant *et al.*, 2000).

As population grows, greater demands are placed on land use, leading to deforestation, loss of biodiversity, water resource shortage, wasted natural resources, loss of soil fertility and increased soil erosion. This is especially serious in the developing countries where deforestation is at its highest. The depletion of soil fertility and water reserves is due to over farming and increased crop production. In order to maintain soil productivity, farmers have to use chemical fertilisers (Gilland, 2002). Crops, which are dependent on chemical fertilisers, tend to rob the soil of its fertility which, in turn, will require more fertilisers in succeeding years. As a result, after a number of years overall productivity may decline, and so even more fertilisers may need to be applied.

This increased fertilisation has further speeded up the rate of global warming in two ways. Fertiliser production involves mining and processing phosphate and nitrogen bearing ores, and this process consumes fossil fuels increasing carbon dioxide production, methane and other greenhouse gases. Fertilisers also reduce the ability of soil microorganisms to remove carbon from the atmosphere. The economic activities and population pressures on rural economies cause migration, especially the urban centres. In accordance with the World Health Organisation, the global urban population has increased from 32 percent in 1955 to 38 percent in 1975 and 45 percent in 1995 (Moore *et al.,* 2003). In 2002, the United Nations Environment Program predicted that the world's urbanisation would increase from 47 percent to 65 percent by 2015 (Moore *et al.,* 2003). The number of cities with a population greater than 1 million has increased from 90 in 1955 to 336 in 1995, representing an increase of 35 percent of the world's population situated in urban areas (Moore *et al.,* 2003).

This rapid urbanisation has caused further environmental problems through contamination of soils, surface water and aquifers from poor sanitation. The results are severe health hazards, especially due to crowding and a poor living environment. Inadequate quality water supply, air pollution, water pollution, poor sanitation services and solid waste collection (Chew, 2001; Moore *et al.,* 2003). The increase in diseases associated with these conditions is further evidence of a declining standard of living.

2.2.4 Protecting the environment

There is no doubt that resource depletion, pollution and population growths are seen as the main causes of biologically and ecologically destructive phenomena. The increase in the amount of human activities is responsible for the amount of pollutants dumped onto land, into water and the atmosphere, causing various pollution problems to the environment, hazardous wastes generated from economic activities and stratospheric ozone depletion from chlorofluorocarbons. Evidently the planet is in environmental crisis and these environmental problems are inter-related. The environment needs to be treated as a whole, rather than paying attention to its individual parts. The links between the environment and the economy established earlier also ensure that the environmental crisis is also an economic crisis. It is caused by economic activities and it undermines the very functions on which economy depends. Thus there is need therefore to find an approach to balance economic growth and protection of the environment.

2.3 Emergence of sustainable development

2.3.1 Background

Sustainable development has become pre-eminent in the discussions on the relationship between humankind and nature. It has also evolved as a mainstream research focus and much attention has been devoted to the sustainability agenda from researchers of various backgrounds. In 1987, the United Nations released the Brundtland report, which defines sustainable development as "development which meets the need of the present without compromising the ability of future generations to meet their own needs" Numerous organizations and individuals have proposed sustainable development as an alternative model for global economic development as a result of worldwide recognition of the negative effects of current and potential environmental degradation on social development.As a result, a substantial amount of information has been generated. The widespread rise of interest in, and support for, the concept of sustainable development is potentially an important shift in understanding relationships of humanity with nature and between people. It is in contrast to the dominant outlook of the last couple of hundred years, especially in the 'Northern hemisphere', which has been based on the view of the separation of the environment from socio-economic issues (Hopwood *et al.,* 2005). For most of the last couple of hundred years the environment has been largely seen as external to humanity, mostly to be used and exploited, with a few special areas preserved as wilderness or parks. Environmental problems were viewed mainly as local. On the whole the relationship between people and the environment was conceived as humanity's triumph over nature. This Promethean view (Dryzek, 1997) was that human knowledge and technology could overcome all obstacles including natural and environmental ones.

This view was linked with the development of capitalism, the industrial revolution and modern science. As Bacon, one of the founders of modern science, put it, 'The world is made for man, not man for the world'. Environmental management and concern amongst most businesses and governments, apart from local problems and wilderness conservation, was at best based on natural resource management. A key example was the ideas of Pinchot in the USA (Dryzek, 1997), which recognized that humans do need natural resources and that these resources should be managed, rather than rapidly exploited, in order to ensure maximum long-term use. Economics came to be the dominating issue of human relations with economic growth, defined by increasing production, as the main priority (Douthwaite, 1992). This was the seen as the key to humanity's well-being and, through growth, poverty would be overcome: as everyone floated higher those at the bottom would be raised out of poverty.

2.3.2 The concept of sustainability

The concept of sustainable development as we know it today emerged in the 1980s as a response to the destructive social and environmental effects of the prevailing approach to "economic growth". The idea originated within the environmental movement. One of the earliest formulations of the concept of sustainable development can be found in the 1980's World Conservation Strategy jointly presented by the UN Environment Programme, the World Wildlife Fund and the International Union for conservation of nature and natural Resources (UNEP/WWF/IUCNNR, 1980). This early formulation emphasised that:

For development to be sustainable, it must take account of social and ecological factors, as well as economic ones; of the living and non-living resource base; and of the long-term as well as the short-term advantages and disadvantages of alternative actions (UNEP/WWF/IUCNNR, 1980).

It called for three priorities to be built into development policies: the maintenance of ecological processes; the sustainable use of resources; and the maintenance of genetic diversity. However, the concept of sustainable development gained a wider recognition only after the World Commission on Environment and development (WCED) published its report "our common future" (also known as "the Brundtland Report") in 1987. The WCED report set the benchmark for all future discussions on sustainable development. The starting point for the Commission's work was their acknowledgement that the future of humanity is threatened. "Our common future" opened by declaring:

The earth is one but the world is not. We all depend on one biosphere for sustaining our lives. Yet each community, each country, strives for survival and prosperity with little regard for its impacts on others. Some consume the earth's resources at a rate that would leave little for future generations. Others, many more in number, consume far too little and live with the prospects of hunger, squalor, disease, and early death (WCED, 1987).

To confront the challenges of over consumption on one hand and grinding poverty on the other, the Commission called for sustainable development. In order to reverse unsustainable trends, the WCED recommended the following seven critical actions aimed at ensuring a good quality of life for people around the world (WCED, 1987):

- revive growth;
- change the quality of growth;
- meet essential needs and aspirations for jobs, food, energy, water and sanitations;
- ensure a sustainable level of population;
- conserve and enhance the resource base;
- reorient technology and manage risk; and
- include and combine environment and economic considerations in decision-making.

The purpose is to avoid environmental and/or social meltdown, thus ‘sustaining’ the existence of not only modern society, but the future of the human species. According to Du Plessis (2007) the relationship between humans and their environment is determined by a number of factors. The first is the interpretation of ‘quality of life’ held by a particular society. This is the main determinant of the needs that have to be met. The second factor is the choices made in terms of the technological, political, economic and other systems adopted by mainstream society. These two factors are informed by the particular value system a society subscribes to. This value system not only determines the relationship between people within that society, but also how a society responds to its biophysical environment. The biophysical, in turn, influences these choices through the limitations of its source and sink capacities. Within this complex relationship (described in Figure 2.4) a number of responses are possible, some wiser than others. Sustainable development tries to identify and promote the responses that will allow the continued existence of the community (or species) at the best possible quality of life.

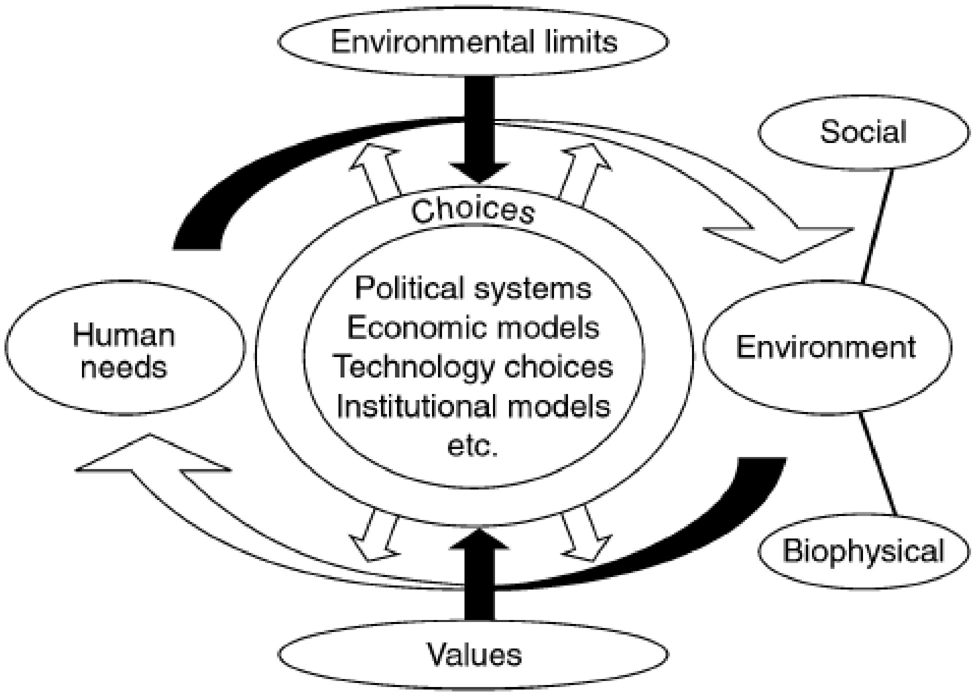


Figure 2.4. A relational model of sustainable development
Source: Adapted from Du Plessis (2007)

Since the Brundtland report, a whole series of events and initiatives have brought us to the wide-ranging interpretation of sustainable development that we see today. One of the key events was, undoubtedly, the United Nations Conference on environment and Development, more informally known as the earth summit, held in Rio de Janeiro in 1992. At the earth summit, representatives of nearly 180 countries endorsed the Rio Declaration on Environment and Development which set out 27 principles supporting sustainable development. The assembled leaders also signed the Framework convention on Climate Change, the Convention on Biological Diversity, and the forest principles. They also agreed a global plan of action, Agenda 21, designed to deliver a more sustainable pattern of development and recommended that all countries should produce national sustainable development strategies.

Ten years later, in September 2002 at the World Summit on Sustainable Development (WSSD) in Johannesburg, leaders and representatives of 183 countries reaffirmed sustainable development as a central element of the international agenda. The governments present agreed to a wide range of concrete commitments and targets for actions to achieve sustainable development objectives, including (WSSD, 2002):

- to halve, by the year 2015, the proportion of people in poverty;
- to encourage and promote the development of a 10-year framework of programmes to accelerate the shift towards sustainable consumption and production;
- to diversify energy supply and substantially increase the global share of renewable energy sources in order to increase its contribution to total energy supply;
- to improve access to reliable, affordable, economically viable, socially acceptable and environmentally sound energy services and resources;
- to accelerate the development and dissemination of energy efficiency and energy conservation technologies, including the promotion of research and development;
- to develop integrated water resource management and water efficiency plans by 2005; and
- to achieve by 2010 a significant reduction in the current rate of loss of biological diversity.

The Johannesburg summit moved the sustainability agenda further and consolidated and broadened the understanding of sustainable development, particularly the important linkages between poverty, the environment and the use of natural resources. These political events brought sustainable development firmly into the public arena and established it as a widely accepted goal for policy makers. As a result, we have seen a proliferation of sustainable development strategies and policies, innovative technological, scientific and educational initiatives, and new legislative regimes and institutions. The concept of sustainable development now influences governance, business and economic activity at different levels, and affects individual and society lifestyle choices.

2.3.3 Mapping Sustainable Development

In the last three decades, a continuing debate about what sustainability truly means has produced a plethora of definitions. However, it has often been noted that there appears to be no common understanding either on the definition of sustainable development or on the possible measures needed to be taken in order to achieve it (e.g. Bebbington, 2001; Callens and Tyteca, 1999; Gray and Bebbington, 2001; Islam et al., 2003; Livesey and Kearins, 2002; Meadowcroft, 2000; Robinson, 2004). Previous research suggests the total numbers of definitions are in the range of 100 – 200 (Pezzey, 1989; Holmberg and Sandbrrok, 1992; Hill, 1998; Parkin, 2000; Moffatt, 2001). The broad appeal of the concept (SUE-Mot, 2004) and multiplicity of definitions are causing confusion and dichotomy among its protagonists. A simple database search indicates a tremendous wealth of literature has been accumulated over the past few years. This information overload on the concept makes its practical application very difficult to every institution that embarks upon the journey toward a sustainable environment and those institutions tasked with creating a sustainable society.

A wide variety of groups-ranging from businesses to national governments to international organization- have adopted the concept and given it their own particular interpretations. Table 2.2 lists just a small number of such definitions and the varied interpretations of the concept which have flowed from these different ideas. Definitions are important, as they are the basis on which the means for achieving sustainable development in the future are built. Hill and Bowen (1997) describe sustainable development as that development effort which seeks to address social needs while taking care to minimise potential negative environmental impacts. Postle (1998) goes further, suggesting that sustainability, as a concept, has a far wider reach than the environment, encompassing a whole range of social and ethical factors such as employment, social welfare, culture, infrastructure and the economy. In other words, sustainability requires that all of the factors that contribute to long-term societal benefit be catered for in decision-making. Ball (2002) supports the idea that sustainable development is a broader concept than sustainability and includes issues on the quality of life and the integration of social, economic and environmental spheres of activity. Indeed, sustainable development need not always be seen as restrictive to making choices among the issues, but as an integrated approach to consider all the issues.

As described by Du Plessis (1999), sustainable development initially only addresses the conflict between protecting the environment and natural resources, and answering the development needs of the human race. However, he believes that sustainable development would not be possible without tackling the problems of poverty and social equity both between people and between nations. Indeed, as Spence and Mulligan (1995) state, the only way to reduce environmental deterioration is to eliminate poverty by raising standards of living. This is particularly important in the developing countries as environmental degradation is closely related to rapid population growth, land degradation and loss of the tropical forest (Spence and Mulligan, 1995; Ofori, 1998; Du Plessis, 2001). Du Plessis (2001) further states that social responsibility as a principle of sustainability is achieved through sharing the benefits of wealth with the community.

Table 2.2 Sustainable development definitions

Authors	**Definitions of sustainable development**
Turners, 1988	'in principle, such an optimal (sustainable growth) policy would seek to maintain an "acceptable" rate of growth in per-capita real incomes without depleting the national capital asset stock or the natural environmental asset stock.'
Conway, 1987	'the net productivity of biomass (positive mass balance per unit area per unit time) maintained over decades to centuries.'
WCED, 1987	'development that meets the needs of the present without compromising the ability of future generations to meet their own needs.'
	Interpretation of sustainable development
Mitchell, 1997	'a creatively ambiguous phrase . . . an intuitively attractive but slippery concept.
Redclift, 1997	'like motherhood, and God, it is difficult not to approve of it. At the same time, the idea of sustainable development is fraught with contradictions.'
Barbier, 1987	' it is indistinguishable from the total development of society.'
O'Riordan, 1995	'its very ambiguity enables it to trascend the tensions inherent in its meaning.'
Mawhinney, 2001	'sustainable development appears to be an over-used, misunderstood phrase.'

Therefore, development is guided by community interest, not individual profit. From these discussions it is clearly shown that the means of achieving sustainable development deals with the concepts of environment, futurity and equity, with the emphasis that the welfare of future generations should be considered in the decision- making process. On the other hand, The International Institute of

Sustainable Development (IISD) stipulates that sustainable development should also simultaneously consider the improvement of the economy. Beder (1996), Berggren (1999), Stigon (1999) and Rohracher (2001) all discuss the concept of sustainable development in the context of considering economic growth in addition to the social and environmental dimensions). Economic growth, with an emphasis on aspects such as financial stability and material welfare creation, is the ultimate goal for every government in order to secure rising standards of living and increase the capacity of providing goods and services to satisfy human needs.

The UK government, for example, in its sustainable development strategy defines sustainable development as "the simple idea of ensuring a better quality of life for everyone, now and for generations to come" (DETR, 1999). The strategy emphasises that sustainable development means meeting the following four objectives at the same time, in the UK and the world as a whole:

- social progress which recognises the needs of everyone;
- effective protection of the environment;
- prudent use of natural resources; and
- maintenance of high and stable levels of economic growth and employment.

Evidently, different disciplines have influenced and contributed to the sustainability debate, 'each making different assumptions about the relation between environment and the human subject' (Lee *et al.,* 2002). Differences are even more important when thinking about policy development: how the human and environmental condition is thought about, viewed or understood underpins subsequent planning and interventions in the form of development and conservation projects, yet different disciplines and philosophies may assign quite divergent ‘order of priority’ to these policies and programmes. During the course of this text, it will be apparent that, although there are many signs of progress, there is also much debate and uncertainty as to the most appropriate strategies to foster sustainable change. Indeed as suggested in table 2.2, the attractiveness (and the dangers) of sustainable development may lie precisely in the varied ways in which it can be interpreted and used to support a whole range of interests or causes.

The challenges of understanding what this idea of sustainable development may mean, and how people can work towards it, are evident in a brief analysis of the definition of sustainable development provided by the WCED. Their apparently simple definition of sustainable development is immediately seen to contain a distinction and a potential conflict between the interests of the present and those of the future generations. To help make sense of them (Hopwood *et al.,* 2005) suggested a mapping methodology based on combining environmental and socioeconomic issues. O’Riordan (1989) in his widely used categorization of environmental views, from strong eco-centric to strong techno-centric, pointed out that these often combine with socio-economic viewpoints so that eco-centrics tend towards social and economic equity and redistribution while techno-centrics are more likely to support the economic and political status quo.

However this is not always the case as Dobson (2000) points out, ‘sustainability and social justice do not necessarily go hand in hand’, with sustainability masking injustice or on the other hand social justice masking environmental damage. In many cases the linking of environmental and social concerns is based on a moral (Blowers, 1993) or sympathetic outlook rather than seeing the two as materially and socially related and inseparable. Others (Merchant, 1992; Dryzek, 1997) have also outlined useful ways of analysing environmental concerns; however, there has been less effort in mapping the many viewpoints on sustainable development. Further, very challenging notions can be identified such as those of needs and limits. Fundamentally, ‘needs’ means different things to different people and are linked to our ability to satisfy them, i.e. are closely aligned to ‘development’ itself. So, society is able to define and create new ‘needs’ within certain groups (that could be interpreted as ‘wants’), without satisfying even the basic needs of others. These questions highlight the many sources of conflict in the debates over the meaning of sustainable development: conflict between the interests of present generations and those of the future; between human well being and protection of nature; between poor and rich; and between local and global.

Furthermore, the substantial challenges of operationalising the concept of sustainable development were clear in the report of the WCED, back in 1987. Table 2.3 displays the critical objectives identified by the commission and the necessary conditions for sustainable development in the future, evidently encompassing a huge breadth and scale of activity. A more prosperous, more just and more secure global future was seen to depend on new norms of behaviour at all levels and in the interest of all. The conditions for such a future encompass all areas of human activity, in production, trade, technology and politics, for example, and encompass cooperative and mutually supportive actions on behalf of individuals and nations at all level of economic development.

Table 2.3 Critical objectives and necessary conditions for sustainable development

Critical objectives
• Reviving growth • Changing the quality of growth • Meeting essential needs for jobs, food, energy, water and sanitation • Ensuring a sustainable level of population • Conserving and enhancing the resource base • Re-orientating technology and managing risk • Merging environment and economics in decision-making
Pursuit of sustainable development requires
• A political system that secures effective citizen participation in decision-making • An economic system that provides for solutions for tensions arising from disharmonious development • A production system that respects the obligation to preserve the ecological base for development • A technological system that fosters sustainable patterns of trade and finance • An international system that fosters sustainable patterns of trade and finance • An administrative system that is flexible and has the capacity for self-correction

Source: World Commission on Environment and Development (WCED), 1987.

In spite of differing perceptions about the precise meaning and the possible interpretation of the term 'sustainable development', it is widely accepted that for a development to be sustainable it must examine ecological, economic, social and ethical aspects of reality (see fig.2.5). It also places emphasis on the importance of combining economics and ecology in development planning (Tisdell, 1993; Van Pelt, 1994; Spence and Mulligan, 1995; Moffatt, 1996; Berggren 1999; Stigon 1999). The divergence of opinion relating to the term proves that sustainability is so broad an idea that a single definition cannot adequately capture all meanings of the concept. While there is little consensus about a definition for sustainable development, there are certainly commonly accepted principles that can be used to guide the process of development (du Plessis, 1999). Sustainable development is a continuous process of dynamic balance instead of a fixed destination that must be reached at a certain time (Berggren, 1999; du Plessis, 1999).

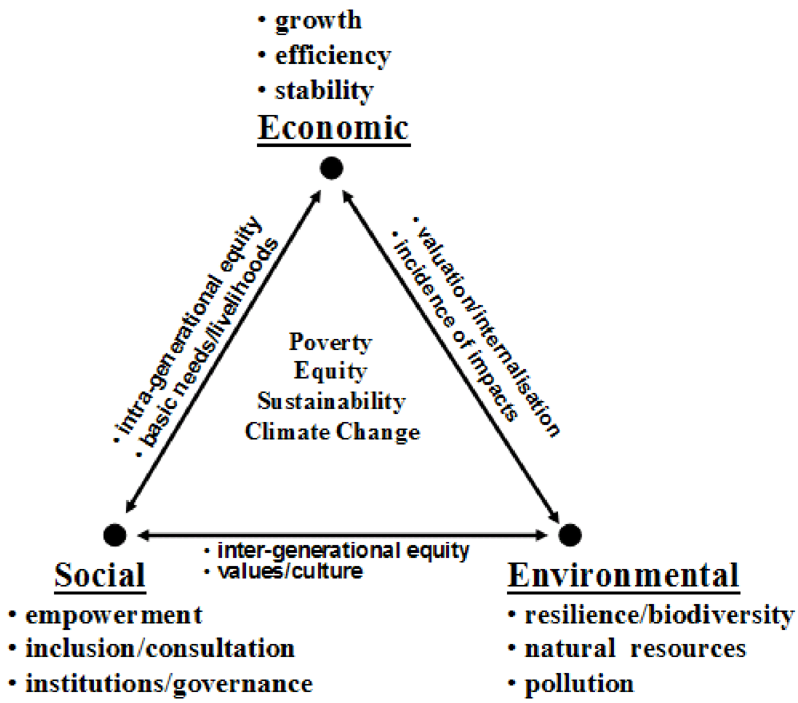


Figure 2.5 Sustainable development triangle – key elements and interconnections
Source: adapted from Munasinghe (1994)

In summary, the concept of sustainable development must consist of the examination of economic, social and environmental aspects of a development. In addition, sustainable development may not be viewed as one-dimensional, but consists of multiple facets of issues that concern people today and in the future. It is the concept of sustainable development on which this research is based to develop a sustainability model for material selection. The Brundtland report, although it has been shown to be vague in its own way, provides sufficient explanation of what sustainable development may have meant. To this end, to find a precise definition of sustainable development that satisfies all needs may be difficult. It is more important to find ways to achieve sustainable goals in order to maintain and conserve the environment, so that future generations will not be disadvantaged. It is also difficult to derive a definition that applies to all sectors in the economy; therefore it is more realistic to define the concept of sustainable development with particular reference to each sector.

2.4 Environmental valuation techniques

2.4.1 Introduction

Environmental valuation refers to the process of identifying environmental issues, the collection of information and incorporating the information into the decision-making process. Before a decision is made, all environmental effects are to be expressed in numeric form and then converted to a single unit of measurement that has a dollar value. Therefore environmental valuation is to put a monetary value on the environmental effects of economic decisions, and to provide a framework for comparing the environmental loss with economic gains (Herendeen, 1998; Boughey, 2000). Such monetary units offer consistency and direct access to policy-makers (van de Bergh, 1996). Winpenny (1991) describes three reasons for valuing the environment. Firstly, it helps a better selection of materials as the environmental costs are considered. Secondly, it provides a measure of economic efficiency and finally, it offers a basis for resolving use conflicts and awarding compensation in a fairer distribution of wealth.

In Section 2.1, environmental problems are closely linked with the absence of market value for environmental goods and services (Harding, 1998; Boyd, 2007). There is no pricing mechanism to acknowledge an ecosystem's value to the economy and to be included in the current gross domestic product (GDP) accounts (Alexander *et al.,* 1998). The ecosystem is typically unpriced, or not priced correctly because of a lack of private and organised markets for such services. It is because most environmental services are considered 'free' goods, in that they are not marketed and so no price exists to assess their values. Omitting this environmental valuation can lead to an underestimation of environmental damage (van de Bergh, 1996; Alexander et al., 1998; Harding, 1998).

Over the years, attempts have been made to incorporate the value of ecosystems in the traditional GDP accounts: termed 'green' GDP (Pearce *et al.,* 1989; Boyd, 2007). Green gross domestic product (green GDP) is meant to account for nature's value on an equal footing with the market economy. However, according to Boyd (2007) several problems bedevil green GDP. One is that nature does not come pre-packaged in units like cars, houses, and bread. Even worse, green GDP requires measurement of the benefits arising from public goods provided by nature for which there are no market indicators of value and fails to account for the productivity of ecological inputs and is, therefore, of little use. The United Nations has developed the Satellite System for Integrated Environmental and Economic Accounting (SEEA) as a way of expanding the overall scope of the national accounts, while leaving the core accounts undisturbed (Lintott, 1996; van den Bergh, 1996; Herendeen, 1998). Other attempts such as regulations or fiscal policies, introduction of tradable abstraction rights and pollution permits have been used to promote environmental protection (Field, 1996; Boughey, 2000).

Valuing environmental resources is using market forces to determine resource allocation and ensure less wasteful consumption. The approach helps to place an upper limit on resource usage and allowing a trade-off process to establish market prices by which these resources will be allocated (Boughey, 2000; Boyd, 2007). According to Pearce and Turner (1990) the adoption of monetary valuation can help to stimulate environmental awareness, justify a decision, and evaluate regulation so as to indicate relevance to macroeconomic objectives and to determine compensation. However, the problem is that some potential consumers are not even born and cannot help to determine current prices.

There are several different ways to assign monetary values to environmental benefits or damages. In accordance with OECD (1995), the valuation techniques can be grouped into three main kinds namely (i) market valuation of physical effects, (ii) stated preference and (iii) revealed preference methods as shown in Table 2.4. The market valuation of physical effects observes environmental changes in physical terms and the differences are estimated accordingly. The stated preference methods obtain values of environmental assets by asking people directly to place monetary values on environmental issues such as the value of preserving a forest. It is a questionnaire-based social survey to obtain individuals' willingness to pay for an environmental gain or to accept compensation for a loss (Turner *et al.,* 1994). The revealed preference methods concern the examination of people's behaviour to the environment. It is based on surrogate markets, which act as a proxy for the missing environmental goods and services in the market (Turner *et al.,* 1994).

Each valuation technique has strengths and weaknesses. Deciding which technique to use will depend on the nature of environmental goods. Therefore, these techniques should be considered as complementary rather than competitive (OECD, 1994).

Table 2.4 Summary of environmental valuation techniques

Market valuation of physical effects	
Dose-response method	Based on developing a dose-response relationship between output level of economic activities and environmental qualities. This technique is used to identify the consequences of changes in environmental issues to the economic return. To assess the gain or loss of benefits resulting from such a change requires the analysis of biological process, technical possibilities and the effect of resulting production changes on consumer welfare (Hanley & Spash, 1993; Hoevenagel, 1994).
Damage functions	Uses dose-response data to estimate the economic cost of environmental change using the market prices of the units of output (OECD, 1995).
Production function approach	Estimates the change in the environment on output and valued at market prices (Winpenny, 1991; Hanley and Spash, 1993; OECD, 1995).
Human capital methods	Cost estimated using the impact of workers' productivity in relation to bad health caused by environmental changes (Winpenny, 1991; OECD, 1995).
Replacement cost method	Uses the cost of preventing or restoring environmental damages as a way to estimate the value of protecting the environment, such as the cost of pollution (Winpenny, 1991; OECD, 1995; Anon, 1996).
Stated preference methods	
Contingent valuation method	It is a direct valuation method which determines a value by surveying people's `willingness to pay' for an environmental gain or `willingness to accept' compensation for a loss on a hypothetical market scenario (Cameron and Englin, 1997; Harding, 1998; Foster and Mourato, 2002). It was originally proposed by Davis in 1963 and has been widely used by resource economists (Hanley and Spash, 1993) that enable economic values to be estimated for a wide range of commodities not traded in the markets (Tunstall and Coker, 1992; Abelson, 1996).
Revealed preference methods	
Travel cost approach	Developed by Clawson in 1959, it is widely used to evaluate recreational benefits (Thampapillai, 1991; Hanley and Spash 1993; Anon, 1996; Harding, 1998). This approach has simple methodology and it is an indirect environmental valuation method, in which the costs incurred in visiting an area are taken as a proxy to value the site itself. Market-related prices are used to estimate the demand curve for non-market goods. The information is obtained through visitors' surveyed on the distance and costs of travel and the origin of each group, thus providing an indication of the cost of conversion to another use.
Avertive behaviour Defensive expenditure	Information is obtained on the cost of protecting people from potential harm caused by declining environmental quality (Hoevenagel, 1994; OECD, 1995; Langston and Ding, 2001).
Hedonic pricing technique	This is a form of revealed preference analysis attempting to assess the value of environmental assets by estimating the prices of their closest market substitutes such as house prices (Beder, 1996; Gilpin, 1995). Hedonic pricing technique seeks to find a statistical relationship between the levels of environmental services and the prices of the marketed goods using regression analysis (Hanley and Spash, 1993; Anon, 1996). The technique focuses on a single environmental factor such as noise levels or air pollution (Langston and Ding, 2001).

2.4.2 The limitations of environmental valuation techniques

The usefulness and accuracy of environmental valuation techniques is highly controversial. The complex nature of the ecosystem has made it difficult to ascertain the quantity of natural resources and the functions they perform in relation to our daily activities. Moreover, environmental effects have no natural units of measurement. Consequently, it is difficult to translate them into economic valuations and bring them into national account calculations (El Serafy, 1991). Foster and Mourato (2002) suggests that environmental valuation techniques need a unique ability to deal with situations as environmental damages are multidimensional and the trade-off between the dimensions is of particular importance. However as Prato (1999) states, most environmental valuation techniques are single-dimensional, therefore unsuitable for evaluating multifaceted ecological impacts. For a technique to be useful and adequately address environmental issues, it needs to be more diverse and embrace the complex nature of the environment. However as van de Bergh (1996) explains no single valuation method yet exists that provides a satisfactory valuation across the full range of environmental goods and services. It is also argued that the benefit of the environment to society is too complex to be captured by a single dollar value and to attempt to do so is to underestimate the importance of the environment (Gregory *et al.,* 1993; Harding, 1998). Indeed, shadow pricing method is particularly difficult and it becomes even harder as the valuation involves evaluating future demands over a number of generations and over different social groups (Harding, 1998). Consequently, environmental impacts are often ignored in the decision-making process.

According to Hanley and Spash (1993), the only inclusive method that can be used to value a variety of environmental resources is the contingent valuation (CV) method. Other methods are restricted to measuring a limited class of environmental impact. However the CV method's usefulness to value environmental services is debatable and must be viewed with caution (Gilpin, 1995). Gilpin (1995) further states that a willingness to pay might be overstated to encourage preservation of an area, or might be understated to minimise the possibility of a significant user charge or levy. The possibility of over or understatement in the CV method is a major problem in environmental valuations as it is unable to provide a true market value to be incorporated in the decision-making process (Hanley and Spash, 1993).

Another problem with survey-based approaches is that biases may arise (Hanley and Spash, 1993; Anon, 1996; Crookes and de Wit, 2002). The CV method is a typical example as it relies heavily on an individual's view rather than actual market behaviour, which is highly responsive to supply and demand theory. The sums of money stated may exceed the willingness to pay because the participants knew they would not really have to pay (Hanley and Spash, 1993; Anon, 1996; Prato, 1999). The biases may also be caused by the survey design (Abelson, 1996) or due to the hypothetical situation with which survey respondents are unfamiliar or lack of experience with the environmental resource being valued (OECD, 1995; Cameron and Englin, 1997) necessitating the provision of explicit background information about the resource. Environmental valuation techniques also attract argument about the feasibility and desirability of converting all environmental benefits and costs into dollar values; the main argument being that ethical issues such as the worth of a human life is beyond any monetary valuation (van de

Bergh, 1996; Prato, 1999; Hobbs and Meier, 2000). Many people dispute that it is possible to assign accurate economic values to aspects of the environment, which often do not have any direct use in the economy. Therefore they consider that it is morally unacceptable to attempt to estimate non-use values. Thus many natural resources are considered priceless and cannot be compared with ordinary market commodities (Abelson, 1996; Harding, 1998). Crookes and de Wit (2002) further state that if such an approach is incorrectly interpreted, unethical issues are attached. So far, trying to put a monetary value on environmental assets using environmental valuation is inadequate and undesirable.

Environmental valuation requires extensive information to be collected and analysed. Except for the travel cost method, most valuation methods require extensive data collection, which is lengthy, costly and time-consuming (Tunstall and Coker, 1992; OECD, 1995; Crookes and de Wit, 2002). Additionally, the information required for valuation by various methods might either not be available or only available in an elementary form. This is a particularly serious concern in developing countries (Tewari *et al.,* 1990; Crookes and de Wit, 2002). Each valuation method has its own methodological limitation. As shown in table 2.4 previously, in the hedonic pricing technique, the proposition is simple but the application is complex (Gilpin, 1995) because using house prices as a proxy is highly unreliable as there are too many variables that may affect the price such as age, size, location, quality and layout. Therefore the selection process of which factors to be included will significantly influence the results (Hanley and Spash, 1993; Anon, 1996). Abelson (1996) further states that the whole of the environment is greater than the sum of its parts and it cannot be valued simply on the collection of separate pieces of real property.

The travel cost method is restricted to measuring a limited class of environmental impacts (Anon, 1996) and only direct use values of actual users are measured with this method (Hanley and Spash, 1993). In the dose-response method there may be problems of interdependence between causal variables and whether the alternative costs fully reflect the cost of the externality (Anon, 1996). Conducting a survey-based contingent valuation method could exaggerate the importance of the issue. The result depends on how well the study is designed, carried out and interpreted (Hanley and Spash, 1993; Gilpin, 1995). In avertive behaviour and defensive expenditure methods the problem of underestimating the damage has suffered due to imperfect substitutability is unavoidable in the evaluation (Hoevenagel, 1994). Distribution problems are inherent in valuation techniques. Environmental assets in an area populated with wealthy people cannot be directly compared with poorer people in another without any income adjustment (Anon, 1996). As Abelson (1996) states, everyone has an equal right to natural environmental assets and therefore techniques that are based on income, such as the willingness to pay, are irrelevant and unfair.

2.4.3 Summary of section

The purpose of putting value on environmental assets is to limit environmental degradation and to promote its protection. However, as discussed in this section, putting a price on environmental quality is not useful for protection as the valuation techniques suffer from methodological limitations and cannot accurately value the environment. Furthermore, environmental issues such as biodiversity cannot be priced at all, since plants and animals have an intrinsic value that cannot be represented in dollars. However, even though the environmental valuation techniques are constrained, it will always be better to do something rather than nothing. If putting a price on the environment cannot save the environment, it at least allows the decision-maker and general public to realise the potential damage and, in the process, highlight the importance of environmental conservation and its incorporation into the decision- making process.

As has been shown, the concept of putting a dollar value on environmental assets is controversial and there is no doubt that the current environmental valuation techniques are deficient. Therefore, it is important to transfer the focus from pricing the environmental assets to evaluating them using a non-monetary approach such as multi- criteria analysis. It is the purpose of this research to examine the usefulness of a non- monetary approach to assess environmental issues and to incorporate this into the decision-making process. The next section will present the concept of using such an approach to evaluate environmental issues with focus on building construction and in particular material selection.

2.5 Life cycle cost and multi criteria analysis

2.5.1 Background

This section examines the usefulness and limitation of life cycle cost approach for environmental decision making. It is argued that Life cycle cost analysis as a single dimensional tool is theoretically insufficient to consider environmental effects as they are unable to have a dollar value appended to them (details refer to Section 2.3). The issues raised in the literature have called for a review of the method. The debates are working towards a complementary assessment tool such as multi-criteria analysis. Multi-criteria analysis does not require a dollar value to be appended to environmental effects, nor does it exclusively focus on efficiency measurement. This section provides a detailed discussion of the issues raised in the literature and the usefulness of both methodologies in environmental valuation.

2.5.2 Life cycle cost analysis as an evaluation tool

Life Cycle Costing (LCC) according to Dahlen and Bolmsjo (1999) is an economic evaluation techniques used when quantifying the cost related to a production system or a product during its life cycle. When applied to building construction, the BS ISO 15686 of service life planning (BSI 2000) defines LCC as "a tool to assist in assessing the cost performance of construction works, with the aim of facilitating choices where there are alternative means of achieving the client's objectives". Bartlett and Howard (2000) went further by saying the alternatives not only need differ in their initial cost, but also in their subsequent operational cost. The concept covers the total cost performance of an asset over time, including the acquisition, operating, maintenance and disposal cost (Rausand and Hoyland, 2004; IEC, 2004; Utne, 2009).

The development of LCC has its origin in the normative neoclassical economic theory which states that firms seek to maximise profits by always operating with full knowledge (Cyert and March, 1963 cited in Gluch and Baumann, 2004). The theory sought consistent preferences from decision makers and reminds them of the need to know their preferences as well as the available alternatives (Caroll and Johnson, 1990). Therefore access to information and the ability to combine the information in the face of significant consequences is important in selecting alternative from options.

Caroll and Johnson (1990) pointed out that the behaviour of the 'economic man' in neoclassical economic theory is always rational and descriptive decision-making studies by the same author have shown that individuals do not make rational decisions, especially when uncertainty is involved because of complex and long-term consequences, which is typical for environmental decision-making. Gluch and Baumann (2004) listed at least four inherent limitations in neoclassical economic theory that restricts its use in an environmental context:

- Since it assumes that the decision-maker is always rational and has access to complete information concerning alternatives and outcomes, it cannot handle decision-making under genuine uncertainty
- It assumes that alternatives are always available. With such a view irreversible changes, such as extinction of species, are not considered as a problem since they can be 'replaced' without changing the ecosystem.
- It ignores items that have no owner, such as the natural environment.
- It over-simplifies multi-dimensional environmental problems since it assumes that everything can be expressed as a one-dimensional unit, such as monetary figures.

The above limitations suggest that tools based on the neoclassical theoretical theory will always be beset with severe shortcomings and are inappropriate in handling environmental issues (Gluch and Baumann, 2004). Detail limitations in relation to environmental applications of LCC are discussed more extensively in the following section following the work of Gluch and Baumann (2004).

2.5.2.1. Uncertainty in decision making

The environmental consequences of a decision according to Gluch and Baumann (2004) often occur long after the decision was made, and not necessarily in the same location. Moreover according to English (1998), it is difficult to detect the impact of environmental decisions on the environment. Wolff (1998) went further saying environmental decisions, being closely coupled with society's built-in uncertainties and risks, are genuinely uncertain since the way ecological systems as well as social systems change in the future need to be considered in the decisions. Issues that are not considered as problems today may well be in the future, in the same way as today's environmental problems were not anticipated yesterday (Wolff, 1998).

Environmental decisions therefore are characterised by considerable uncertainty at all stages of the decision-making process, such as the problem definition, possible outcomes and probabilities of the outcomes (Gough, 1996). Buildings, for example, are long-term investments associated with large environmental impacts over a long duration. To estimate environmental costs so far into the future may result in an LCC calculation that is faulty (Ashworth, 1996), i.e. the calculated LCC may have little resemblance to future real cost. Bejrum *et al;* 1996 cited in Gluch and Baumann (2004), listed investment decisions that affect a building to be the business, physical and institutional uncertainties. Physical risks are often due to uncertainty as to a building's design or a material's functional characteristics and performance change during the building's lifetime. Such uncertainty may involve building material that through new scientific evidence has become unsuitable, as for example asbestos cement sheeting and CFC (Gluch and Baumann, 2004). In addition Ashworth (1996) wrote that uncertainty in business has a relationship with the unpredictable fluctuations in the market as could be seen in the effect of changing regulations on building and construction industry. Many political decisions can instantly change the "rules of the game". For example, building materials may become prohibited, as with the asbestos (Gluch and Baumann, 2004).

It is also easy to envisage that materials and components that are difficult to recycle will be expensive to dispose of in the future both for technical reasons and due to increasing disposal taxes. In addition to political decisions, external market factors, institutional regulations and environmental changes may also lead to changing conditions. The modernity of a real-estate project is affected by customers' (tenants') increased awareness of environmental issues, which implies that buildings that are not continually adjusted to environmental norms or to presumptive regulations run the risk of becoming outdated rather quickly (Gluch and Baumann, 2004)

An analysis that relies on estimation and valuation of uncertain future incidents and outcomes is therefore problematic. There are numerous techniques available that attempt to decrease the uncertainty of future consequences, for example scenario forecasting, sensitivity analysis, probability analysis, decision trees and Monte Carlo simulation (Flanagan *et al;* 1987). However, these techniques presuppose that decision makers are aware of the nature of the uncertainties that can be expected during the building's lifetime. A study of risk management (Ashworth, 1996) revealed that real-estate managers when conducting a sensitivity analysis of LCC only considered tangible aspects such as interest rate, rental degree and increase or decrease of rent. Furthermore, when estimating risk and uncertainty the property managers relied more often on their intuition and rules of thumb than on techniques, such as sensitivity analysis. This implies that easily accessible information and subjective values to a large extent influence the parameters considered in estimating risk and uncertainty, i.e. the result from the LCC are biased.

2.5.2.2 Irreversible decisions

Individual or collective choice theories in Andrikopoulos and Zacharias (2008) assume that individual makes choices among a set of alternatives (a range of choice options) that are feasible or available and which maximize his own preference relation. However, as Gough (1998) and English and Dale (1999) observed, the consequences of the decision to invest in building projects extend across a long period of time and many decisions lead to irreversible outcomes. This could be seen in the radical changes and damages to the natural topography, as a result of a construction project, of which is not restorable. Therefore gaps exist between the current environmental realities with the basic assumption of the existence of availability of alternatives, in the consideration environmental issues in decision-making. The large number of materials in a building implies that several subsequent decisions must be made during the building's lifetime. The investment process therefore contains sequential decisions, meaning that earlier decisions will influence subsequent decisions. Since irreversible changes take place in ecological systems as well as in sequential decisions it is not possible to ignore irreversibility as the neoclassical economic theory does (Gluch and Baumann, 2004).

2.5.2.3 A monetary unit

In order to simplify a complex reality, which is necessary out of a practical perspective, LCC aims at translating all impacts (including environmental impacts) into a single unit of measure -monetary unit. (Pecas *et al.,* 2009). However, according to Gluch and Baumann (2004), a problem is that LCC in its attempt to translate environmental problems into a monetary unit may oversimplify reality. Neoclassical economic theory presupposes that all relevant aspects have a market value, i.e. a price. As mentioned in the previous section, there are items that are not possible to price. This leads to monetary calculations being incomplete with regard to environmentally related costs. Many economic theorists suggest different ways to put a price on environmental items for example through environmental taxes (Pearce and Turner, 1990; Hanley *et al.,* 1997), but others argue that it is impossible to catch all relevant aspects of complex environmental problems into one monetary figure (Soderbaum, 1998 cited in Gluch and Baumann, 2004). The money value attached to LCC consequently results in loss of important details which in turn limits the decision maker's possibility to obtain a comprehensive view of environmental problems (Gluch and Baumann, 2004)

In the light of the foregoing, Multi criteria analysis (MCA) approach has been advocated as an alternative technique that can incorporate environmental issues into decision making process. MCA is a more flexible methodological approach as it can deal with quantitative, qualitative or mixed data for both discrete and continuous choice problems and does not impose any limitation on the number and nature of criteria (van Pelt, 1994). However, LCC is limited to quantitative data for discrete choice problems. As a result, MCA is a more realistic methodology in dealing with the increasingly complex nature of building project. Principles of MCA are discussed hereafter.

2.5.3 The principles of multi-criteria analysis

Decision makers are faced with building evaluation techniques as a tool to characterise, assess and structure the complex array of data relevant to a building process into a manageable form and provide an objective and consistent basis for choosing the best solution for a given situation. In LCC, much effort has been put into assessing total cost performance by means of a market approach. With the increasing awareness of possible negative external effects, LCC usefulness in this respect is increasingly controversial. Consequently, increasing attention is shifting to multi-dimensional evaluation approaches (Gough and Shackley, 2006). One such approach is known as multi-criteria analysis (MCA).

Ding (2008) report that the identification of value for money on construction projects is clearly related to monetary return. His report also observes significant increase in other issues particularly in social infrastructure projects. For example, issues such as welfare enhancement and resource efficiency are seen vital to the assessment of environmental impact in the wider social context. Since no single criterion can adequately address all the issues involved in complex decisions of this type, a multi-criteria approach to decision-making offers considerable advantages (Ding, 2008).

Ecologically sustainable development (ESD) is now a constant focus for the mass media and a matter for widespread public concern (Joubert *et al.,* 1997). As a consequence, intangibles and externalities have become major issues in building design and construction. The presence of externalities, risks and spillovers generated by building construction often preclude the meaningful and adequate use of a market-based methodology (Ding, 2004), but when the analysis turns to assessment of environmental quality or loss of biodiversity, Nick and Valence (2004) observed it is rarely possible to find a single variable whose direct measurement will provide a valid indicator of the severity of these effects. The need to incorporate environmental issues into the building process is becoming increasingly apparent, and as it does, applying market prices to these factors becomes more and more questionable.

MCA is now widely accepted as a non-monetary evaluation method to aid decision-making when dealing with environmental issues in building projects. As discussed in previous sections, LCC is a well-established decision tool as long as there are no "externalities" involved. MCA has thus emerged as a technique to evaluate building projects with a potential environmental impact. As San-Jose and Cuadrado (2010) state, MCA is a useful technique for drawing together all of the complex information in building design and construction.

2.5.4 Multi-criteria analysis as a non-monetary assessment technique

Non-monetary evaluation techniques originated in operational research and developed in response to criticism of monetary methods (Janssen, 1992; Powell, 1996). Since the 1970s, a number of non-monetary evaluation techniques have been developed under MCA system. These techniques aim to provide a method for the systematic assessment and incorporation of a number of alternative options involving a range of different criteria into the decision-making process (Powell, 1996; Postle, 1998). Most of the differences between the various multi-criteria evaluation methods arise from the arithmetic procedures used as a means to aggregate information into a single indicator of relative performance. The use of such mathematical models to predict impact on each of the attributes lies at the heart of the MCA process (Voogd, 1983; Ding, 2008).

MCA has in the past decade, become one of the most powerful methodologies in optimisation analysis (Papadopoulos and Karagiannidis, 2008). It serves to enhance decision-making quality by providing a thorough methodological platform for decision analysis and an operational framework. MCA techniques offer the possibility of accounting for non- efficiency criteria as well as non-monetary building impacts, and can address subjective views of various parties in society (Van Pelt, 1994; Hobbs and Meier, 2000). It is particularly useful for those environmental impacts that cannot easily be quantified in terms of normal market transactions. MCA transfers the focus from measuring criteria with prices, to applying weights and scores to those impacts and to determine a preferred outcome thus avoiding the ethical debates surrounding the issues of monetary valuation as environmental matters are largely priceless and unique (Van Pelt, 1994).

MCA as a utility approach has been structured in such a way that public participation can be readily included in terms of criteria selection, alternative evaluation and weighting assignments through questionnaires. Stakeholder groups may participate to review the results and identify areas of agreement and disagreement (Hobbs and Meier, 2000). In addition, MCA contains tools that facilitate the decision-making process by displaying trade-offs between criteria and improving the decision-maker's ability to assess those trade-offs. (Joubert *et al.,* 1997; Hobbs and Meier, 2000). Total scores are used in MCA to rank alternatives to indicate the best option. Despite its flexibility, MCA may also have limitations. Ding (2004) report that its usefulness is governed by an explicit view on the relative priorities in terms of weights, and stakeholder groups' priorities may fail to reflect the values of the community at large. It would be more useful if MCA was used to evaluate several alternatives since the decision on a single alternative is either “rejected” or “approved” (van Pelt, 1994; Hobbs and Meier, 2000). As Hobbs and Meier (2000) state, with the amount of data generated in the MCA methodology concerning the performance of alternatives on numerous criteria, there is a possibility that stakeholders may not be easily able to digest. The true preferences of the stakeholders may be distorted and lead to inconsistencies across jurisdictions regarding value judgements (van Pelt, 1993; Hobbs and Meier, 2000). In addition, there are so many techniques to choose from that confusion may result and different MCA techniques may be improperly applied to a particular problem resulting in the different outcomes. The problem of method uncertainty deserves specific attention and it may require applying several MCA techniques to a particular problem to test the results (van Pelt, 1994).

Finally, even though sustainability issues are difficult to fully evaluate in a broad sense, measurable sub-criteria using methods other than market transaction may indicate at least relative movement towards these goals. Detail description of various MCA methods available is provided in chapter seven. The choice of MCA method for sustainability model development is also discussed in the same chapter.

The sustainability model as developed in this research is a way to address multiple criteria in relation to building material decision-making and the economic and environmental effects are quantified as much as possible. Using a sustainability model will greatly enhance the assessment of environmental issues generated by construction activity, realise sustainable development goals and thereby make a positive contribution to the identification of optimum material solutions.

2.6 Summary of the chapter

Life cycle cost analysis is a systematic and consistent method of building evaluation widely used by developers, investors, governments and international funding agencies. All building development, policies and programs will have different approaches or proposals in order to achieve the same objectives. Building materials need to be properly evaluated before a decision is made to proceed with its use. The approach used in building material evaluation, therefore, becomes important in choosing the best option from the available alternatives. LCC is a tool used to assist decision-makers to compare alternatives by applying economic theory. The main theme of LCC is to choose the most cost effective approach from a series of alternatives.

However, the technique is not without its problems and for public projects where externalities and intangibles are common, the calculated outcomes may be highly questionable. Much advantage lies in the rigour of the technique itself and the ability to evaluate different scenarios using a range of variables that are significant to the analysis. In a sense, the greatest benefit of LCC is its ability to allow for social and environmental issues objectively, and yet this is also its greatest weakness. Material selection involves complex decisions and the increased significance of external effects has further complicated the situation. Society is not just concerned with economic growth and development but is also conscious of the long-term impacts on living standards for both present and future generations. Sustainable development is now an important issue in building decisions. Environmental sensitive materials require a different approach to evaluation than most traditional materials. The engagement of a conventional single dimensional evaluation technique such as LCC in assisting decision-making is no longer relevant and a much more complicated model needs to be developed to handle multi-dimensional arrays of data. Multi-disciplinary evaluation teams and an overall methodology are essential to uphold the goal of a sustainable development.

2.7 Conclusion of chapter

There is no doubt that the environment is closely linked to economic growth and the continued depletion of environmental assets will be detrimental to the well-being of mankind. As such, much research has been undertaken to evaluate environmental issues and their consideration in building evaluation. This chapter has fulfilled the first and second objective of the research by reviewing the current environmental problems that are experienced around the world and their impacts on present and future generations. The techniques that are available in the valuation of environmental issues are also discussed but as this chapter described, they suffer from serious methodological shortcomings. These are closely related to the single- dimensional nature of these techniques which have restrictive methodology in assessing the complex nature of the natural world. This chapter also discussed the emergence of valuing the environment using a non-monetary approach in lieu of the conventional market-based approach.

This chapter, whilst discussing the issues on a global viewpoint, has laid down the fundamental platform for the discussion of the impact of the construction industry and its related activities on the environment in the next chapters.

CHAPTER 3: THE CONSTRUCTION INDUSTRY AND THE ENVIRONMENT

3.1 Introduction

The construction industry is a vital element of any economy but has a significant impact on the environment. Construction is not by nature an environmentally friendly activity (Shen and Tam, 2002). By virtue of its size, construction is one of the largest users of energy, material resources, and water, and it is a formidable polluter. The extent of its impact is still being debated because information and data about the environmental impacts of the construction industry are still not being collected and analyzed systematically (Horvath, 2004). However, the construction industry must not only comply with the ever-growing number of environmental rules and regulations but go beyond compliance, proactively internalizing environmental performance in a way similar to that of other industrial sector (Horvath, 2004).

This chapter has two purposes. First, it reviews characteristics of Global and UK construction industry and identifed the principal ways in which construction contributes to environmental stress. Secondly, it considers the means available to reduce these environmental impacts through a conceptual framework and strategies to implement sustainability principles in the construction industry from a life-cycle perspective. This review is by no means exhaustive but serves to demonstrate the fragmented nature and complexity of the problem.

3.2 Global construction industry

3.2. 1 Background and Context

From a global perspective, Low and Jiang (2004) acknowledge the construction industry as one of the oldest internationalized economic sectors which can be traced back to more than 100 years ago. A similar review by Ngowi (2005) pointed out that in traditional societies, construction relied on the environmental resources of land, climate and was an activity in which all members of the community participated to create shelter forms which reflected a precise and detailed knowledge of local climatic conditions and a reasonable understanding of the performance characteristics of the construction materials available. Colean and Newcomb (1952); Lange and Mills (1979) and Bernold and AbouRizk (2010) view construction as an aggregation of businesses engaged in closely related activities. Nam and Tatum (1989) suggest that, historically, construction refers to all activities associated with the erection and repair of immobile structures and facilities. Likewise Wells (1985) describes construction as an activity involving the creation of physical infrastructure, superstructure and related facilities.

In a review of statistics on construction in the United Kingdom "construction" was interpreted to mean the resources directly used in construction, the products of construction activity, and financial and operational aspects of the building materials and construction industries (Ofori, 1991). Considering the participants in the construction process, Ofori (1991) portrayed the industry as a series of related but discrete activities, persons or organizations as shown in fig 3.1.

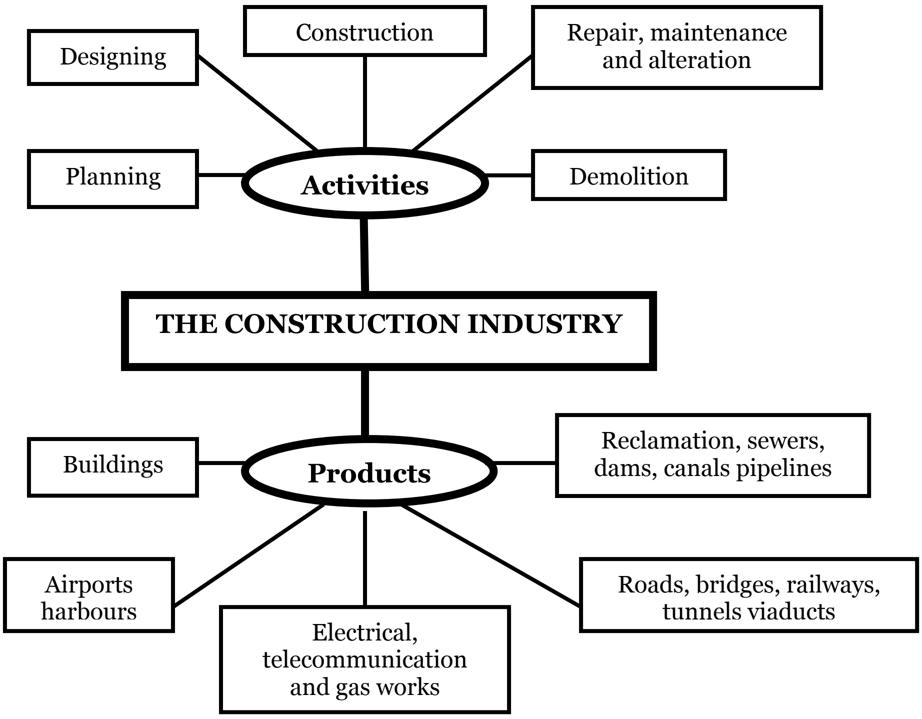


Figure 3.1: The construction industry

Source: Ofori, 1991

According to Ngowi (2005), the first shelters and settlements were constructed from stone, mud and materials collected in the forests, and provided protection against cold, wind, rain and other weather elements. The methods used to construct these shelters using the said materials grew out of countless experiments and accidents and the experience of generations of constructors who continued to use what worked and rejected what did not. The 18th Century gave birth to the industrial revolution, which ushered in large scale industrial developments. Apparently, construction did not innovate significantly during this period, but the 19th Century saw great strides in the development of construction materials, particularly cast iron, wrought iron and later steel that enabled new structures such as railways, bridges, and building frames; glass used for steel-framed buildings with large glazed envelopes; Portland cement and with it concrete and later reinforced concrete structures (Ngowi, 2005). The 19th Century witnessed the emergence of a new industrial sector producing building equipment - elevators, boilers, radiators and pipes (Mawhinney, 2001).

The large number of building materials resulting from the industrial revolution coupled with the demand for new housing in Europe resulting from the World Wars I and II, particularly the latter, provided a base for the development of more efficient construction technologies. This necessitated a leap from the traditional labour intensive methods to modern ones, and this process has been referred to as the industrialisation of construction (Sebesteyen and Platzer, 1989 cited in Ngowi, 2005). Different definitions of construction industrialisation have been put forward. Blachere (1988) and Sarja and Hannus (1995) defined industrialisation as being mechanization, and added that it is also characterised by the technology of construction and not the product. Sebesteyen (1998) considers that the industrialisation of construction comprises the introduction of new technologies, such as prefabrication, or of modern in situ processes, such as the various uses of slip-forms for chimneys, bunkers and silos, and the use of modern framework ("tunnel" shutters, etc.) and pre-stressing methods. Furthermore, industrialisation is also characterised by modern design methods that use scientific knowledge about structures, building physics, fire, and computer technologies (Sarja and Hannus (1995).

The extensive projects in housing, industry, transport and city development that followed the advent of modern construction materials formed the background of what emerged as modern construction industry. However, most building construction remained in the hands of small and medium-sized local contractors, whereas civil engineering projects required much larger scale operations and hence formed a launching pad for international construction (Ngowi, 2005).

3.2.2 Market trend analysis

World construction spending grew by 3% in 2007, to reach US$4.7 trillion and is expected to grow at 4.6% annually until 2011 (Global Insight, 2007), though this might not be realistic as a result of the current financial crisis. In terms of the regional breakdown of this market, Asia accounts for 37% of the global market volume with US$ 1.7 trillion, followed by Europe - US$ 1.42 trillion or 31% and North America - US$ 1.057 trillion or 23% (Han *et al.,* 2010).

Construction activity within the EU-27 in 2006 (FIEC, 2007; Pellicer *et al.,* 2009) generated almost 1,200 Billion Euros (10.4 per cent of the EU's Gross Domestic Product) and it engaged more than 15 million people (more than 7 per cent of all employment), being the largest industrial employer in the EU-27. Furthermore, the sector is formed by more than 2.7million companies, mostly small and medium enterprises or SMEs (FIEC, 2007). When looking at the outlook based on the Global Insight forecast, Eastern Europe will see the highest annual average market growth rate of 8.5% by 2011 due to growing demand there for infrastructure construction. Asia will continue to grow annually at 6.5% on average to amount to over 40% of the world construction market (Global Insight, 2007).

In terms of construction volume classified by nations, as shown in Table 3.1, the U.S. is the biggest with US$ 881.5 billion, with Japan (US$ 769.8 billion), China (US$ 418.2 billion) and the UK (US$ 263.4 billion) following the lead. As for the market growth rate, Vietnam posts the highest annual growth rate of 15.1% due to the rising inflow of foreign investments. China also shows a high average annual growth rate of 13.7% on average. Rumania. Venezuela and Panama all boast impressive growth rates of over 10%.

However, Han *et al.* (2010) report that much of the world's construction, approximately 80% of the total volume, has been done by small scale local builders who construct single houses or maintain roads over small areas, using very traditional materials and methods. This implies that only 20% of the total volume of the world's construction is considered to be a potential market accessible by foreign construction firms (National Research Council, 1988; Han and Diekmann, 2001; Han *et al.,* 2010).

Table 3.1 Annual Average Growth Rates of Some Nations

Top 10 market size country			Top 10 annual growth country		
Country	Market size (100mil.USD)	Annual growth (%)	Country	Market size (100mil.USD)	Annual growth (%)
U.S.A	8815	0.4	Vietnam	115	15.1
Japan	7698	1.6	Romania	82	14.4
China	4182	13.7	China	4182	13.7
UK	2634	4.5	Venezuela	262	11.9
France	1783	3.6	Panama	18	11.0
Germany	1692	2.9	Columbia	132	10.6
Spain	1553	3.5	India	1130	10.5
Italy	1417	0.9	Peru	80	10.3
South Korea	1247	3.5	Ukraine	56	10.1
Canada	1185	2.9	Russia	414	9.8

Source: Adapted from Global Insight (2007)

In addition, the construction volume in other markets such as the Pacific Rim, Latin America, Africa, and the Commonwealth of Independent States (CIS, the international organization consisting of eleven former Soviet republics) is also growing dramatically as developing economies require more industrial plants and social infrastructure facilities (Han *et al.,* 2010).

3. 2.3 The UK construction industry

The UK construction industry is unique; it is a large and highly diverse sector of industry activities. It has literally built Great Britain, and its monuments are around for all to see. Its activities are concerned with the planning, regulation, design, manufacture, construction and maintenance of buildings and other structures (Harvey and Ashworth, 1997; ONS, 2002). Projects can vary from work worth a few hundred pounds undertaken by jobbing builders, to major schemes costing several million pounds such as the Channel Tunnel which is an international joint venture, estimated to cost over £10bn (Banister and Thurstain-Goodwin, 2010). Whilst the principles of execution are similar, the scale, complexity and intricacy vary enormously. In terms of size and structure, the industry can be viewed as having a narrow and a broad definition (Pearce, 2003). As shown in Figure 3.2 below, the narrow definition focuses attention on the actual on-site construction activities of contractors whilst the broad definition, which actually covers the true extent of the construction industry, draws in the quarrying of construction raw materials, manufacture of building materials, the sale of construction products, and the services provided by the various associated professionals (Pearce, 2003).

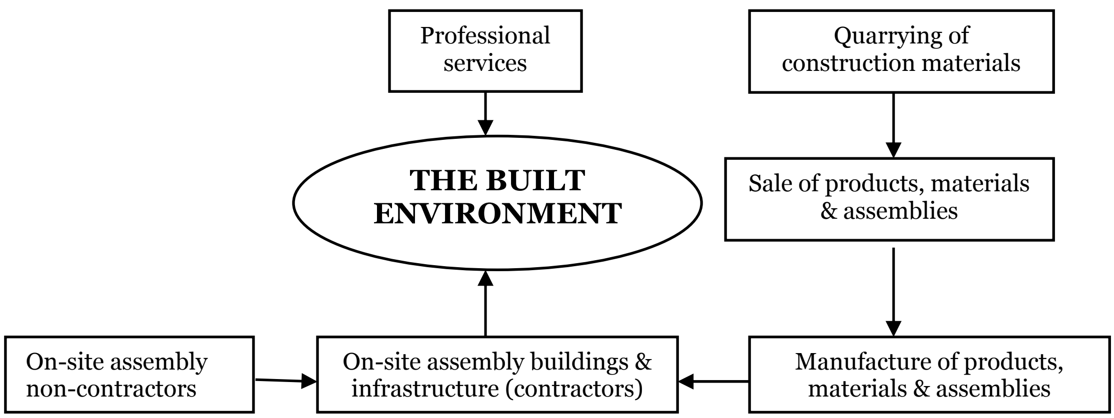


Figure 3.2 The composition of the construction industry
Source: Adapted from Pearce, 2003

According to Ashworth (2006), the construction industry has characteristics which separate it from all other industries. These are:

1. The physical nature of the product
2. The product is normally manufactured on the client's premises, i.e. the construction site.
3. Many of its projects are one-off designs and lack any prototype model being available.
4. The arrangement of the industry, where design has normally been separate from construction.
5. The organization of the construction process.
6. The methods used for price determination.

These characteristics mean that the delivery of the built environment is project-based with involvement of numerous participants whose responsibilities are set out in contracts. There is also limited control over the production environment (Ashworth, 2006). The risk and uncertainty associated with this method of production and method of price determination also means that margins are thin, uncertain and easily eroded, and considering the fact that an individual project can often represent a large proportion of the turnover of a participant in any year (Harvey and Ashworth, 1997; Fellows *et al.*, 2002), there is inevitably mistrust among the participants because everyone is struggling to avoid making a loss, and as a result relationships are very often adversarial. Notwithstanding these challenges, the UK construction industry is still economically very significant, and its contribution to the UK economy is examined in more detail below.

3.2.4 Economic significance of the UK construction industry

The UK construction industry is renowned for its complex and dynamic industrial environment. It is highly responsive to the economy, especially in terms of new construction, and is often used as a key indicator by economists (Telegraph, 2008; Morgan *et al.,* 2008). In examining the significance of the construction industry, various indicators can be employed as the basis of analysis. Among these are number of firms, output and employment. As highlighted by Pearce (2003), each of these indicators reveals part of the story that is relevant to our understanding of the state of the construction industry. The distinction between the broad and narrow definitions also becomes very significant when examining these indicators.

3.2.4.1 Number of firms

In terms of the number of firms, the construction industry has in excess of 350,000 firms in total, of which over 190,000 are contractors as per the narrow definition (Pearce, 2003). More current statistics published by the Office of National Statistics (ONS) for the construction industry also give 3rd Quarter figures of approximately192,000 private contractors in the UK for the year 2007 (ONS, 2008), though rising to 300,000 firms if the entire value chain (small & medium-sized family and local businesses) is included. The breakdown of this figure by the size of firm is shown in Table 3.2. These 192,000 firms include the main trades comprising non-residential building, house building and civil engineering (about 47,000 firms), and the specialist trades including demolition, reinforced concrete specialists, asphalt and tar sprayers, scaffolding, painting, glazing, and so on which make up the remaining 145,000 firms (ONS, 2008).

Table 3.2 Number of firms by size in UK Construction

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
							3rd quarter each year:			**number**	
By size of firm											
1	86,269	87,837	88,018	87,712	77,926	71,431	70,370	71,620	73,117	71,960	74,325
2-3	47,664	47,918	49,350	48,773	50,653	50,306	53,002	55,027	57,320	58,910	60,313
4-7	15,737	16,391	16,969	16,584	22,455	23,963	25,704	26,865	28,435	30,375	31,814
8-13	3,787	3,988	4,148	3,790	8,044	9,819	10,508	10,982	11,599	12,230	12,669
14-24	3,101	3,274	3,271	3,104	4,920	5,427	5,892	6,161	6,341	6,656	6,860
25-34	1,176	1,201	1,332	1,201	1,782	1,809	1,932	1,985	2,037	2,056	2,128
35-59	1,156	1,263	1,188	1,109	999	1,782	1,821	1,906	1,928	2,034	2,129
60-79	396	419	397	364	354	457	583	550	573	583	597
80-114	296	319	304	271	304	425	451	464	469	467	490
115-299	381	405	379	341	433	520	535	560	556	562	595
300-599	107	125	105	91	129	123	135	148	148	148	154
600-1,199	60	56	58	51	68	62	75	75	65	72	65
1,200 and over	38	40	42	35	56	57	64	60	56	54	60
All firms	160,148	163,236	165,561	163,426	168,123	166,181	171,092	176,403	182,644	186,107	192,199

Source: Office of National Statistics (ONS, 2008)

3.2.4.2 Output of construction

Another useful indicator of the economic significance of construction is the contribution to UK's Gross Domestic Product (GDP). Pearce (2003) estimated this to be about 5% as at 2002 for contractors (the narrow definition) and 10% for the broader definition. Although no distinction is drawn between the narrow and broad definitions, the Office of National Statistics (ONS, 2008) gave the output of the construction industry at approximately £124 billion a year (Fig. 3.3 & 3.4), accounting for approximately 8.5% of Gross Domestic product (GDP).

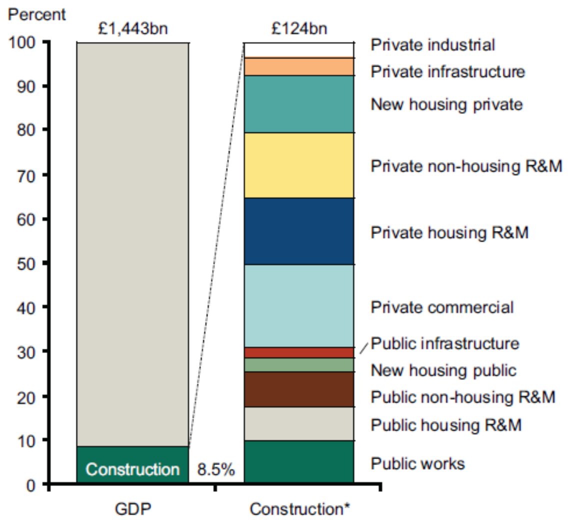


Figure 3.3 UK GDP and Construction Output 2008

Source: Office of National Statistics (2008)

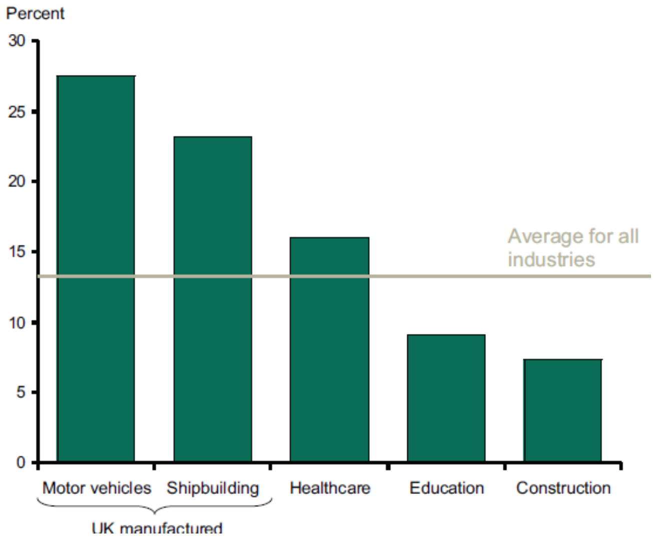


Figure 3.4 Imports as a Percentage of Intermediate Consumption 2007

Source: Office of National Statistics Annual Business Enquiry (ONS), 2008)

According to ONS (2008) publication, Construction total output includes £80 billion of direct value-add and £44 billion of intermediate consumption. Intermediate consumption comprises the total amount of materials and services used in construction, including Sub-contracting services. The industry also contributes a net trade surplus to the UK (£223m in 2008).The publication also noted that since little construction output is imported, increased construction demand is therefore more likely than any other sectors to generate additional economic activity within the UK and directly benefit domestic UK firms (Fig.3.4 shows that in 2007, construction imported less than 8% of its supply, while UK manufactured motor vehicles imported nearly 28%). Furthermore, construction supports high-value net-export service sectors such as engineering consultancy and design, architectural activities, and property management.

In relation to its European counterparts, the UK has suffered from a more pronounced decline in construction activity since the onset of the recession which has sharply affected the output (ONS, 2008). The impact on the construction sector is already apparent through sharp increases in company closures (an increase of over 40% between Q4 2008 and Q1 2009) and individual bankruptcies and redundancies (an increase in bankruptcies of 35% between Q4 2008 and Q1 2009 and a redundancy rate of 28 per 1,000 employees in Q1 2009 – the highest amongst UK industries)

3.2.4.3 Employment generation

As noted in a World Bank report on the wealth of nations, the output of any nation, or in the context of this study the construction industry, fundamentally depends on its human resources – i.e. "the skill, dexterity, and judgment of its labour" (World Bank, 1997). Although figures vary from source to source, it is estimated that between 1.4 – 2.0M people are employed in the UK construction industry. Pearce (2003) estimated that as at 2001, contractor employment was of the order of 1.7M, accounting for about 6% of total UK employment. ONS (2008) also provide more current estimates of 2.6M employees respectively, representing over 8% of all jobs in the UK from highly skilled professionals through to lower skilled workers. According to Construction Skills Network (2009), lower skilled workers (trades and operatives) represent approximately 63% of the UK construction workforce. This also varies by region, with Northern Ireland (75%) and the North East (72%) having the largest proportion of lower skilled workers. Across all regions, lower skilled workers represent more than 55% of the regional construction Workforce.

The labour market characteristics of the construction industry are unique, with high rate of self-employment, making up approximately 40 per cent of the workforce, the largest proportion of self-employed workers in the UK's industrial makeup (ONS, 2008). These high levels compared to other industries can be explained by high levels of subcontracting in the industry, as 'main contractors use subcontractors as a means of surviving the volatility of the construction business cycle' (Dainty *et al.* 2001). In addition, government policies have made the setting up of small businesses fiscally attractive (HM Treasury and HMRC 2009; Edgell, 2006).

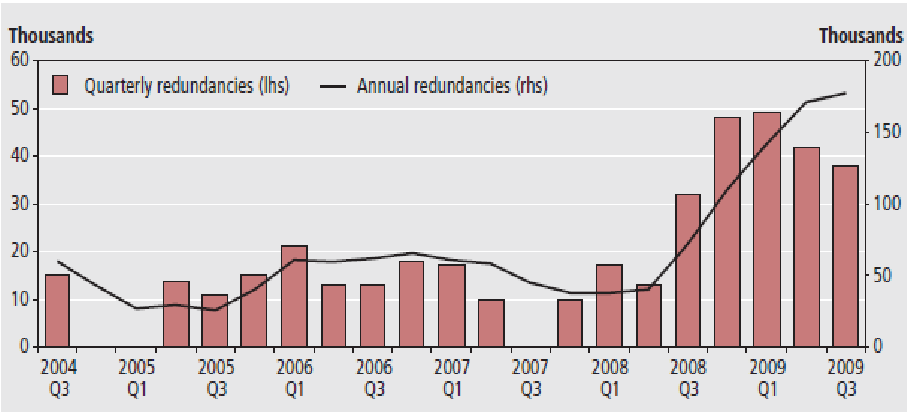


Figure 3.5 Redundancies per quarter in the Construction Industry
Source: ONS (2008)

However, the second quarter of 2008, witnessed the recession of the UK economy and the construction sector also entered a period of negative growth according to the labour market statistics published in 2009. The report also observed quarterly output growth in the construction sector was negative for four successive quarters (from the second quarter of 2008 to the first quarter of 2009), resulting in a peak to trough loss of output of approximately 14 per cent. However, while construction output figures started to decline in the second quarter of 2008, employment growth figures for the industry remained positive for most of 2008 and only started falling slowly in the fourth quarter of 2008. The number of redundancies in the industry started to pick up in the third quarter of the 2008 and have been elevated since (Figure 3.5) leaving the construction sector with the highest redundancy rate in the UK.

3.3 Construction industry and environmental stress

A wide range of adverse impacts can result from construction activities. They vary in severity, predictability and nature (i.e. permanent vs. temporary). In the late 1960s and early 1970s people started to worry about the ability of the ecosystems to support ever-increasing economic activities (Azqueta, 1992). Throughout the world, the building industry is responsible for high levels of pollution resulting from the energy consumed during raw materials extraction, processing and transportation (Holton *et al.,* 2008). Industrialised building methods, based on the widespread use of high energy materials such as aluminium, cement, concrete and steel, must now comply with new directives for the protection of the environment. Today, it is widely accepted that sustainable development has three foundations: environmental, social and economic. If we accept this, the link between sustainable development and construction becomes clear; construction is of high economic significance but has strong environmental and social impacts. The following sections focus primarily on environmental impacts relevant to construction activities.

3.3.1 Environmental impact of construction activities

Globally, the construction sector is arguably one of the most resource-intensive industries. Concern is growing about the impact of building activities on human and environmental health. It is clear that actions are needed to make the built environment and construction activities more sustainable (Hill and Bowen, 1997; Barrett *et al.* 1999; Cole, 1999; Holmes and Hudson, 2000; Morel *et al.,* 2001;

Scheuer *et al.* 2003; Abidin, 2010). The construction industry and the environment are intrinsically linked and it has found itself at the centre of concerns about environmental impact. According to Abidin (2010), buildings are very large contributors to environmental deterioration. Kein *et al.* (1999) and Ding (2008) describe the building industry as uncaring and profit motivated, and the members as destroyers of the environment rather than its protectors. Indeed, the construction industry has a significant irreversible impact on the environment across a broad spectrum of its activities during the off-site, on-site and operational activities, which alter ecological integrity (Uher, 1999; Ding, 2008).

Construction activities affect the environment throughout the life cycle of a construction project. This life-cycle concept refers to all activities from extraction of resources through product manufacture and use and final disposal or recycle, i.e. from "cradle to grave" (Fig. 3.6).

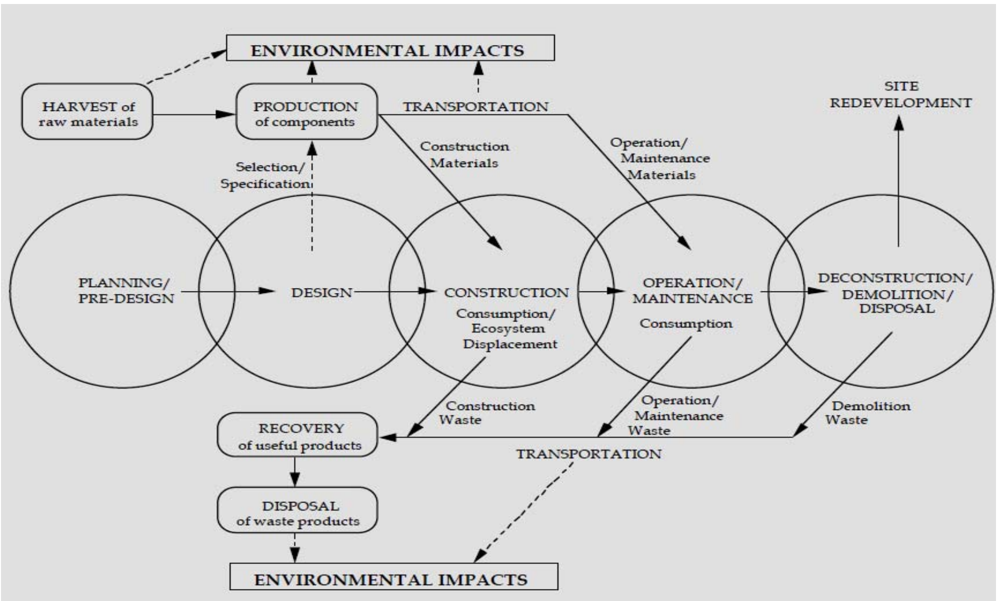


Figure 3.6 Life Cycle Environmental Impact of Building Construction

Source: Franklin Associates (1990)

Even though the construction period is comparatively short in relation to the other stages of a building's life, it has various significant effects on the environment. Therefore the analysis of the impact of the construction industry on the environment may need to look at a ‘cradle to grave’ viewpoint (Ofori *et al.* 2000).

3.3.1.1 Raw material consumption and its associated impacts

The construction industry is one of the largest exploiters of renewable and non-renewable natural resources (Spence and Mulligan, 1995; Curwell and Cooper, 1998; Uher, 1999, Abidin, 2010). According to World-watch Institute (2003), building and construction activities worldwide consume 3 billion tons of raw materials each year, or 40% of total global use. According to Levin (1997), in the USA construction uses 30 percent of raw materials, 40 percent of energy and 25 percent of water. In Europe, the Austrian construction industry has about 50 percent of material turnover induced by the society as a whole per year (Rohracher, 2001) and 44 percent in Sweden (Sterner, 2002). The UK construction industry consumes around 420 million tonnes of materials annually, the highest of any sector (DTI, 2006; Plank, 2008). It relies heavily on the natural environment for the supply of raw materials such as timber, sand and aggregates for the building process. This extraction of natural resources causes irreversible changes to the natural environment of the countryside and coastal areas, both from an ecological and a scenic point of view (Ofori and Chan, 1998; Langford *et al.,* 1999; Godfaurd *et al.,* 2005). The subsequent transfer of these areas into geographically dispersed sites not only leads to further consumption of energy, but also increases the amount of particulate matter in the atmosphere.

3.3.1.2 Pollution generation and its associated impacts

Raw materials extraction and construction activities also contribute to the accumulation of pollutants in the atmosphere, mostly in the processing of materials for construction. And again, not surprisingly, the construction industry has the biggest effect of all sectors because of the quantity of materials used in construction. According to Holton *et al.,* (2008), the UK construction is responsible for 40 percent of atmospheric emissions, 20 percent of water effluents and 13 percent of other releases. Dust and other emissions include some toxic substances such as nitrogen and sulphur oxides. They are released during the production and transportation of materials as well as from site activities and have caused serious threat to the natural environment (Spence and Mulligan, 1995; Ofori and Chan, 1998; Rohracher, 2001). The DTI (2006) reports that the global greenhouse gas emissions increased more than four-fold in the last half of the twentieth century. Other harmful materials, such as chloroflucarbons (CFCs), are used in insulation, air conditioning, refrigeration plants and fire-fighting systems and have seriously depleted the ozone layer (Clough, 1994; Langford *et al.* 1999).

Pollutants have also been released into the biosphere causing serious land and water contamination, frequently due to on-site negligence resulting in toxic spillages which are then washed into underground aquatic systems and reservoirs (Huberman and Pearlmutter, 2008). According to Langford et al (1999), about one third of the world's land is being degraded and pollutants are depleting environmental quality, interfering with the environment's capacity to provide a naturally balanced ecosystem. The BRE defined pollution from construction as "particles, noise, vibration and vaporous discharges" (Kukadia and Hall, 2004; Pitt *et al.,* 2009). Risk should be identified and steps taken to minimise potential pollution (OGC, 2005). The construction industry must consider enhancing or at least protecting biodiversity as it "considers all things and their habitats" and there is an obligation to consider biodiversity in developments in terms of good design and material selection (OGC, 2005). If the construction industry continues to overuse these natural resources, a limit on economic growth will eventually emerge. In other words, the destruction of the environment will inevitably affect the construction industry.

3.3.1.3 Waste generation and its associated impacts

The construction industry produces an enormous amount of waste. A large volume results from the production, transportation and use of materials (Kein *et al.*, 1999; Osmani *et al.,* 2008). Construction activity contributes approximately 29 percent of waste in the USA and more than 28 percent in Malaysia (Teo and Loosemore, 2001; MohdNasir *et al.,* 1998). McDonald's (1996) reports that 14 million tons of wastes are put into landfill in Australia each year, and 44% of this waste is attributed to the construction industry. In the European Union, the construction industry contributes about 40–50 percent of wastes per year (Sjostrom and Bakens, 1999; Sterner, 2002). Furthermore, waste from construction and demolition constitutes one of the largest waste streams in Europe (Burgan and Sansom, 2006). Burgan and Sansom, (2006) report of a study carried out for the European Commission in 1999 showed that in the EU-15 arising of 'core' construction and demolition waste amount to around 180 million tonnes each year and that only about 28% across the EU-15 as a whole is re-used or recycled with the remaining 72% going to landfill. Five Member States (Germany, the UK, France, Italy and Spain) accounted for around 80% of the total, broadly consistent with the share of the overall construction market accounted for by these countries (see Table 3.3).

Table 3.3 Construction and Demolition Waste Arising and Recycling

Member state	"Core" construction and demolition waste	% re-used or recycled	% incinerated or landfilled
Germany	59	17	83
UK	30	45	55
France	24	15	85
Italy	20	9	91
Spain	13	<5	>95
Netherlands	11	90	10
Belgium	7	87	13
Austria	5	41	59
Portugal	3	<5	>95
Denmark	3	81	19
Greece	2	<5	>95
Sweden	2	21	79
Finland	1	45	55
Ireland	1	<5	>95
Luxembourg	0	N/A	N/A

Source: Burgan and Sansom (2006)

In the UK 90 million tonnes of inert construction waste (suitable for reprocessing into aggregate) is produced every year (ODPM, 2004). Of this, some 50 per cent is reused and recycled and just over 30 per cent goes to landfill. Other non-inert waste accounts for around 20 million tonnes annually. This includes site construction and refurbishment waste and a further 1.7 million tonnes of hazardous waste (RICS, 2005). The UK government projected that landfill capacity will be reached by 2017 (better Buildings summit, 2003). To lessen the the cost associated with waste disposal and to increase levels of recycling and recovery, the government have introduced landfill tax and aggregate levy which has helped to drive waste management practices among construction organisation (OECD, 2006). As a result, most major construction organisations now have waste management policies and practices in place (The sustainability construction task group, 2003).

Most construction waste is unnecessary according to Sterner (2002) who says that many construction and demolition materials have a high potential for recovery and reuse. However, due to the economic nature of the building industry, every stage of the construction period is minimised. In addition, time and quality are crucial and virgin materials are considered superior to second hand products for these reasons alone. Screening, checking and handling construction waste for recycling are time consuming activities and the lack of environmental awareness amongst building professionals may create significant barriers to the usefulness of recycling (Langston and Ding, 2001). The depletion of natural resources by the building industry is a topic of serious discussion as most of the recyclable material from building sites ends up in landfill sites. Sterner (2002) states that implementing a waste management plan during the planning and design stages can reduce waste on-site by 15 percent, with 43 percent less waste going to the landfill through recycling, and it delivers cost savings of up to 50 percent on waste handling.

3.3.1.4 Energy consumption and its associated impacts

Apart from waste generation, the building industry rapidly growing world energy use and the use of finite fossil fuel resources has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts (ozone layer depletion, carbon dioxide emissions, global warming, climate change (Clough, 1994; Spence and Mulligan, 1995; Ofori and Chan, 1998; Langford *et al.* 1999; Uher, 1999; Perez-Lombard *et al.,* 2007; IIha *et al.,* 2009). Building material production consumes energy, the construction phase consumes energy, and operating a completed building consumes energy for heating, lighting, power and ventilation. The existing building stock in European countries accounts for over 40% of final energy consumption in the European Union (EU) member states, of which residential use represents 63% of total energy consumption in the buildings sector (Balaras *et al.,* 2005; Poel *et al.,* 2007).

The built environment is responsible for 50% of the total UK energy consumption; 45% to heat, light and ventilate buildings and 5% to construct them (Edwards, 2002), while arguably more than 50% of all UK carbon emissions can be attributed to energy use in buildings (including residential and business emissions) (Department for Environment, Food and Rural Affairs, 2008a). The government set a target to achieve 60% energy reduction by 2050 (Better building summit, 2003). However, the Royal Institution of Chatered Surveyors (RICS) believed that the government is failing in its energy policy to make enough difference. In response to the UK energy Review, RICS (2006) believed the "Energy review is a failed opportunity to challenge the wider and more fundamental issues about sustainability and how we live and work". The current low levels of energy efficiency in the built environment offer vast scope for improvement in energy performance, which may be achieved through the deployment of an array of techniques ranging from simple plant and insulation upgrades to the deployment of advanced energy monitoring and control.

3.3.1.5 Health and well being

Burgan and Sansom (2006) observe that on average we spend some 90% of our lives in buildings, therefore the internal environment of the buildings we live, work and play in has proved to be a major contributor to our quality of life. For example, the fact that poor quality living space is responsible for health problems has been recognized by the World Health Organization (W.H.O.) for some 15 years in what it terms “sick building syndrome” and the W.H.O. estimates that worldwide, 30% of offices, hotels, institutions and industrial premises have the syndrome. Younger *et al.,* (2008) observe a similar trend in that inadequate heating or cooling, waste disposal, and ventilation systems result in adverse health effects, including respiratory illnesses, asthma, infectious diseases, injuries, and mental health disorders. Carbon dioxide emissions from buildings are primarily caused by the use of electricity to provide heating, cooling, lighting, water, information management, and entertainment systems. (Brown *et al.,* 2005; Younger *et al.,* 2008). Because of their long life expectancies, buildings affect the environment and public health for many years. In England, for example, the construction industry accounted for 31% of all fatal injuries to workers in 2002/3, significantly higher than other industrial sectors, and workers with the least time with their current employer (or least time self-employed) had the highest rate of reportable injury (Burgan and Sansom, 2006). The figures for Europe are shown in Fig. 3.7

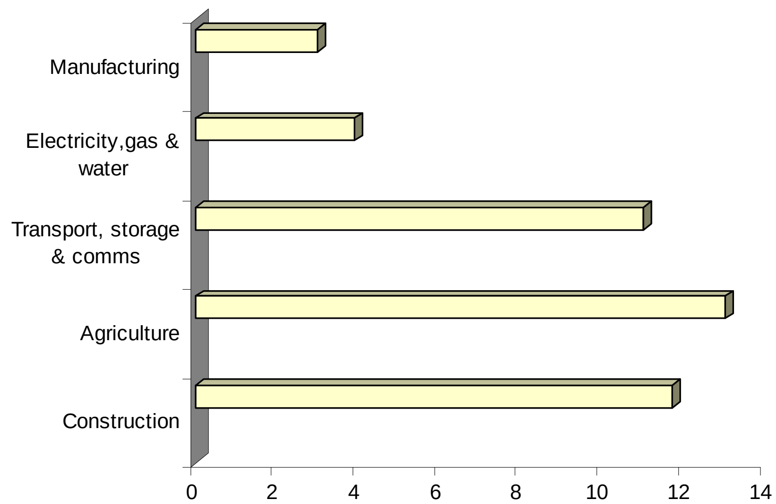


Figure 3.7 Rates of Fatal Accidents per 100,000 Workers (EU Average, Eurostat).
Source: Burgan and Sansom (2006)

Construction industry must inevitably change its historic methods of operating with little regard for environmental impacts to a new mode that makes environmental concerns a centrepiece of its efforts. According to Abidin (2010), the concern on environment is previously a relatively small part of most of construction development. However, with the growing awareness on environmental protection, this issue have gain wider attention by the construction practitioners worldwide. Implementing sustainable construction practices has been advocated as a way forward in fostering economic advancement in the construction industry while minimizing impact on the environment (Hills and Bowen, 1997; Myers, 2004; Ugwu and Haupt, 2007; Kuhtz, 2007; Ding, 2008). A shift in paradigm is now necessary from developing with environmental concern as a small part of the process into integration of all building projects within the wider context of environmental agenda (Abidin, 2010). Thus, the activities of construction industry must work and comply with the needs to protect and sustain the environment.

3.4. Sustainable construction practices

Sustainable construction is considered as a way for the construction industry to move towards achieving sustainable development taking into account environmental, socio and economic issues. It is also a way to portray the construction industry's responsibility towards protecting the environment (Pitney, 1993; Spence and Mulligan, 1995; Hill and Bowen, 1997; Ofori and Chan, 1998; Bourdeau, 1999; Ofori *et al.* 2000; Ding, 2008; Abidin, 2010). Within the broader context of sustainable development, construction has a prominent role. The promotion of sustainable construction practice is to pursue a balance among economical, social, and environmental performance in implementing construction projects (Shen *et al.* 2010). Sustainable construction practice refers to various methods in the process of implementing construction projects that involve less harm to the environment - i.e. prevention of waste production (Ruggieri *et al.* 2009), increased reuse of waste in the production of construction material - i.e. waste management (Asokan *et al.*2009; Tam, 2009), beneficial to the society, and profitable to the company (Tseng, *et al.* 2009; Turk, 2009; Tam and Tam, 2006; Tam *et al.* 2007).

The total environmental damage can be significantly reduced if the construction industry takes proper action to improve its environmental performance (Ofori and Chan, 1998; Ball, 2002) and this potential damage has to be analysed when considering sustainable development (Bourdeau, 1999). Hill and Bowen (1997) state that sustainable construction starts at the planning stage of a building and continues throughout its life to its eventual deconstruction and recycling of resources to reduce the waste stream associated with demolition. They then describe sustainable construction as consisting of four attributes: social, economic, biophysical and technical.

These attributes form a framework for achieving sustainable construction that includes an environmental assessment during the planning and design stages of projects, and the implementation of environmental management systems. Improvements in environmental performance of buildings are often perceived as a cost burden. At the same time, because the construction industry is fragmented and because many of its products have cultural significance, the industry has been particularly slow to change and embrace environmentally friendly practices (Teo and Loosemore, 2001; Ball, 2002; Abidin, 2010). With the widespread identification and publication of environmental problems, there has been increasing pressure on the construction industry to take a more responsible attitude towards the environment.

3.4.1 Principles of Sustainable Construction

In terms of the principle for sustainable construction, various efforts have been made to examine several definitions of sustainability in an attempt to enunciate principles to be upheld in attaining sustainable construction. Amongst the published work relating to the principles of sustainable construction are Kilbert (1994), Hill (1994), Lindle (1994), Hill and Bowen (1997), Robbert (1995), Graham (2000) Long (2001), DETR, (2000), Ding, (2008) and Abidin, (2010). A few examples are collated in the table below (see table 3.4 below). In general, there is a consensus that the breadth of the principle of sustainable construction mirrors those of sustainable development, which is about synergistic relationships between economic, social and environmental aspects of sustainability. Each of these three pillars (and their related principles) is over-arched by a set of process-orientated principles, including:

1) the undertaking of assessments prior to the commencement of proposed activities assists in the integration of information relating to social, economic, biophysical and technical aspects of the decision making process;
2) the timeous involvement of key stakeholders in the decision making process (WCED, 1987);
3) the promotion of interdisciplinary and multi-stakeholder relations (between the public and private sectors, contractors, consultants, nongovernmental) should take place in a participatory, interactive and consensual manner;
4) the recognition of the complexity of the sustainability concept in order to make sure that alternative courses of action are compared. This is so that the project objectives and the stakeholders are satisfied with the final action implemented;

5) the use of a life cycle framework recognizes the need to consider all the principles of sustainable construction at each stage of a project's development (i.e. from the planning to the decommissioning of projects);
6) the use of a system's approach acknowledges the interconnections between the economics and environment. A system's approach is also referred to as an integrated (design) process;
7) that care should be taken when faced with uncertainty;
8) compliance with relevant legislation and regulations;
9) the establishment of a voluntary commitment to continual improvement of (sustainable) performance;
10) the management of activities through the setting of targets, monitoring, evaluation, feedback and self-regulation of progress. This iterative process can be used to improve implementation in order to support a continuous learning process; and
11) the identification of synergies between the environment and development.

Table 3.4 Principles of sustainable development

Authors	Proposed principles for sustainable construction
DETR (2000)	Profitability and competitiveness, customers and clients satisfaction and best value, respect and treat stakeholders fairly, enhance and protect the natural environment, and minimise impact on energy consumption and natural resources.
Hill and Bowen (1997)	Social pillar: improve the quality of life, provision for social self determination and cultural diversity, protect and promote human health through a healthy and safe working environment and etc Economic pillar: ensure financial affordability, employment creation, adopt full-cost accounting, enhance competitiveness, sustainable supply chain management. Biophysical pillar: waste management, prudent use of the four generic construction resources (water, energy, material and land), avoid environmental pollution and etc. Technical pillar: construct durable, functional, quality structure etc.These four principles are contained within a set of over-arching, process-oriented principles (e.g. prior impact assessment of activities).
Miyatake (1996); CIB (1999)	Minimisation of resource consumption, maximisation of resources reuse, use of renewable and recyclable resources, protection of the natural environment, create a healthy and non-toxic environment, and pursue quality in creating the built environment
Cole and Larsson (1999)	Reduction in resource consumption (energy, land, water, materials), environmental loadings (airborne emissions, solid waste, liquid waste) and improvement in indoor environmental quality (air, thermal, visual and acoustic quality)

These principles can be used to guide the process of building development at all levels and within all disciplines. From them, it is possible to extrapolate an endless series of project- or discipline-specific principles and guidelines, which can assure that decisions taken follow the road of sustainable development.

Construction practitioners worldwide are beginning to appreciate sustainability and acknowledge the advantages of building sustainably. For example, the concept of sustainable building costs lower than conventional method and saves energy as demonstrated by Hydes and Creech (2000). This was further supported by Heerwagen (2000), Bartlett and Howard (2000) and Pettifer (2004), who added that sustainable buildings will contribute positively to better quality of life, work efficiency and healthy work environment. Yates (2001) explored the business benefits of sustainability and concluded that the benefits are diverse and potentially very significant.

3.4.2 Sustainable construction in the UK

The UK Government commitment to sustainable construction is set out in *'Building a better quality of life- a strategy for more sustainable construction'* (DETR, 2000). Ever since its publication, the sustainable construction agenda has been taken forward through a dynamic partnership between the government and industry. As a result, there have been several developments as summarised below.

• There has been an increase in the number of voluntary policies, legislations, regulations, economic measures and fiscal incentives such as Landfill Tax, Climate Change Levy, Aggregates Levy, Renewable Grant Schemes, Land Use Incentives and changes to the Building Regulations.

• The Building Regulations, the Planning White Paper, the Communities Plan and the Energy White Paper have been amended to reflect sustainable construction agenda.

• There are several joint initiatives to promote awareness, capacity building and reporting mechanisms such as Global Reporting Initiatives, CIRIA's industry sustainability indicators, sustainable construction task force and the sustainable building task force etc.

• Sectors within the industry (e.g. steel, concrete, brick, civil engineering, etc.) have developed their own sustainability strategy and action plans and have started reporting on progress.

• A host of demonstration projects on sustainable construction initiatives providing tangible evidence of positive outcome such as the Rethinking Construction, WRAP, Sustainable Construction Road Show and so on.

• Research centres on sustainable construction funded by the government have been organised nationwide, numerous conferences, books, journals and publications are available, and universities are offering various courses and degrees in the fields.

• There are plethora of research on sustainable construction concepts, tools, frameworks, technologies, materials, energy systems, water conservation systems and other related issues, such as waste minimisation, recycling techniques, alternative materials and environmental management. The results are available as publications (e.g. CIRIA and TRL Reports), digests (e.g. BRE), guidance notes (e.g. Environment Agency Pollution Prevention Guidance (PPG), videos and training packs.

On the surface, at least, it would appear that these efforts are a significant success story and the industry movement toward more sustainable construction has gained significant momentum. However, the actual situation may not be so upbeat as the industry is still faced with major challenges (Kilbert, 2005; CIRIA, 2001). The use of sustainable building material represents one important challenge in the design of a building.

3.5 Building materials and sustainability

The overall performance of the building is the most important consideration in achieving more sustainable construction. Building materials play an essential role in increasing the sustainability of buildings and contributing to economic prosperity. The usage of building materials has a substantial impact of the environment, mainly because of the large quantity of non-renewable resources with the potential for depriving future generations of their use (Ofori, 2002; Godfaurd *et al.,* 2005). Moreover, all building materials affect the environment during their life cycles. From extraction of raw materials to disposal of demolition waste, various forms of pollution are created, with adverse effects on the atmosphere, land, and water system. The raw materials are processed before becoming suitable for use within buildings; this process often involves consumption of large amounts of energy.

Construction practitioners have begun to pay attention to controlling and correcting the environmental damage due to their activities. The selection of materials has attracted scrutiny. In the past the factors further influencing the choice of building materials were predominantly cost, availability and appearance. However, these days environmental suitability of materials is another important factor that is being acknowledged by construction practioners (Asif *et al.* 2007).

3.5.1 Sustainable building materials

The search for environmentally responsible design is not a new phenomenon. Ofori and Kien (2004) summarise these efforts by studying the extent to which architects are aware of the implications of their design decisions, and are using the available material information and techniques to make appropriate choices. Zeiher (1996) traces ecological design practice from pre-history and presents the ideas and works of leading American exponents. Farmer (1997) presents a history of sustainable architecture and highlights lessons for the present endeavour. Knowledge on environmental impact of building materials has increased in the past decade. Ofori(1999) notes that several factors account for this, including the efforts of professional institutions to enhance the awareness of their members through publications of policy documents and best practice guides on material selection. Spiegel and meadows (1999) and Huberman and Pearlmutter (2008) suggest that sustainable approaches here focus on two questions: what are we using? How well are we using it? They note that sustainable building materials: respect the limitations of non-renewable resources, work within the pattern of natures cycles and inter-relationships of ecosystems, are non-toxic, are energy and water efficient, are made from recycled materials and are themselves recyclable.

Kibert and Bosch (1998) cite the following characteristics of sustainable materials:

- Acceptable levels of environmental performance characteristics should be determined
- All aspects of material's entire life cycle should be considered
- No permanent environmental contamination should occur during the material's life
- Materials should not be combined into composites which cannot be disassembled
- The material production and application should be energy efficient
- Third party certification for some product is desirable
- They are often more affordable than commonly perceived.
- Using them efficiently can save on costs.
- They provide improved indoor air quality.

- Deconstruction after building use should be possible.

3.5.2 The selection of sustainable building materials

It is estimated that by 2056, global economic activity will have increased fivefold, global population will have increased by over 50%, global energy consumption will have increased nearly threefold, and global manufacturing activity will have increased at least threefold (Matthews *et. al.* 2000; IIha *et al.,* 2009). For these reasons, it is important to reduce the environmental impact of products and materials in terms of their production, rate of use and overall building performance, and to optimize their longevity, either in terms of first life or via re-using or reprocessing. The pace of actions towards sustainable application depends on the awareness, knowledge as well as an understanding of the consequences of individual actions (Braganca *et al.,* 2007; Abidin, 2009). Among these is the environmentally responsible approach to the selection of building materials (Anderson *et al.,* 2009). Accroding to Nassar *et al.* (2003) and Alibaba and Ozdeniz (2004), the selection of building materials is one of several factors that can impact the sustainability of a building project. This was also reaffirmed in the work of Treloar *et al.* (2001) and Zhou *et al. (*2009), that an appropriate choice of materials for a design process plays an important role during the life cycle of a building.

Kibert (2005) view sustainable material selection as one of the most difficult tasks to undertake in a building project. In part, this is because:

• so many different products and materials need to be evaluated, both individually and as assembled building components

• assessment parameters are not consistent across product categories or different countries of origin

• manufacturing processes lack transparency

• products and materials evaluation has no universally agreed approach.

Several manuals now provide guidelines for material selection. These include Doran (1992), Brantley and Brantley (1995), public technology inc. (1996) and Spiegel and meadows (1999). Spiegel and meadows (1999) note that in selecting sustainable materials, designers should aim to maximise durability, energy efficiency, recyability, maintainability, and use of local materials to minise the use of hazardous materials, and synthetic chemicals. Anink *et al* (1996) describe a strategy for the choice of sustainable building materials: design building to be efficient and to utilise as few resources as possible, specify the use of renewable and recycled sources in order to close the life-cycle loop of materials and select materials with the least environmental impact throughout their entire lifetime.

3.5.3 Barriers to use of sustainable materials

Although the sustainability imperative is gaining in importance, there are still major barriers preventing this 'new style' engineering practice becoming the norm. From the literature several studies (Anderson *et al.*, 2000; Davis, 2001; Eisenberg *et al.*, 2002; Landman, 1999; Mendler, 2001; Owen, 2003; Rao and Brownhill, 2001) were reviewed to provide a summary of the main barriers to integrating sustainability or sustainable innovation into the building industry. The main barriers are:

1. the real or perceived financial cost and risk (Anderson *et al.*, 2000; Davis, 2001; Landman, 1999; Owen, 2003; Rao and Brownhill, 2001) which includes the

problem of the upfront cost and the ongoing costs usually coming from separate budgets, if not separate organisations;

2. the lack of information and training (Davis, 2001; Landman, 1999; Owen, 2003; Rao and Brownhill, 2001) of the designers, contractors and clients;

3. naturally following the second is the lack of demand from the clients (Anderson *et al.*, 2000; Davis, 2001; Landman, 1999; Owen, 2003). The European report written by Rao and Brownhill (2001) introduces the idea of the circle of blame: 'designers and contractors say clients don't ask for it, clients say designers don't provide it';

4. closely followed and again logically by the lack of support from subcontractors (Landman, 1999; Owen, 2003); and

5. finally regulators (Eisenberg *et al.*, 2002).

These barriers have real or perceived impacts on the risk and profit of various industry groups, and may therefore influence their decision not to use new sustainable materials.

3.6 Strategies for the sustainable development of the construction industry

In order to achieve a sustainable future in the construction industry, Asif *et al.* (2007) suggest adoption of multi disciplinary approach covering a number of features such as: energy saving, improved use of materials, material waste minimization, pollution and emissions control. There are many ways in which the current nature of construction activity can be controlled and improved to make it less environmentally damaging, without reducing the useful output of construction. To create a competitive advantage using environment-friendly building practices, the whole life-cycle of the building should, therefore, be the context under which these practices are carried out. A review of literature has identified three general objectives which should shape the implementation of sustainable design and construction, while keeping in mind the three categories of sustainability issues (social, environmental, and economics) identified in sector 3.3. These objectives are:

- Resource management (Mumma, 1997; Clough et al., 2000; Kennedy, 2001; Graham, 2002; EEA, 2006; Kibert, 2007; Walker 2007; Marcouiller and Tremble., 2009);
- Cost efficiency (Green, 1994; Bartlett and Howard, 2000; Langdon, 2007; Smith and Jaggar, 2007; Kibert, 2007) and
- Design for human and environment (Keoleian and Menerey, 1994; Jackson, 2003; Sorvig and Thompson, 2008).

The following subsections, present specific strategies for approaching each of the three objectives, along with examples of technologies and opportunities related to each of the strategies.

3.6.1 Resource Management

All building activities involve the use of some components of the earth's resources, such as water, energy and materials. During these activities effects occur, changing the ecology of that part of the biosphere (Hudson, 2005). The continued existence and maintenance of the built environment involves dependence on the earth's resources and environment, which must supply it with certain inputs. The inputs into the built environment include not only construction materials but also the energy derived from non-renewable sources for the transportation of materials, their assembly and construction on the site as well as the energy required to sustain indoor environmental conditions (Sev, 2009). For these reasons the design team, must regard the creation of a building as a form of resource management. Since the non-renewable resources that play major role in the creation of a building are energy, water, material and land, the conservation of these non-renewable resources has vital importance for a sustainable future. Resource management yields specific design methods, as defined in Figure 3.8.

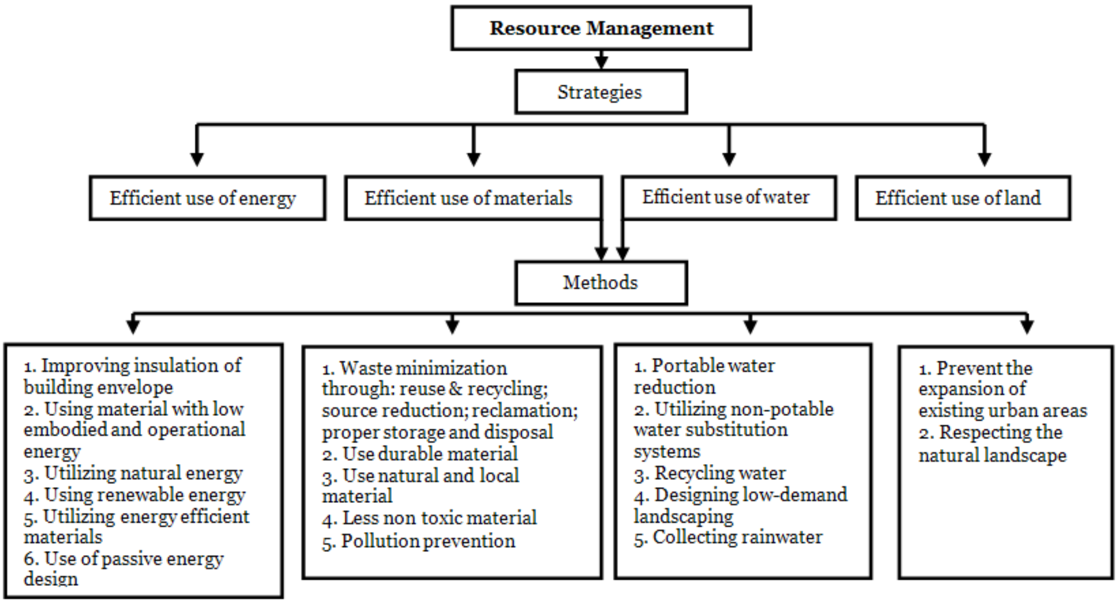


Figure 3.8 Methods to achieve the 'resource management' principle (Source: Sev, 2009)

3.6.1.1 Efficient use of Energy

Energy use is one of the most important environmental issues and managing its use is inevitable in any functional society. In the industrialized world, the development of energy resources is an indispensable factor for economic progress and has become essential for agriculture, transportation, waste collection, information technology, communications which is a prerequisite of a developed society. However, the fossil fuels (oil, natural gas and coal) from which most energy is generated are not inexhaustible, and burning them releases carbon dioxide (CO_2), one of the principal "greenhouse gases" which are thought to be responsible for global warming along side other air pollutants, such as nitrogen oxides, sulphur dioxide, volatile organic compounds and heavy metals.

Buildings are the dominant energy consumers. Buildings consume energy and other resources at each stage of building project from design and construction through operation and final demolition. (Cole and Rousseau, 1992; Hui, 2001). According to (Borjesson and Gustavsson, 2000), the kind and amount of energy use during the life cycle of a building material, right from the production process to handling of building materials after its end life can, for example, affect the flow of greenhouse gases (GHGs) to the atmosphere in different ways over different periods of time. Their consumption can be largely cut back through improving efficiency, which is an effective means to lessen greenhouse gas emissions and slow down depletion of non-renewable energy resources (Lee and Chen, 2008). With this realization, increasing more attention is being paid to the improved energy efficiency in building sector over the years, partly because the sector harbours a considerable potential of primary energy saving and reduction of emissions, having a negative impact on the environment. (Sasnauskaite *et al.,* 2007).

Energy use in a life cycle perspective includes energy needed for both operational and embodied energy. The operational energy requirements of a building can be considered as the energy that is used to maintain the environment inside that building (Dimoudi and Tompa, 2008). Thormark (2006) life cycle analysis of building shows that operational energy accounts for 85 - 95% of the total energy consumption and CO_2 emissions of a building which comes from occupancy through heating, cooling, ventilation, and hot water use. This will include energy from electricity, gas, and the burning of fuels such as oil or coal. Application of energy efficient materials when designing a building envelope has been advocated as an effective way in the reduction of building energy requirements, increase its life span and ensure consistent performance over time (Martinot, 1998; Santamouris, 2004; Moss, 2006).

Energy needed for operations can be reduced considerably by improving the insulation of the building envelope, technical solutions, etc. However, studies by Thormark (2006) have also shown that the total energy needed in a low-energy building may be even higher than in a building with a higher amount of energy needed for operation, because large amounts of energy are needed for production and maintenance of the technical equipment. Therefore, as the energy needed for operation decreases, more attention has to be paid to the energy use for the material production, which is the embodied energy. The embodied energy of a building is the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy that is required to manufacture the materials and components of the building (Huberman and Pearlmutter, 2008). This indirect energy will include all energy required from the raw material extraction, through processing and manufacture, and will also include all energy used in transport during this process and the relevant portions of the energy embodied in the infrastructure of the factories and machinery of manufacturing, construction and transport.

The energy life of a building can therefore be considered to be made up of numerous inputs of operational and embodied energy throughout a building life cycle as shown in Fig. 3.9. There is a clear advantage to building with a low total embodied energy. Products with lower embodied energies are typically more economical, easier to work with, and are less damaging to the environment (Lenzen and Treloar 2002).

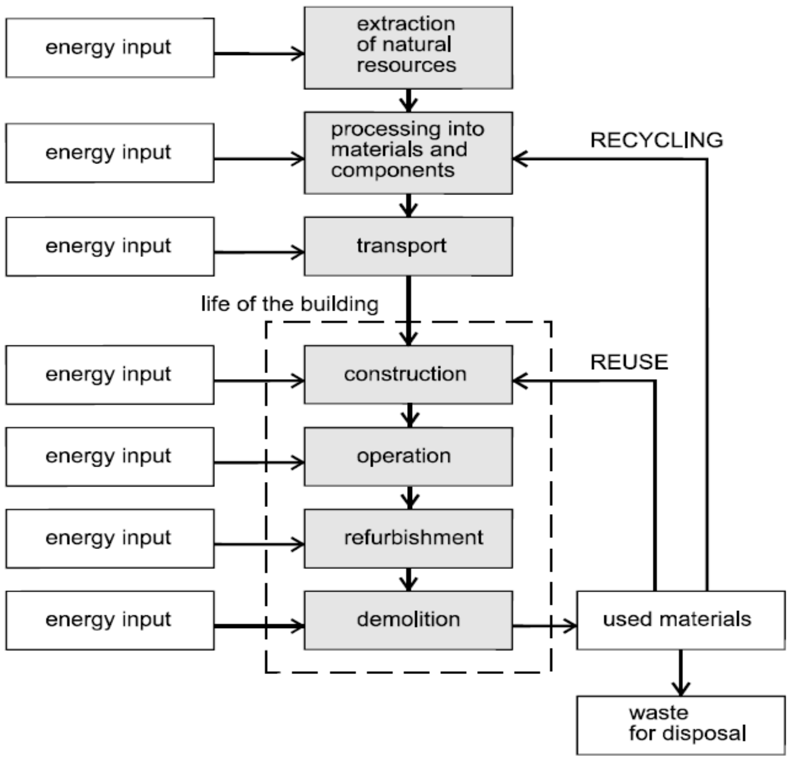


Figure 3.9 Stages of energy input during the life of a building

Source: Adapted from Crowther, 1999

The main goal in energy conservation is to reduce the consumption of fossil fuels, as well as increasing the use of renewable energy sources. This could be achieved by selecting materials and components with low embodied energy, developing designs that will lead to energy efficient building operation, perhaps even energy self–sufficient building operation, designing for energy efficient deconstruction and recycling of materials, selecting means of transport for delivering materials and components to construction sites that are energy efficient, and developing energy efficient technological processes for construction, fitout and maintenance of buildings. A truly integrated approach to energy efficiency in building processes would need to be instigated by the project team right from the beginning to achieve the target energy consumption levels.

3.6.1.2 Efficient Use of Water

Water is an increasingly precious and scarce resources all over the world.Using it sustainably requires being thoughtful, to avoid both waste and pollution. With the fast development of the global economy, depletion of water resources is becoming an environmental issue of the utmost concern worldwide. All industrialized economies require water of some form, quality and quantity, for all production processes. Besides the social and environmental problems, some industries are beginning to feel the effects of a limited supply McCormack *et al.,* (2007). The United Nations World Water Development Report (WWDR) indicates that water for all our uses is becoming scarce and is leading to a water crisis (UNESCO, 2003). On January 24th, 2008, U.N. Secretary-General Ban Ki-moon urged business and political leaders that the looming crisis over water shortages should be at the top of the global agenda in an effort to prevent conflicts over the growing scarcity of freshwater supplies.

In comparison to many other developed nations, consumption of water in the UK has been experiencing an incredible growth over the last few decades; the Worldwide Fund for Nature (WWF) has categorized the UK as mildly water stressed (Optimum Population Trust, 2007). The effects a sector can have on the environment are nowhere more apparent than in the building industry (McCormack *et al.,* 2007). Building construction and operation draw heavily on water from the environment. Growth in urban water use has caused a significant reduction of water tables and necessitating large projects that siphon supplies away from agriculture (Roodman and lenssen, 1995). Water used to operate buildings is a significant component of national water consumption (Hubacek *et al.,* 2010). However, this is not the only form of water consumed throughout a building's life cycle. Water is also consumed in the extraction, production, manufacturing, and delivery of materials and products to site, and the actual on-site construction process. McCormack *et al.,* (2007) called this the 'embodied' water. This 'embodied water' contains both direct and indirect water paths that have not previously being included when considering the water consumption of the construction industry. As a result, strategies and policy has focused on the operational water use of the built environment, neglecting the embodied water of various goods and services required for construction (McCormack *et al.,* 2007).

Ilha *et al.* (2009) observed that water conservation technologies and strategies are often the most overlooked aspects of a whole-building design strategy. However, the planning for various water uses within a building is increasingly becoming a high priority, in part because of the increasing recognition of the water savings that can be realized through the implementation of water saving initiatives. The literature reveals a number of strategies (Mendler and Odell, 2000; McCormack *et al.,* 2007; Sev, 2009; Ilha *et al.*, 2009; Hubacek *et al.,* 2010) that can be employed to reduce the amount of water consumed through a building life cycle. In general terms, these methods include:

- System optimization (i.e., efficient water systems design, leak detection, and repair);
- Water conservation measures; and
- Water reuse/recycling systems.

More specifically, a wide range of technologies and measures can be employed within each of these strategies to save water consumption. These include:

- Water-efficient plumbing fixtures (ultra low-flow toilets and urinals, waterless urinals, low-flow and sensored sinks, low-flow showerheads, and water-efficient dishwashers and washing machines, Design for dual plumbing to use recycled water for toilet flushing or a gray water system that recovers rainwater or other non-potable water for site irrigation;
- Minimize wastewater by using ultra low-flush toilets, low-flow shower heads, and other water conserving fixtures;
- Use re-circulating systems for centralized hot water distribution;
- Recycling water;
- Designing low-demand landscaping;
- Collecting rainwater using rainwater and grey water storage and
- Using low flow showerheads, dual flush toilets and self-composting toilets.

3.6.1.3 Efficient use of Material

Extraction and consumption of natural resources as building materials or as raw materials for production of building materials and building materials production itself in implementing construction works has a direct impact on natural bio-diversity due to the fragmentation of natural areas and ecosystems caused by construction activities (Spence and Mulligan, 1995). In particular, large amount of minerals resources are consumed in the built environment, and most of these mineral resources are non renewable. Therefore, it is important to reduce the use of non-renewable materials. According to Abeysundara *et al.* (2009), this should be incorporated for consideration at the project initiative and design phases, where the selection of materials is very important and the choice should be based on the materials' environmental impacts. At the construction and deconstruction phases, various methods can also be used for reducing the impacts of materials consumption on the natural environment, for example, materials recycling and reuse, construction-for-disassembly by using modular, using the materials and components available locally. The sub-section discusses some of the factors to be considered in the use of materials for building project.

Waste Minimization

The construction industry is one of the major waste generators, which causes several environmental, social and economical problems. Waste takes the form of spent or unwanted materials generated from construction and demolition processes. Prevention and reduction of waste in the construction of housing can save considerable amounts of non-renewable resources. An increasing body of scholarly work, notably that produced by (Osmani, 2008; Coventry *et al.,* 2001; Greenwood, 2003; Poon *et al.,* 2004; Baldwin *et al.,* 2006; Ortiz et al. 2010) has demonstrated that the building designers have an important role to play in construction waste minimisation and reduction. As such, Coventry *et al.* (2001) suggested three key roles that designers should play, namely: giving advice to clients; initiating waste reduction at a project level; and improving design practices generally. However, Osmani (2008) question whether the architectural profession is culturally, strategically and logistically prepared for proactive supply chain partnering to engender significant improvements in waste minimisation performance. Additionally, the challenge to architects is how to embed waste reduction strategies within conventional design processes (Osmani, 2008) some of which are discussed below.

Reducing and recovering construction waste- According to Esin and Cosgun (2007), the most effective measure of reducing the environmental impact of construction waste is by primarily preventing its generation and reducing it as much as possible. This will reduce reuse, recycling and disposal needs thus providing economic benefits. If waste generation could not be prevented or only prevented to a certain degree, the next step should be to ensure that the construction waste is reused and recycled as much as possible (Esin, and Cosgun, 2007). An analysis has shown that recovery reduces the amount of waste and Green House Gas (GHG) emissions, saves energy, and reduces the use of raw materials (Pimenteira *et al.*, 2005). Recovery of useful energy and materials from wastes has also been emphasized as one of the most important environmentally friendly practices for achieving energy savings to alleviate the pressing energy situations (Marchettini *et al.,* 2007). An example could be seen in a waste recycling industry, where the collection of scrap iron reduces the demands for virgin materials, and energy consumption as well because more energy is consumed for processing virgin material (Holmgren and Henning, 2004). A similar recovery strategy was also conducted by (Hainsworth *et al.,* 1995) in the steel industry, where the recovered waste blast furnace gas (contains 28% carbon monoxide, and 72% nitrogen) is mixed with natural gas as an alternative fuel to curb the consumption of the natural gas. Waste recovery also reduces the cost of disposal and the amount of waste in the landfills (Osmani, 2008).

Reuse and Recycling- Recycling products reduce general environmental impacts, particularly the use of resources and waste creation. The importance of alternatives (such as recycling and reuse) for re-entering building materials and components in the production chain has been already presented in the literature (Peng *et al.,* 1997; Hill and Bowen, 1997; Tam and Tam, 2006; Curwell and cooper, 1998). The reuse of building materials is an alternative for the reduction of construction and demolition waste (CDW) when renovating and demolishing buildings, by performing building deconstruction, which enables the recover of building parts as functional components such as bricks, windows, tiles, differently from traditional demolitions in which parts are transformed back into raw materials to processing (Da Rocha and Sattler, 2009). This requires that buildings are designed and constructed with adaptability in mind (Roodman and Lenssen, 1995).

Thormark (2002) stressed the importance of reusing and recycling the buildings parts in order to save energy. Gao *et al.,*(2001) verified that the energy consumption for producing new construction materials by using recycled materials can be lower than using new materials and that the energy savings by reusing components can be even higher than by recycling building materials. For example, the fabrication of steel from old iron needs about half the energy used to produce steel from iron ore, according to Haberstatter (1992 cited in Polster *et al.*, 1996) and Peuportier (2002). The former releases as well only about half of CO_2 than the later and creates about 280 kg less waste per ton of steel. (Peuportier, 2002). As a result, reuse and recycling seems to be a key strategy to be considered for the adoption of more sustainable practices, as it contributes with a great percentage of the total reduction in waste generated in building process.

The storage and disposal of construction waste- In situations where construction waste could not be prevented and recovered, they need to be stored in an appropriate manner and kept under control (Esin and Cosgun, 2007). Non-hazardous construction debris and construction debris classified as special waste are landfilled in either municipal solid waste (MSW) landfills or in landfills that only accept construction debris. In the UK, decisions on the types of waste acceptable at landfills were entirely based on site-specific risk assessment.

Licenses controlled the quantities and types of waste to be accepted and often, in the case of hazardous waste, specified maximum loading rates for particular wastes or components substances. Landfill operators had to have systems (acceptance procedures) in place to ensure that incoming waste was within those limits (UK Environment Agency, 2010).

Durability/Longer life of materials

Mora (2006) defined durability as an indicator which informs of the extent to which a material maintains its original requirements over time. The sustainability of a building can be enhanced by increasing the durability of its materials (Malholtra, 2002), and a material, component or system may be considered durable when its useful service life (performance) is fairly comparable to the time required for related impacts on the environment to be absorbed by the ecosystem.

Materials with a longer life relative to other materials designed for the same purpose need to be replaced less often. This reduces the natural resources required for manufacturing and the amount of money spent on installation and the associated labor. The greater the material durability, the lower the time and resources required to maintain it (Cafi and Rejna, 2000; Silva *et al.,* 2004). Durable materials that require less frequent replacement will require fewer raw materials and will produce less landfill waste over the building's lifetime.

Use of Natural and Local Materials

Natural materials are generally lower in embodied energy and toxicity than man-made materials (Godfaurd *et al.,* 2005). They require less processing and are less damaging to the environment. Many, like wood, are theoretically renewable. When natural materials are incorporated into building products, the products become more sustainable (Godfaurd *et al.,* 2005). The use of building material sourced locally can help lessen the environmental burdens, shortens transport distances, thus reducing air pollution produced by vehicles (Joseph and Tretsiakova-McNally, 2010). Often, local materials are better suited to climatic conditions, and these purchases support area economies. . For instance, the decorative use of marble quarried halfway around the world is not a sustainable choice. Steel, when required for structural strength and durability, is a justifiable use of a material that is generally manufactured some distance from the building site (Kim and Rigdon, 1998).

Pollution prevention

Pollution prevention measures taken during the manufacturing process can contribute significantly to environmental sustainability. Kibert (2008), suggest selecting materials manufactured by environmentally responsible companies encourages their efforts at pollution prevention. Although these products may have an initially higher "off-the-shelf" price, choosing products that generate higher levels of pollution exploits the environment (Kim and Rigdon, 1998). Pollution comes in form of air, water and soil. However, emissions to soil are hardly discussed in any LCA literature, and the data available are very limited. In the building industry, soil pollution is mainly a problem at the construction site. It may also be a problem in the extraction of some minerals, when the waste is deposited, especially hazardous waste. Water is used in large quantities in many manufacturing processes, especially in the production of paper, cement, and metals (Allen, 1999). This wastewater is often released directly into streams and can contain toxic substances. By becoming aware of which manufacturers use environmentally sustainable manufacturing methods, specifying their products, and avoiding goods produced through highly polluting methods, building designers can encourage the use and marketing of sustainable building materials.

Since most of the pollution resulting from construction activity is the result of fossil-fuel burning, the principal means of reducing pollution is through increased energy-efficiency in all activities. All the ways of improving energy efficiency discussed in section 3.6.1.1 above will reduce pollution as well. Further opportunities for pollution reduction in site operations, in transport, and through fuel substitution include site operations, transport and fuel substitution.

The principal means for reducing atmospheric pollution resulting from site operations are:

- reducing avoidable transportation of materials;
- improving site management efficiency;
- reduction of the quantity of site wastes produced;
- systematic separation of all unavoidable construction wastes, to facilitate recycling.

In some cases, possibilities may exist for the use of human or animal labour in place of mechanical energy to minimise overall fuel consumption. Operations in which this may be considered include excavation, mixing of materials and transport of components within the site. Low-rise buildings, and those using traditional technologies and relatively small components, are most suited to this approach (Spence and Mulligan, 1995). The means of transport is also important: approximately four times as much carbon dioxide is emitted by the transportation of a load by road than the equivalent journey by rail or water (Hodges, 1977 cited in Spence and Mulligan, 1995). Emissions from road transport are a major cause of photochemical smog, of which the main components are carbon monoxide, nitrogen oxides, hydrocarbons and ozone released by the action of sunlight on organic compounds in the lower atmosphere (Spence and Mulligan, 1995). Because of their bulk, and the large quantities involved, moving building materials contributes very significantly to the total pollution emissions from transport.

Use of Non-Toxic or Less-Toxic Materials

Non -or less-toxic materials are less hazardous to construction workers and building's occupants. Many materials adversely affect indoor air quality and expose occupants to health hazards. Some building materials, such as adhesives, emit dangerous fumes for only a short time during and after installation; others can contribute to air quality problems throughout a building's life (Kim and Rigdon, 1998). By using building materials with lower or non-existent levels of toxic substances, environmental health problems can be avoided and the need for air scrubbers reduced. Material toxicity is of increasing concern with the growing number of building products containing petroleum distillates. These chemicals, known as volatile organic compounds (VOCs) can continue to be emitted into the air long after the materials containing them are installed (Rossi and Lent, 2006). The severity of this process, called "outgassing," is dependent on the chemicals involved, rate emission, concentration in the air, and length of exposure (Kim and Rigdon, 1998). Many adhesives, paints, sealants, cleaners, and other common products contain VOCs. Often, the substances are only exposed for a short time during and after installation; the outgassing diminishes drastically or completely once the offending materials have cured or been covered by other building materials. Therefore, Kim and Rigdon (1998) recommend higher air cycling rates during installation of these materials and for several months following building occupation.

3.6.1.4 Efficient Use of Land

Land is one of the limited and non-renewable resources on our earth. It is an important resource upon which the construction industry depends. Land use through urban expansion has been identified by Uher (1999) as a growing problem in both developed and developing worlds. The anticipated long–term population growth will ensure the continuation of a strong demand for urban land in the future. Although more land may be reclaimed from the ocean, land reclamation on a large scale is undesirable since it could severely interfere with ecosystems. In many places, the land is more damaged than previously believed. Soil erosion, groundwater contamination, acid rain and other industrial pollutants are damaging the health of plant communities, thereby intensifying the challenge and necessity to restore habitats. Sustainable design must develop a respect for the landscape and expend more effort understanding the interrelationships of soils, water, plant communities and associations, and habitats, as well as the impacts of human uses on them. Adaptive reuse of an existing building may also eliminate the need for new construction, thus preventing the expansion of built environment and occupation of agricultural and eco-sensitive areas (Sev, 2009).

Urban sprawl will need to be minimized or stopped if any further losses of arable land on urban fringes, deforestation and soil degradation are to be avoided. This will be a challenging task that will require the development of a new urban development strategy by closely integrating the principles of urban planning with those of sustainable construction to achieve a functional, comfortable, healthy and environmentally responsible living environment (Uher, 1999). The impact of the construction industry on the environment and the expansion of urban areas show the importance of land as a vital indicator of sustainability with the potential to become an absolute indicator of sustainable construction (Uher, 1999; Haberl, *et al.,* 2004). A possible strategy according to Best and Valence (2002) is to adopt a policy of zero expansion of existing urban areas. This strategy would promote better use of urban land through a higher population density that would make better use of infrastructure services and transport systems. It would also lead to adaptation and regeneration of the existing built environment by taking account of future needs. This strategy would also encourage rehabilitation of degraded, contaminated or arid land for urbanization.

3.6. 2 Cost efficiency

Construction clients are demanding assurance of their buildings' long-term economic performance and costs (Bartlett and Howard, 2000). In addition, the construction project supply chain of developers, suppliers, manufacturers, design and construction teams are under increasing pressure from clients to minimize total project cost and consider how much a building will cost over its life cycle and how successfully it will continue to meet occupier's requirements. According to Ozsariyildiz and Tolman (1998), the construction industry is facing increased demands from clients asking for high quality building, lower cost and shorter lead-time. Buildings represent a large and long-lasting investment in financial terms as well as in other resources (Oberg, 2005). Improvements of cost effectiveness of buildings is consequently of common interest for the owner, the user and society.

There is considerable evidence to suggest that many organizations, in both the private and public sectors, make decisions about building related investment based on estimates of the initial construction cost, with little or no consideration for costs relating to operation and maintenance throughout the life of the building (Woodward, 1997). Design decisions require choice of construction structure, building materials and building installations (Giudice *et al.,* 2005), which is often accompanied by errors in investment through an inadequate economic control of decisions. Sharply rising energy costs have highlighted the opportunity for overall savings in the life of a building that can be achieved by investing in more energy efficient solutions initially. Savings on other operating and maintenance costs can also be considered, e.g. using building finishes that do not need frequent re-painting. A building's economic operation should be considered throughout the construction stage and also in terms of its maintenance and conservation throughout its useful life. This requirement may be assessed by using "Life-Cycle Costing (LCC)" (Sarja, 2002; Lombera and Cuadrado, 2010) analytical techniques. The significance of LCC model in this regard has been discussed in chapter 2.

In the UK, bodies such as OGC (OGC, 2003 and 2005), HM Treasury (2000), NAO (2001) have issued and endorsed several initiatives and policy reviews in order to change the approach of the public sector to procuring construction projects. Other countries like Norway have taken public procurement a stage further and have issued a standard NS 3454 (1998) identifying and detailing the life cycle costs and methods of economic evaluation. It has been widely recognized that private sector uses the LCC calculations in a much unstructured way, for their internal purposes. They rarely rely on it for the environmental or quality choices. The implementation of LCC is driven by public sector and is getting recognition and subsequently support in most EU member countries (Langdon, 2007). The effective implementation of life-cycle costing involves utilizing a thoughtful, comprehensive design along with quality material and construction practices with selected environmental considerations. Life cycle cost (LCC) for buildings is therefore an important tool for involving the construction client better in early stage design decisions.

Castillo and Chung (2004) assert that the lifecycle cost of a building includes initial design and construction costs and ongoing expenses such as maintenance, energy, and repair costs. However, quantifying the benefits of sustainable construction from a cost perspective must go beyond these typical life cycle costs and include usage costs, capturing all stakeholder costs. Emmitt and Yeomans (2008) in his review of LCC have identified three principal costs to be considered at the outset of a construction project. The initial building cost, the cost of the building in use, and the recovery cost.

3.6.2.1 Initial cost

Also referred to as the acquisition cost or the development cost, the initial cost covers the entire cost of creating, or remodelling, the building (Emmitt and Yeomans, 2008), such as cost of land/building acquisition costs, professional consultants fee, the cost of the materials that compromise the completed building, and the cost of putting it all together. When planning the acquisition of a major asset, Emmitt and Yeomans (2008) observed that organizations spend considerable time and effort in making an economic evaluation of the initial (capital) cost. For many clients, this is their primary and often only concern. Cost reductions may be possible by selecting less expensive building materials and reducing the amount of time required to assemble them on site, but this assumes that these costs can be discovered. Other strategies associated with initial cost reduction in building include the following:

- Using locally sourced materials
- Minimizing use of imported materials
- Choosing construction techniques that can be managed locally
- Designing so as to avoid conflict between different trades

3.6.2.2 Cost in use

Otherwise known as the running cost or operation cost, the cost in use is set by the decisions made at the briefing stage and the subsequent decisions made during the design and assembly phases (Emmitt and Yeomans, 2008). It also involves regularly scheduled adjustments and inspection to protect a building so that it goes on to supply the same comfort and appliances-resources and the cost of parts to perform repairs (Woodward, 1997, Arpke and Strong, 2006). Furthermore, decoration, fabric of building (i.e., roof, external walls), services (i.e., heating and ventilation) also took place at this level.

For many years, running costs were only given superficial attention at the design stage, although this has changed with the use of life cycle costing techniques that help to highlight the link between design decisions and costs in use. Materials and components with long service lives do cost more than those not expected to last so long and designing to reduce both maintainace and running costs may result in an increase in the initial cost (Emmitt and Yeomans, 2008). However, over the longer term, say 15 years, it might cost the building owner less than the solution with lower initial cost. Cost reduction in the use of building can achieve by considering the following:

- Taking adequate measures within the design of key building elements to make them readily accessible for regular cleaning, maintenance, and repair.

- To ensure that the skills required are within the competency of available labour supply.
- Choosing minimum-maintenance materials
- Adopting an appropriate process during the design stage to characterize service life requirements and relating material and component choices to such requirements.
- Protecting materials from destructive elements such as sun, temperature variations, rain or wind, or migration of moisture-laden air through defects in the envelope. Best practice measures for envelope detailing may include:
- Minimizing premature deterioration of the walls and roof by specific measures appropriate to the region such as shading screens, eaves, overhangs, etc.
- Use of surface materials appropriate to exterior conditions
- While fully meeting the operational requirements of the building, provide easy-to-understand and easy-to-use building control systems for occupants and building operators to ensure effective operation of energy efficient technologies and components. If a simple system can achieve the objective, then a complicated one should be avoided.
- Designing building structure and enclosure, for ease of adaptation to suit new building functions.
- Designing building so that adapting to a new fuel source or renewable energy technology will require only minor adjustments to architectural, HVAC, or electrical systems
- Designing HVAC and communications systems for ease of removal, relocation, or addition for changes in operation.

3.6.2.3 Recovery cost

There is a third cost that is rarely considered – the cost of demolition and material recovery (Emmitt and Yeomans, 2008). This is partly because the client may well have sold the building long before the building is recycled and partly because such costs are traditionally associated with the initial cost of the future development. Again this may be of little concern to the current client who is looking for short term gain with minimal outlay. However, if we are to take environmental issues seriously, then the recycling potential and ease of demolition should be considered during the design phases and costed into the development budget.

Attention to the principal cost of building project in terms of both design and choice of materials will minimize the overall costs for owner and users. It is important to determine how long the building is designed to last and whether it is likely that functional requirements will change in this time (Douglas, 1996). Moreover, if it is likely that re-sale value will be enhanced by ability to adapt to new uses, then appropriate design can substantially reduce the costs of adapting to new uses. Thus, increasing cost effectiveness of a building is a critical strategy for creating sustainable building.

3.6.3 Design for Human

Every sustainable building strategy must enhance the purpose of the building, which is to provide occupant comfort (Sev, 2009). Sustainable buildings must provide a healthy and comfortable indoor environment while conserving resources and protecting the nature. Several factors has been identified as affecting the indoor environmental quality, some of which are, but are not limited to, indoor air quality, thermal property, humidity, natural light and ventilation, noise level and furnishing.

A sustainable construction industry must balance human needs with the carrying capacity of the natural and cultural environments. In a modern society, where individuals spent more than 90% of their time indoors - and more than 70% of their time indoors at home (Adgate *et.al.,* 2002), an essential role of architecture is to provide occupants' safety, health, physiological comfort, physiological satisfaction and productivity. Many building designers have been preoccupied with style and form-making, disregarding environmental quality and human satisfaction in and around the built environment. According to Sev (2009), a product may save energy and perform well; however, if it does not positively affect the occupants' comfort and enhance productivity, it is not a sustainable product. A review of the literature (Nikolopoulou *et al.,* 2001; van der Linden *et al.*, 2002; Brager and Dear, 1998) have identified the following strategies (but not limited to) as a necessity in enhancing the coexistence between the environment, buildings and their occupants.

Thermal comfort - Thermal comfort improves the occupants' health, comfort and productivity (van der Linden *et al.*, 2002). The space inside a building provides conditions that allow occupants to survive freezing cold or blistering hot outdoor conditions. Air temperature, humidity, solar radiation, velocity of air flow and human metabolism are determinants of thermal comfort. Building envelope considerations, such as reflective roofing, low-E windows, window tinting and solar shading are some of the tools that enable designers to optimize thermal comfort as well as improving energy efficiency. Siting the building according to seasonal heat gain and use is another key to thermal comfort, as is landscaping. Individual control over a space is also important for comfort.

Daylighting- Daylighting is an important issue providing quality of light and improving the productivity of occupants, and includes controlling and distributing light for uniform levels, avoiding glare and reflections and controlling artificial light to achieve energy efficiency. Edwards (2006) suggests that natural conditions are of significance in achieving not just a comfortable working environment but also a productive one. Occupants of spaces having daylight are certainly happier, and evidence shows that they are more productive (Armstrong and Walker, 2002).

Natural ventilation -Natural ventilation is the process of replacing air in any space to provide high indoor quality without the use of mechanical means. Ventilation conditions inside a space have a direct influence on the health, comfort and well-being of the occupants. Natural ventilation has become an important strategy in building designs. Natural ventilation has the potential of reducing the energy needed for cooling and ventilating commercial buildings, while providing acceptable thermal comfort and indoor air quality. The climate suitability, window orientation and operable windows are the key factors for natural ventilation. Examples include providing cross-ventilation to make use of wind chimneys to induce stack ventilation, and using water evaporation systems in hot dry climates to induce air movement. Being able to open a window, to sit in the sun or shade and to have contact with nature appears to be key characteristics in sustainable building design (Edwards, 2006; Raw and Roys, 1993). Over-engineered buildings, no matter how energy efficient, can be counterproductive if occupants are denied power to intervene in the quality of living and working spaces (Battle, 2000).

Acoustic comfort -Acoustic comfort must be achieved by controlling sources of noise from mechanical and electrical equipment and from sources exterior to the building. Proper selection of windows, wall insulation and wall framing, and materials are essential to reducing noise from outside. Some sound insulating materials, such as acoustic ceiling tiles and straw-bale construction, can offer the advantages of recycling and using natural materials (Oral *et al.,* 2004; Sev, 2009). Hard versus absorbent surfaces also have a major impact on noise level inside a space. Noise elimination, control or isolation from HVAC equipment should also be addressed through acoustic zoning, equipment selection, construction and appropriately designed ducts, piping and electrical systems.

Safety and risk prevention- The construction sector is very complex and decision making between developers, designers, constructors, sub-contractors and the end user are by no means straightforward as, in many cases, they involve conflicting interests. It is highly useful in the initial stages of the project, when safety and health measures, which will last throughout its life cycle, may easily be integrated into building design thereby achieving the elimination and/or reduction of accident rates at each stage: construction, useful life and reuse. Moreover, legislative measures imposed by the authorities on the construction sector in order to reduce high accident rates have never been as successful as might be expected (Chan, 2006 cited in Lombera and Cuadrado, 2010[b]). Consequently, it may be argued that the legislative approach is not enough in itself and needs to be accompanied by other approaches that attack the root of the problem.

Functionality-Building functionality should be planned to enable the smooth operation of the activity for which the building is designed. The capacity of a building to absorb future industrial processes should be studied at the outset, to avoid additional enlargements in the event of company growth, and to reduce the additional material and building waste disposal costs. The use of durable constructive elements that require minimum levels of maintenance is of special importance, even where it may not be strictly necessary in the long term.

Aesthetics-Building aesthetics is a further value to bear in mind, with a view to conserving the architectural asset that blends in with the built environment of the industrial area or promotes a company image. A company will often promote the construction of its buildings with a corporate image, which identifies it and gives it greater prestige and by doing so, it is emphasizing the aesthetical requirement as a sustainable aspect.

3.7 Summary of chapter three

Environmental protection is effected by implementing resource-efficient sustainable practices, preserving ecosystems and maintaining the carrying capacity of the planet. According to Ofori and Chan (1998), sustainable construction can be achieved by the clients and contractors forming a team to manage environmental issues. It is important that every development includes environmental protection to the list of project objectives which traditionally include only time, cost and quality considerations (Ofori *et al.,* 2000). Bourdeau (1999) believes that sustainable construction can be achieved through the cooperation of various parties in the construction industry. Building clients and developers can promote sustainable construction since they represent the demand of the building sector. The development of environmentally awareness processes, and the consideration of proficiency in formulating, evaluating and verifying relevant environmental requirements to include these aspects, is crucial to development (Ofori, 1998; Ofori *et al.,* 2000; Sterner, 2002).

In addition, it is also important for building designers to show environmental consciousness in their design (Ofori, 1998). Bourdeau (1999) suggests that a more integrated approach to design be adopted to consider the fundamentals of sustainable building design. Bourdeau (1999) continues, suggesting that building designers should work together with manufacturers to create new designs which facilitate material recycling. The environmental qualities of construction materials may be considered as fundamental to the design and life cycle assessment models may be used to facilitate product development. However, life cycle analysis in its present form is too complex for efficient use and the input data is not sufficient for a complete assessment of building materials since there are over 40,000 materials on the market with material in the pipeline (Sterner, 2002). Therefore, it will take a long time for a life cycle assessment to be carried out on all materials in the market. Nevertheless, it is important for designers to adopt environmentally conscious techniques in building design (Ofori, 1998).

3.8 Conclusion from chapter three

This chapter presented a literature review of the relationship between construction and the environment. The literature has revealed that the construction industry undoubtedly shares the responsibility of conserving natural resources and protecting the environment. The principle of sustainable construction, even though it is vague in its definition, is still the goal. The future direction for construction is a more responsible attitude and more environmentally friendly practices.

The principal conclusion of this chapter is that the area of sustainable construction is one of increasing interest which has many levels and complex dimensions. This chapter has provided an overview of the wide range of environmental issues in the construction industry, while emphasizing the need for an integrated approach and understanding of the different components of a sustainable system. In order to achieve sustainability for society as a whole and for construction in particular, intelligent decision making is required which includes full consideration and knowledge of the many trade-offs and impacts associated with each building material available to be chosen. Sustainability is a desirable state towards which to strive, but the journey is not easy. The information provided in this chapter provides the platform for further research on the conceptual development of the sustainability index for building material selection which follows in the next chapter.

CHAPTER 4: A CONCEPTUAL FRAMEWORK OF A SUSTAINABILITY MODEL FOR MATERIAL SELECTION

4.1 Introduction

The Construction Industry has been beset with myriads of problems ranging from excessive consumption of significant percentage of the world primary resources to the generation of large percentage of solid waste and pollution (Nelms *et al,* 2007). As suggested in the previous chapter, the construction industry is closely related to environmental degradation. In response to these impacts, there is growing interest among organizations committed to environmental performance targets in recommending sustainable construction practices and in encouraging the construction of 'sustainable' buildings.

However, Ding (2008) stated that relying on the design of a building to achieve the goal of sustainable development is not sufficient to handle the current problem. Sustainability assessment should be considered in early stage, before any detailed design or even before a commitment is made to go ahead with a building project. Little concern has been given to the importance of selecting more sustainable material during project conception phase, where environmental issues are best incorporated (Lowton 1997; Edwards and Hyett, 2005; Ding, 2008). The conception stage in fact, is one of the major steps in a project life cycle, as it has the largest impact on cost and performance (Hegazy, 2002), and the consideration of sustainability at this stage will save time, effort, money and resources (Akadiri and Olomolaiye, 2009).

This chapter therefore investigates the current models used to assess the environmental performance of building materials and to present the concept of a new, multi-dimensional approach to assess material sustainability. The chapter first examines the development, role and limitations of current models in ascertaining material sustainability, thereafter discussed a conceptual framework for building material evaluation based on a multi-dimensional approach.

4.2 Building material environmental assessment models

As suggested in the previous section, the construction industry is closely related to environmental degradation. Concerns are being expressed about how to improve construction practices in order to minimise their detrimental affects on the natural environment (Holmes and Hudson, 2000; Shen *at al.,* 2010). The environmental impact of construction, sustainable building, designing for recycling and eco-labelling of building materials have captured the attention of building professionals across the world (Johnson, 1993; Cole, 1998; Osmani, 2008). In addition, material performance is now a major concern of professionals in the building industry (San-Jose and Garrucho, 2010) and environmental building material performance has emerged as one of the major issues in sustainable construction (Kibert, 2008).

According to Cole (1998), the definition of building material performance varies according to the different interest of parties involved in building development. For instance, a building owner may wish his building to perform well from a financial point-of-view, whereas the occupants may be more concerned about indoor air quality, comfort, health and safety issues. Therefore, an ideal environmental building material assessment will include all the requirements of the different parties involved in building project. However, using a single method to assess a building material environmental performance and to satisfy all needs of users is no easy task. Building material performance assessment methods are currently one of the emerging areas in research and development (Cole, 1998; Holmes and Hudson, 2000, Ding, 2008).

4.2.1 A review of existing assessment methods

For many years, a variety of building material performance evaluation methods has been developed internationally and domestically. This is due to an increasing awareness of the need to reduce the impact of building materials on global environment and individual health (Kim et *al.,* 2005). Considerable work has gone into developing systems to measure a building material environmental performance and physical facilities over its life cycle. Separate indicators, or benchmarks based on a single criterion, have been developed to monitor aspects of building performance such as air quality and indoor comfort. Such assessments focused on related tools, mainly on building energy use, indoor climate, and many other environmental issues (Forsberg and Malmborg, 2004; Ding, 2008). Nowadays, considering that buildings present many qualities or performances which should be taken into account for a proper evaluation (Roulet, 1999), several evaluation methods that cover building material environmental performance more comprehensively have been introduced. In spite of this, a comprehensive assessment tool is essential to provide a thorough evaluation of building material performance against a broader spectrum of environmental criteria. In this section, some of the popular assessment methods were examined in detail and they are broadly divided into two categories, building material specific and building as whole.

4.2.1.1 Building Environmental assessment models – building material specific

ENVEST - Envest is the first UK software for estimating the life-cycle environmental impacts of a building from the early design stage (Erlandsson and Borg, 2003). Currently, envest is designed for offices and commercial buildings and enables architects and designers to evaluate the environmental impacts of different design option for a chosen building. It considers the environmental impacts of materials used during construction and maintenance, and energy and resources consumed over the buildings life. Using minimal data entered through simple input screens, envest allows designers to quickly identify those aspects of the building which have the greatest influence on the overall impact. All impacts are assessed using Ecopoints, a measure of total environmental performance, which allow the designer to compare different designs and specifications directly. Envest uses Ecopoints to calculate the environmental impacts of the design. It considers the same environmental issues as the Environmental Profiles, with the exception of transport pollution and congestion. Envest has been created principally for designers, to help them compare different options in terms of environmental performance. It is intended for use from the early design stages. Clients may also be used envest to establish an environmental performance requirement for their design team.

ENVEST is therefore an attempt to simplify LCA studies by expressing the results in terms of a single point score, rather than as a series of environmental impact categories. It should be noted, however, that this approach is not recommended by the international standard dealing with life cycle impact assessment, i.e. ISO14042

[BSI, 2000], due to the complexity of the environmental issues involved and the inherently subjective nature of any weighting exercise.

BEES - (Building for Environmental and Economic Sustainability), is a computerised tool for choosing environmentally preferable building materials. (Lippiatt and Ahmad, 2004). The BEES project started at NIST (National Institute of Standards and Technology in US) in 1994, and the third version was released in October 2002. The purpose of the BEES has been to "*develop and implement a systematic methodology for selecting building products that achieve the most appropriate balance between environmental and economic performance based on the decision makers values"* (Lippiatt and Ahmad, 2004). The BEES environmental performance assessment is based on the LCA standards, including categorising in impact categories, normalising by dividing by the U.S. emission per year per capita, and weighing by relative importance. The economic performance is based on LCC calculation, and normalised by dividing by the highest life cycle cost, thereby ranking the materials from 0 to 100. Finally, an overall evaluation involves the environmental score and the economic score being weighted together using relative importance decided by the user.

ATHENA - ATHENA™ is an LCA tool developed at the ATHENA™ Sustainable Materials Institute in Ontario, Canada (Clements-Croome, 2004). The ultimate goal of this system is to "*encourage the selection of material mixes and other design options that will minimise a buildings potential life-cycle environmental impact and foster sustainable development*" (Trusty *et al.,* 1998). This evaluation of the ATHENA tool is based on the tutorial version of the newest software version (2.0) and an earlier beta version of the software (1.2 Beta). For a more detailed description of the methodology, the reader is referred to the ATHENA website (http://www.athenasmi.ca). The results for the assessment can be presented in terms of:

– Absolute totals of selected measures of the complete design.

– Absolute values on a per unit area basis.

– Values normalised to a selected design that may be one of the alternatives designated as a base case or some previously design of a similar building.

Studying the different results, it reveals that the user phase and demolition is excluded from the evaluation. Economy is not included in the assessment either. The objects of comparison in ATHENA are specific designs of a building. With the background of an LCI (Life Cycle Inventory) database, the tool automatically breaks down the elements into products that are available in the database (Clements-Croome, 2004). From data in the LCI database, the program assesses the environmental properties of the design alternative.

EPM- Environmental Preference Method (EPM) was developed by Woon /Energy, in the Netherlands in 1991, within the program on Sustainable living at the Dutch Steering Committee on Experiments in Housing (Anink *et al,* 1996; Anderson *et al.,* 2009). The main goal of the handbook was to construct a ranking of building materials according to their environmental preference (Anink *et al,* 1996; Anderson *et al.,* 2009). It was adjusted to the needs of local economy, offering possibility for practical and simple choice of ecologically friendly building materials and products that were usually used in construction of residential buildings. The approach to the problem of recognition and evaluation of environmental impacts is based on the method of life cycle assessment, but in a more simple way of estimation, based on accessible data and previously obtained data. (Anink *et al,* 1996; Radivojevic and Nedic, 2008) Unlike LCA method, this one is not focused on the quantitative analyses of certain products, expressed in units like kg or m3, but it makes wider comparative analysis of optional elements – functional units which could be applicable for certain positions in a building (Radivojevic and Nedic, 2008)

The principle of this method is to take simultaneously into account different factors, such as various damages of eco system, consumption/exhaustion of resources, energy consumption (in all phases of production, including transport), environmental pollution with different waste and hazardous materials, waste disposal problems, hazardous emissions into the atmosphere, global warming, impact on human beings, re-use and recycling possibilities, etc.

Result of this method is a list of preferable materials and products, made on the basis of evaluation of environmental impacts of each of them, and adjusted to typical positions within a building. (Anink *et al,* 1996) This method also takes into account whether it is a matter of construction or refurbishment of a building. Material preference for certain position is made through a four level ranking system which puts materials and products into three priority levels - I, II, III preference- (see figure 4.1), or it excludes them from a final choice.

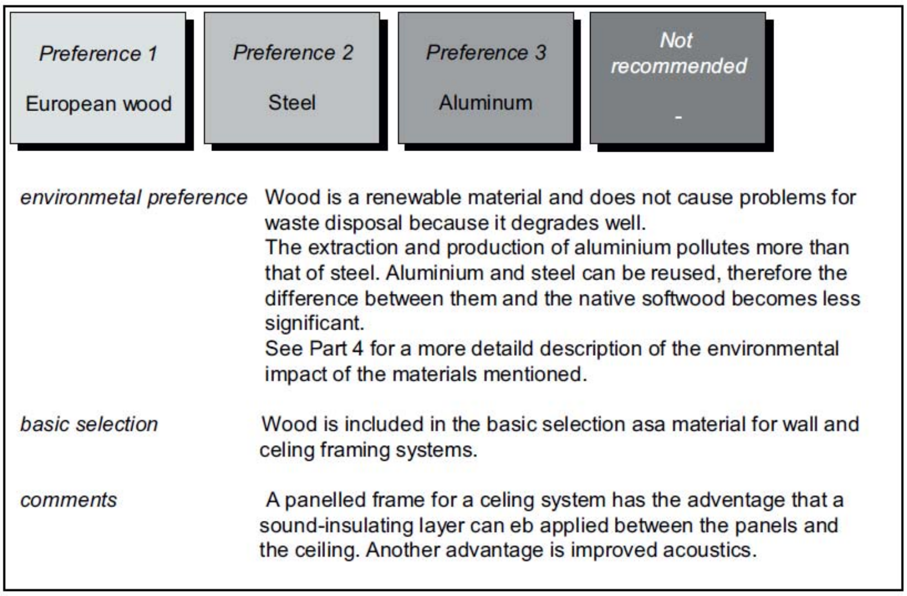


Figure 4.1 Relative ranking of wall and ceiling frame systems in the EPM method (Source: Anink, *et al.,* 2008)

Since this method takes into account all the relevant aspects, it could be considered as a specific combination of global and problem analysis, which easily adapts to the needs of practical implementation. The final product of EPM method is a manual that contains list of preferable materials and products, sorted according to their position in different components of a building and it was already used as a tool for environmental evaluation in some European projects (Radivojevic and Nedic, 2008).

ERG - The Environmental Resource Guide (ERG) was designed by the American Institute of Architects (AIA) with co-operative funding from the U.S. Environmental Protection Agency (American Institute of Architects, 1996). The ERG is a printed guide, primarily aimed at architects and designers. The guide consists of application reports for the different products groups. In addition, the user is presented with a summary table with the main reasons for the scoring. In addition, in a separate part of the guide, extensive information about the lifecycle of each material is found. This is not quantified information, but a qualitative description the material including material acquisition and preparation, manufacturing and fabrication, construction, use and maintenance and waste treatment. The guide provides useful information for those interested in going into details of the different materials.

4.2.1.2 Environmental building assessment methods - Building as a whole

BREEAM—BRE Environmental Assessment Method was the first environmental building assessment method in the world to be developed and remains the most widely used (Larsson, 1998). The Building Research Establishment developed the system in 1990 in collaboration with private developers in the UK. It was launched as a credit award system for new office buildings. A certificate of the assessment result is awarded to the individual building based on a single rating scheme of fair, good, very good or excellent. The purpose of this system is to set a list of environmental criteria against which building performances are checked and evaluated. This system can be carried out as early as at the initial stages of a project. The results of the investigation are fed into the design development stage of buildings and changes can be made accordingly to satisfy pre-designed criteria (Johnson, 1993).

Since 1990, the BREEAM system has been constantly updated and extended to include assessment of such buildings as existing offices, supermarkets, new homes and light industrial buildings (Yates and Baldwin, 1994). Crawley and Aho (1999) suggest that the system is successfully alerting building owners and professionals to the importance of environmental issues in construction. BREEAM has been adopted worldwide, with Canada, Australia, Hong Kong and other countries developing their own environmental building assessment methods largely based on the BREEAM methodology.

BEPAC— Building Environmental Performance Assessment Criteria (BEPAC) were developed by the University of British Columbia in 1993 (Ding, 2008). BEPAC is a more detailed and comprehensive assessment method than BREEAM, but its use is limited to the evaluation of new and existing office buildings (Cole, 1999). It is similar to BREEAM as it evaluates the environmental merits of buildings using a point system (Crawley and Aho, 1999; Kibert, 2008). It has a set of environmental criteria related to interior, local and global scales based on objective performance standards. A certificate of design and management performance is offered to the building on completion of the assessment.

LEED— Leadership in Energy and Environmental Design (LEED) Building Assessment System is a performance-based tool for determining the environmental impact of a facility from the whole-building perspective (Kibert, 2008). It was designed by the U.S. Green Building Council (USGBC) in 1998 through a consensus process (Crawley and Aho, 1999). It is a green building rating system for commercial, institutional and high-rise residential new construction and major renovation in five areas of sustainability: water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. It adopts a whole-building approach that encourages and guides a collaborative, integrated design and construction process. It is also a voluntary and market-based assessment method that is intended to define a green building and is very simple to use. However as Larsson (1999) states, while it is widely accepted and used by the community of building owners and managers because of its simplicity, its completeness in assessing building performance is in doubt.

ENER-RATE—Soebarto and Williamson (2001) developed ENER-RATE software to be a designer-oriented environmental performance rating tool. It is intended to assist designers to test their strategies against different sets of criteria. The system adopts a multi-criteria decision-making approach to assess energy use, indoor air quality, thermal comfort, operating plant load, cost and other environmental degradation. The design proposals are compared with an automatically generated reference building, based on the principle rules of ASHRAE 90.1. The software is still in a developmental stage. However, once it is completed it will be the only software that can be used to consider sustainability issues at the design development stage (Soebarto and Williamson, 2001).

CPA—Comprehensive project evaluation (CPA) is an assessment methodology that embraces all economic, social and environmental costs and benefits in project appraisals developed by the Royal Institution of Chartered Surveyors (RICS) and the Environment Agency (Ding, 2008). CPA is an appraisal framework which enables sustainable development issues to be incorporated into the development evaluation process. CPA is different from a building performance method as it is used to assess projects during the development process using a combination of financial and economic appraisals to provide monetary values where possible, and scoring and weighting techniques for measuring impacts (Woolley *et al.,* 1999). CPA provides a mechanism to evaluate the nature of the impacts, select the most appropriate analysis method, incorporate local sustainability priorities into the analysis, and a framework to select the best development option (RICS, 2001). The framework uses a multi-criteria analysis approach to assess environmental and social impacts.

CPA is a checklist type evaluation framework that requires an independent assessor to undertake the assessment. Subjectivity is inevitable but it is a limitation in most of the environmental building assessment methods. CPA is more useful than most environmental building assessment methods as cost is measured based on the technique of cost benefit analysis. However, energy and other social and environmental issues are only scored by the assessor. Any assessment method that does not quantify criteria as much as possible is potentially problematic. Energy consumption, for instance, is important as it reflects resource allocation and there are methodologies readily available for such measurement. CPA does not allow other parties to participate in the evaluation process, except when determining priorities, which is another shortcoming of the methodology. CPA's usefulness may be to provide an additional service area for the planners, chartered surveyors and others in the construction industry, but may not be useful to assess a building's environmental performance.

BEQUEST—The Built Environment Quality Evaluation for Sustainability through Time (BEQUEST) system is a pan-European network of physical, economic and social scientists and practitioners, latterly supported by the European Union, Research Directorate under the 4th Framework Programme, Human Dimensions of Environmental Change theme in 1997. The project main aim was to identify a common language and framework to assess and implement urban sustainability (Cooper, 1999; Deakin *et al.,* 2002). One objective of the network was to develop a decision matrix able to guide urban practitioners in procuring methods used to assess the sustainability of urban development, from selection of building components through to strategic planning, and so make more informed decisions to further SUD (Hamilton *et al.,* 2002). The BEQUEST represents a similarly successful international research project to GBC for creating greater collaboration of international partners at a multi-disciplinary level using the BEQUEST Extranet as the communication network. The research project combines the diverse knowledge and expertise of a wide range of environmental researchers, professionals, infrastructure providers and managers to produce a framework, directory of assessment methods and set of procurement protocols which are linked together in the form of a tool-kit (Curwell *et al.,* 1998). The vision of the BEQUEST is to enhance sustainability issues in urban decision-making.

The framework of the BEQUEST is different from the existing environmental building assessment methods such as BREEAM for assessing individual building sustainability. Instead, the BEQUEST aims at advising users on incorporating sustainability in urban design. As Kohler (2002) suggests, the BEQUEST is a framework for the preparation of projects for the 'City of Tomorrow'. Indeed, the successful implementation of the BEQUEST will no doubt enhance the sustainable development concept in urban development.

The principle of BEQUEST is based on the four principles of sustainable development identified by Mitchell *et al* (1995): to embrace environment, futurity, equity and public participation. However, as Cooper (2002) describes, there is a lack of a clear definition of sustainable urban development and its implementation process. Kohler (2002) further states that the problem of valuing the different aspects of sustainable urban development has not been explicitly identified. Thus no clear basis for future discussions and implementation exists.

4.2.2 Importance of building material environmental assessment methods

As the problems of natural resource depletion and global environmental degradation become evident, building performance has become a matter of public concern. Most building material evaluation methods are concerned with a single criterion such as energy use, indoor comfort or air quality to indicate the overall performance of a building (Cooper, 1999; Kohler, 1999). As environmental issues become more urgent, a more comprehensive building assessment method is required to assess building material performance across a broader range of environmental considerations. An environmental building assessment method reflects the significance of the concept of sustainability in the context of building design and its subsequent construction work on site. Designers aim to improve the overall performance of buildings in relation to their effects on both the natural and man-made environments. The primary role of an environmental building assessment method is to provide a comprehensive assessment of the environmental characteristics of a building (Cole, 1999; Kibert, 2008). It is undertaken by providing a common and verifiable set of criteria and targets for building owners and designers to achieve higher environmental standards.

Additionally, the assessment method helps to define the direction for a building project and provides information on which to make informed design decisions at all stages and to plan effective environmental design strategies. The development of an environmental building assessment method lays down the fundamental direction for the building industry to move towards environmental protection and achieving the goal of sustainability. It also provides a way of structuring environmental information, an objective assessment of building performance, and measure of progress towards sustainability. Assessment methods act as a bridge between environmental goals and strategies and building performance during the design and occupancy stages of a building (Ding, 2008). They comprise a set of environmental criteria that are relevant to building materials, and are organised and prioritised to reflect the performance of a building material. The environmental assessment methods satisfy three major aspects: global, local and indoor issues. They also include a set of standard guidelines for how individual building materials are assessed and evaluated. They are prepared in order to provide a methodological framework to assess building performance in a broad context of decision-making, where environmental issues have a significant role (Yates and Baldwin, 1994; Cole, 1998; Cooper, 1999; Crawley and Aho, 1999; Ding, 2008).

Environmental building assessment methods do not just provide a methodological framework for assessing building material performance but also collect useful information to form guidelines for remedial work in order to meet pre-designed criteria (Ding, 2008). The collected data can also be used as feedback information for planning future building projects of similar design while offering the same level of service. The accumulated knowledge and expertise of environmental building design contributes to the greater consideration of environmental issues within the decision-making process, thus minimising the environmental impacts of a building in the long term. Environmental building assessment methods also enhance the environmental awareness of building practices, highlighting concerns about the design and construction of more environmentally oriented projects. Crawley and Aho (1999) state that environmental assessment methods might provide a means for incorporating more holistic environmental performance requirements in national building regulations, which again aim to significantly reduce the environmental impact of new construction. They go on to state that although largely different from each other and designed around different indicators, these systems nevertheless have a positive impact on reducing environmental stress in the short term. However, work is needed to develop a universal life cycle assessment system based on internationally agreed absolute indicators of environmental performance (Uher, 1999).

4.2.3 Critique on the environmental building assessment methods

As stated by Cole (1998), environmental building assessment methods contribute significantly to the understanding of the relationship between buildings and the environment. However, the interaction between building construction and the environment is still largely unknown. The assessment methods have limitations that may hamper their future usefulness and effectiveness in the context of assessing environmental performance of building materials as discussed below.

4.2.3.1 Environmental building assessment methods used as a design tool

Environmental building assessment methods are most useful during the design stage when any impairment for the pre-design criteria may be assessed and incorporated at the final stage of design development. Incorporating environmental issues can be achieved in the design process which can minimise environmental damages. Even though these assessments are not originally designed to serve as design guidelines, it seems that they are increasingly being used as such (Cole, 1999; Edwards and Hyett, 2005). The more effective way of achieving sustainability in material assessment is to consider and to incorporate environmental issues at a stage even before a design is conceptualised. It is important to separate project design and project assessment as building design takes place at an early stage and most of the outcomes of the design have already been established and incorporated into the final design. However, the assessment process works the opposite way around, thus may not be useful as a design tool (Crawley and Aho, 1999; Soebarto and Williamson, 2001; Ding, 2008). Therefore, in order for environmental building assessment methods to be useful as a design tool, they have to be introduced as early as possible to allow for early collaboration between the design and assessment teams. However, apart from ENER-RATE which has been particularly designed to assist the design process, the other assessment methods were not designed for this purpose (Soebarto and Williamson, 2001).

Some environmental building assessment methods may be used to assess existing buildings, such as BREEAM 4/93: An Environmental Assessment for Existing Office Buildings. However, the usefulness of the environmental building assessment method in this respect is doubtful as the remedial work needed to make a completed building comply with the environmental criteria may be too extensive, too costly and time consuming (Lowton, 1997; Crawley and Aho, 1999). For example, remedial work to existing buildings may be impracticable or difficult to facilitate, e.g. replacing an existing ventilation system with a more environmentally friendly system or installing more windows to allow for natural ventilation. This assessment system has predominantly been applied to new construction, but refurbishment and maintenance of existing buildings are also an important part in future construction activities.

4.2.3.2 Financial issues

Environmental building assessment methods focus on the evaluation of design against a set of environmental criteria broadly divided into three major categories: global, local and indoor issues (Ding, 2008). These tools assess several main issues including resource consumption (such as energy, land, water and materials), environmental loading, indoor comfort and longevity. Some assessment tools such as BREEAM, BEPAC and LEED do not include financial consideration in the evaluation framework (Qian, 2009). This may contradict the ultimate principle of building project as cost minimizing is fundamental to all building projects because a project may be environmentally sound but very expensive to build. Environmental issues and financial considerations should go hand in hand as parts of the evaluation framework when making decisions (Langdon, 2007; Ding, 2008). This is particularly important when the decision-making process starts from the outset at the feasibility stage where alternative options for a development are assessed. As shown, both environmental and financial aspects should be considered when assessing environmental concerns.

4.2.3.3 Regional variations

Most environmental building assessment methods were developed for local use and do not allow for national or regional variations (Ding, 2008). To a certain extent, weighting systems can offer opportunities to revise the assessment scale to reflect regional variations and criteria order. However, according to Ding (2008), regional, social and cultural variations are complex and the boundaries are difficult to define. These variations include differences in climatic conditions, income level, building materials and techniques, building stocks and appreciation of historic value (Kohler, 1999). Many countries have adapted the BREEAM system for their own use giving rise to new systems such as HK-BEAM and Total Environmental Assessment of Buildings in Australia. Adjustments to customise the system include cultural, environmental, social and economic considerations. It is unlikely that a set of pre-designed environmental criteria could be prepared for worldwide use without further adjustments.

The GBC is the first international collaborative effort to develop building environmental assessment tool that participating countries can draw ideas from either to incorporate into or modify their own tools. (Bunz *et al.,* 2006). The prime objective of the GBC was to overcome the shortcomings of the existing environmental assessment tools (Ding, 2008). However, GBTool suffers from other shortcomings. Ding (2008) state that "one of the weaknesses of the GBTool is that individual country teams established scoring weights subjectively when evaluating their buildings". They further state that "most users found the GBTool difficult to use because of the complexity of the framework". GBTool is the first international environmental building assessment method and it is unlikely it will be used as intended without incorporating national or regional variations.

4.2.3.4 Complexity

Environmental issues are a broad area and difficult to capture by using a set of criteria. Consequently, environmental building assessment methods tend to be as comprehensive as possible. For example, the BEPAC comprises 30 criteria, C-2000 comprises 170 criteria and GBTool comprises 120 criteria (Cole, 1999; Larsson, 1999). This approach has led to complex systems which require large quantities of detailed information to be assembled and analysed. Typically, they tend towards generalisation in order to capture most environmental criteria within their evaluation framework. However, this may jeopardise their usefulness in providing a clear direction for making assessments cumbersome. Striking a balance between completeness in the coverage and simplicity of use will be one of the challenges in developing an effective and efficient environmental building assessment tool.

4.2.3.5 Evaluation of quantitative and qualitative data

The assessment system accommodates both quantitative and qualitative performance criteria. Quantitative criteria comprise annual energy use, water consumption, greenhouse gas emissions etc., whereas qualitative criteria include method of extraction of raw material, health and safety, aesthetics and so on. Quantitative criteria can be readily evaluated based on the total consumption level and points awarded accordingly (Ding, 2008). For example, in BREEAM 8 credit points are given for CO2 emissions between 160-140kg/m2 per year and more points are awarded if CO2 emissions are further reduced (BREEAM'98 for Office). However, environmental issues are mainly qualitative criteria, which cannot be measured and evaluated using market-based approaches within the existing environmental assessment framework. They can only be evaluated on a `feature-specific' basis where points are awarded for the presence or absence of desirable features (Cole, 1998). This may largely undermine the importance of environmental issues within the decision-making process. The accurate assessment of environmental issues involves a more complex and operational framework in order that they can be properly handled.

4.2.3.6 Weighting

Weighting is inherent to the systems but not explicitly and, as such, all criteria are given equal weights (Todd *et al.,* 2001; Willetts *et al.,* 2010). The GBC framework provides a default weighting system and encourages users to change the weights based on regional differences. However, since the default weighting system can be altered, users may manipulate the results to improve the overall scores in order to satisfy a specific purpose (Willetts *et al.,* 2010).

There is insufficient consideration of a weighting system attached to the existing environmental building assessment methods. The overall performance score is obtained by a simple aggregation of all the points awarded to each criterion. All criteria are assumed to be of equal importance and there is no order of importance for criteria. Cole (1998) and Ding (2008) states that the main concern is the absence of an agreed theoretical and non- subjective basis for deriving weighting factors. It is currently dependent on the in-depth understanding of the environmental impact of building materials. The relative importance of performance criteria is an important part of the decision if the stated objectives are to be achieved, for example, the public project opinion will definitely differ from that of the private project. Therefore, weighting environmental criteria should be derived on a project-by-project basis and should reflect the objective of a building project. The absence of any readily used methodological framework has hampered existing environmental assessment methods in achieving sustainability goals.

4.2.3.7 Measurement scales

Measurement scales are also based on a point award system and the total score obtained for the evaluation reflects the performance of a building in achieving sustainable goals in the industry. However, Ding (2008) stated that there is no clear logical or common basis for the way in which the maximum number of points is awarded to each criterion. Most building environmental assessment methods award their own points to environmental criteria. Using consistent measurement scales facilitates more comparable assessment results across countries.

There is no doubt that environmental building assessment methods contribute significantly in achieving the goal of sustainable development within construction. On one hand, it provides a methodological framework to measure and monitor environmental performance of buildings, whilst on the other it alerts the building profession to the importance of sustainable development in the building process. However, existing environmental building assessment methods have their limitations as examined in this section reducing their effectiveness and usefulness. There is a requirement for greater communication, interaction and recognition between members of the design team and various sectors in the industry to promote the popularity of building material assessment methods. The inflexibility, complexity and lack of consideration of the weighting system are still major obstacles to the acceptance of environmental building material assessment methods. In an attempt to overcome or improve on this situation, a more effective model will be developed.

4.3 The conceptual development of sustainability model for material selection

4.3.1 Background

Ecologically sustainable development is the central concern of people from all disciplines (Cole, 1999; Holmes and Hudson, 2000). The concept of sustainability in the context of construction is about creating and maintaining a healthy built environment and at the same time focusing on minimising resources and energy consumption, thereby reducing damage to the environment, encouraging reuse and recycling, and maximising protection of the natural environment. These objectives may be achieved by considering the most efficient option amongst competing alternatives through the process of material evaluation at an early stage.

Following the thorough discussion on the usefulness of environmental building assessment methods in the construction industry in achieving the goal of sustainable development, this section sets out to conceptualise the development of a model that can be used in material sustainability evaluation. It is argued in this section that a multiple criteria approach may be considered in the development of a sustainability model.

4.3.2 Single or multiple dimensional assessment approaches?

The decision-making process frequently involves identifying, comparing and ranking alternatives based on multiple criteria and multiple objectives. This process frequently occurs without conscious consideration in our daily life (Tabucanon, 1988; Nijkamp *et al.,* 1990). Decision-makers often employ assessment techniques to structure a complex collection of data into a manageable form in order to provide an objective and consistent basis for choosing the best solution for a situation. However, for big decisions where millions of pounds may be involved, there is a tendency to simplify the objectives of the project into a single decision criterion (Tabucanon, 1988). Single criterion evaluation techniques have dominated material evaluation and they were mainly concerned with economic efficiency (Tisdell, 1993; van Pelt, 1993; Burke, 1999; Lam *et al.,* 2010).

Life cycle cost (LCC) is the leading tool in this respect and it is a well respected evaluation technique widely used in both private and public building project to aid decision- making (Durairaj, *et al.,* 2002; Arpke and Strong, 2006; list, 2007; Utne, 2009). Often minimizing cost is the only concern in building project, but the project that exhibits the best financial return is not necessarily the best option for the environment. In addition, many environmental and social considerations underlying sustainable developments cannot be monetarised (Hobbs and Meier, 2000; RICS, 2001; Glucha and Baumann, 2004) significantly reducing LCC's usefulness.

However, in reality, decision-making is rarely based on a single dimension. Janikowski *et al.,* (2000) argue that using only one assessment criterion cannot be regarded as a correct approach. They go on to advocate that it is necessary to accept a multi-criteria perspective that takes into account a spectrum of issues regarding a development. Since the end of the 1960s it has been gradually recognised that there is a strong need to incorporate a variety of conflicting objectives. An increasing awareness of externalities, risk and long-term effects generated from building project, (Nijkamp *et al.,* 1990; Edwards and Hyett, 2005) fostered this new perspective. Thus single dimensional evaluation techniques are increasingly controversial (Tisdell, 1993; Abelson, 1996; Glucha and Baumann, 2004; Utne, 2009).

The strong tendency towards incorporating multiple criteria and objectives in building material evaluation has led to a need for more appropriate analytical tools for analysing conflicts between policy objectives (Popp *et al.,* 2001; Ding, 2008). Multi- criteria analysis (MCA) provides the required methodology to evaluate multiple criteria and objectives in building material evaluation (Piper, 2002; Alibaba and Ozdeniz, 2003; Wong and Li, 2008; Kahraman and Kaya, 2010).The multi-dimensional framework incorporates the consideration of environmental issues in building construction and it will take an important role in the evaluation approach. Sustainability, as defined by Young (1997), is a measure of how well the people are living in harmony with the environment taking into consideration the well-being of the people with respect to the needs of future generations and to environmental conservation. Young (1997) goes on to describe sustainability as a three-legged stool, with a leg each representing ecosystem, economy and society. Any leg missing from the 'sustainability stool' will cause instability because society, the economy and the ecosystem are intricately linked together. Indeed, Young (1997) explains clearly that a measurement of sustainability must combine the individual and collective actions to sustain the environment as well as improve the economy and satisfy societal needs.

Elkington (1997) expands the concept of sustainability to be used in the corporate community, developing the principle of triple bottom line. Triple bottom line refers to the three prongs of social, environmental and financial performance, which are directly tied to the concept and goal of sustainable development. They are highly inter-related and are of equal importance (Cooper, 2002). It is a term that is increasingly accepted worldwide within the corporate community, and as a framework for corporate reporting practices. The triple bottom line concept focuses not just on the economic value as do most of the single criterion techniques, but equally on environmental and social values. For an organisation to be sustainable it must be financially secure, must minimise the negative environmental impacts resulting from its activities, and must conform to societal expectations (Elkington, 1997; Roar, 2002). The triple bottom line concept underlies the multiple dimensional evaluation process of development. To conform to the concept, a business to be sustainable, must deliver prosperity, environmental quality and social justice. Further, the triple bottom line concept has been expanded and used as an audit approach for sustainable community development (Rogers and Ryan, 2001).

Kohler (1999), states that a sustainable building has three dimensions: ecological, cultural, and economic sustainability. Young's (1997), Elkington's (1997) and Kohler's (1999) frameworks to measure sustainability have many similarities but Kohler (1999) also emphasised the importance of cultural considerations. The assessment of a sustainable building has to make explicit the particular cultural expectation which the development has been designed to maintain (Kohler, 1999; Cooper, 1999).

Apart from this three-dimensional concept of sustainability, Mitchell *et al.* (1995) describe four separate principles: equity, futurity, environment and public participation, which underpin sustainable development, known as the PICABUE (see Figure 4.2). Equity deals with the principle of fair shares, both locally and globally, among the current generation. The principle of futurity is to ensure intergenerational equity within which a minimum environmental capital must be maintained for future generations. The integrity of the ecosystem should be preserved, and its value recognised and respected, in order not to disrupt the natural processes essential to human life and to protect biodiversity. The fourth principle recognises the importance of public participation in decisions concerning them and the process of sustainable development (Mitchell *et al.,* 1995; Curwell and Cooper, 1998).

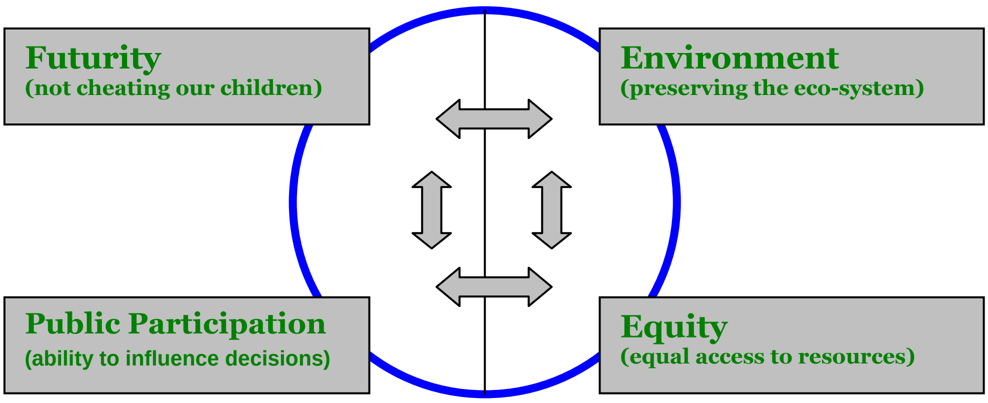


Figure 4.2 The PICABUE definition of sustainable development

Source: Mitchell et al., 1995

PICABUE is a methodological framework designed to develop sustainability indicators. Its name is derived from the seven steps used to develop sustainability indicators to enhance quality of life (for details refer to Mitchell *et al.,* 1995). The PICABUE model of sustainable development has also been adopted by the BEQUEST as the basic principle of development (Bentivegna *et al.,* 2002). The four principles were used to define common understanding and terminology for sustainable development in the BEQUEST network (Cooper, 2002). Cooper (1999) further states that only the environment directly deals with ecology whilst the other three principles are political and socio-economic issues that are concerned with resource allocation and the decision-making process.

Other concepts of multi-dimensional approaches are developed on the same basis. The four system conditions as described in the Natural Step10 have also gained significant attention. Karl-Henrik Robert developed Natural Step in 1989 to address environmental issues. The first three conditions provide a framework and a set of restrictions for ecological sustainability. The fourth condition formulates an international turnover of resources for society, ensuring that human needs are met worldwide (Herendeen, 1998; Chambers *et al.,* 2000). The Natural Step has provided a good sustainable development business philosophy, and has been widely applied in the business and industrial sectors (Bentivegna *et al.,* 2002).

From the above discussion, it is clear that building and material assessment is multi-dimensional and the aspects, as described in the PICABUE and others, have summarised the essential components to be assessed in material selection.

4.3.3 The multiple dimensional model of material assessment

Given the previous discussion of an increased tendency to consider multiple criteria in material evaluation, it is necessary to develop a model to facilitate multiple dimensional assessments of criteria to aid decision-making. A sustainability index for material evaluation is designed to bridge the gap between the current methodology which uses a single objective approach, and the need for a multiple criteria approach in order to incorporate environmental issues in the decision-making process. It is based on a multiple dimensional model that embraces economic, social, technical and environmental values. The criteria included in the sustainability index are based on an absolute assessment approach and are combined into a composite index to rank material options for building projects at the design stage. The purpose of this research is to develop a mathematical model yielding a single index allowing material alternatives to be ranked. Detail of the mathematical model is described in chapter seven.

Generally, material evaluation goes through several distinctive, inter-related stages. The literature describes many models for this process but most of them use similar and, as discussed, flawed, approaches (Nijkamp *et al.,* 1990, Janssen, 1992; van Pelt, 1993; Hobbs and Meier, 2000; RICS, 2001). Figure 4.3 shows the model adopted in this research. The evaluation process for a building material will not be seen as a simple linear process but follows a cyclic nature (Nijkamp *et al.,* 1990, Janssen, 1992; Bentivegna *et al.,* 2002; Ding, 2008). Each stage can supply additional information participate in the feedback loop to provide further information for a more precise consideration for the forthcoming stage or stages (Nijkamp *et al.,* 1990; Ding, 2008).

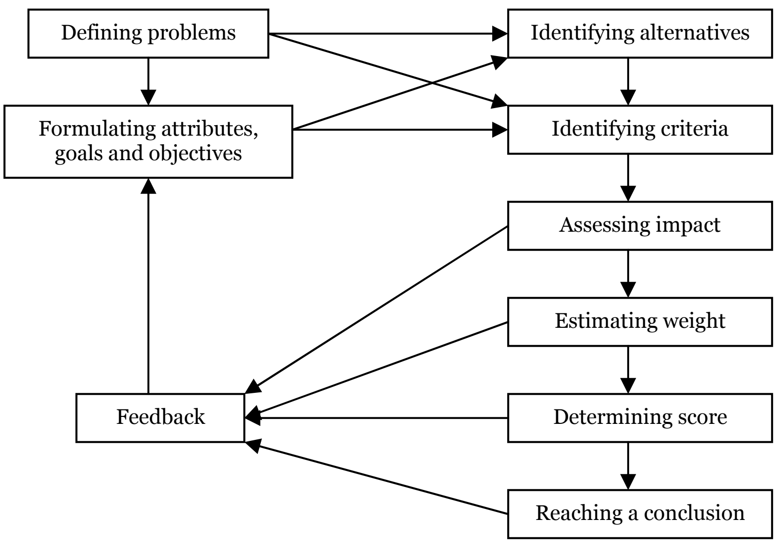


Figure 4.3 Multiple dimensional decision model of building material evaluation and selection Source: Adopted from (Nijkamp *et al.,* 1990)

i. Defining problems

Building material evaluation usually starts by defining a problem then formulating material attributes, objectives and goals (van Pelt, 1993; RICS, 2001). The problem is structured to provide adequate specification of objectives, and so that attributes can be identified. In addition, constraints such as financial, political and external will also be investigated (Ding, 2008). Financial constraints relate to the availability of scarce resources for a building project; political constraints have to be considered when public funds are to be used; and external constraints refer to the external effects generated through development upon the natural environment. These constraints often govern the compilation of alternative criteria sets in a development. Early identification of material constraints is critical to develop a more precise set of alternatives to optimise the best solutions, or acceptable compromise solutions, to problems (Nijkamp *et al.,* 1990; Ding, 2008).

ii. Identifying alternatives

The next step is to identify alternatives, based on the decision problem's structure. Alternatives may include design alternatives, location options, and technology and material options. They are usually derived from observing the project problem and through screening and scoping a number of possible solutions (van Pelt, 1993; Hobbs and Meier, 2000). At this stage, the list of possible alternatives concerns objectives which include optimising renewable and non-renewable resources, minimising disturbance to the environment etc. There is no limit to the number of alternatives, but policy makers tend to reduce the total number in order to facilitate decision-making. A recommended number is approximately seven because an increase in number can create confusion and uncertainty (van Pelt, 1993).

iii. Identifying criteria

Evaluation criteria are defined following the identification of material alternatives. Criteria are reflections of objectives to be achieved and can be used as guidelines to analyse impacts from each material alternative (Nijkamp *et al.,* 1990; van Pelt, 1993; Hobbs and Meier, 2000; Ding, 2008). Criteria about environmental effects will also be formulated and may result in a special environmentally focused analysis of material alternatives at a later stage. The list of criteria should be sufficiently precise and comprehensive to cover the full range of issues (Foxon *et al.,* 2002). The decision model will focus only on the aspects that are salient and eliminate those that are less attractive. If the number of criteria cannot be reduced, a hierarchy of criteria may need to be established to categorise them (Saaty, 2008). However, in such a situation is less than ideal, causing the decision process to become more complicated.

iv. Assessing impact

The proposed criteria may contain objective and subjective issues. For objective issues, such as energy flows (embodied energy), there may be techniques that are readily applicable for their quantification. The main difficulty at this stage is to quantify subjective issues which are largely social and environmental matters. Therefore, at this stage of the impact assessment, different methodologies may be engaged to evaluate satisfactorily each criterion. Detailed analysis of each criterion is an important step in determining the score in relation to material impacts. It involves expressing impacts in numeric terms and information may be presented in an evaluation matrix with alternatives set against criteria in a spreadsheet (Voogd, 1983). Each criterion is measured using the most appropriate method for its nature to reflect its relative importance against each alternative. Each criterion can be measured in either a quantitative method or on a qualitative scale.

A quantitative scale is expressed in monetary or physical units such as dollar or Gj/m2. However, qualitative scales are much more difficult to handle and may be expressed in three different ways (van, Pelt, 1993), through:

- an ordinal11 ranking expressed as 1, 2, 3, ... or + + +,
- a nominal scale which reflects the characteristics of alternatives such as type of colour, or
- a binary scale that contains only two answers such as yes or no.

Whenever a qualitative measure is involved, the measure must be converted to numerical data (Ding, 2008; Saaty, 2008). This is to allow the participation of stakeholders involved in material evaluation. This process may ensure that not just the technical or financial criteria will be considered but, within the multi-criteria assessment model, the social and environmental criteria will also be considered.

v. Estimating weights

In any list some items are likely to be more important than others. For example, in material selection, the social and environmental issues may have more weight than the cost aspects in alternative A. However, the situation may be the reverse in alternative B as cost might be the crucial driver for material selection. It is only a rare scenario when all criteria carry equal weights, such as the PICABUE, triple bottom line, and environmental stool concepts (Mitchell *et al.,* 1995; Elkington, 1997; Young, 1997).

In material evaluation, choosing an option from a list of alternatives means that priorities must be set and weights assigned to each criterion, reflecting each criterion's priority. Nijkamp *et al* (1990) and Saaty (2008) suggest various methods to estimate criteria weighting. These are broadly divided into two main approaches: direct and indirect estimation. Direct estimation of criterion weights refers to the expression of relative importance of the objectives or criteria in a direct way through questionnaire surveys. Respondents are asked questions within which their priority statements are conveyed in numerical terms. Respondents are members of the design team, involved in material selection (Seabrooke *et al.,* 1997). This is another opportunity for the increasing demand for stakeholder's participation in the decision-making process (Joubert *et al.,* 1997; Price, 2000).

Direct estimation method techniques come in various forms:

- The trade-off method where the decision-maker is asked directly to place weights on a set of criteria to all pair-wise combination of one criterion with respect to all other criteria.
- The rating method where the decision-maker is asked to distribute a given number of points among a set of criteria to reflect their level importance.
- The ranking method where the decision-maker is asked to rank a set of criteria in order of their importance.
- The seven-points (or five-points) scale which helps to transform verbal statements into numerical values.
- The paired comparison, which is similar to the seven-point scale, obtains the relative importance of criteria by comparing all pairs of criteria on non-points scale.

However, all these methods run into trouble when the number of objectives becomes large (van Pelt, 1993; Hobbs and Meier, 2000). When this happens, objectives may have to be structured in a hierarchical model to separate objectives into different levels (Saaty, 1994). The indirect approach is based on investigating the actual behaviour of respondents in the past. Weights are obtained through estimating actual previous behaviour derived from ranking alternatives or through an interactive procedure of obtaining weights by questioning the decision-maker and other involved parties. Hypothetical weights may also be used in some projects. Here, the analyst prepares weights to represent the opinion of specific groups in the community, then policy-makers may comment accordingly. Each approach has restrictions and limitations in terms of accuracy and cost. Their usefulness strongly depends on the time required and the attitude of respondents (Voogd, 1983; Nijkamp *et al.,* 1990; Hobbs and Meier, 2000).

vi. Determining score

A total may be obtained by amalgamating the assessment scores of criteria and their related weights using combined methods, because criteria may contain objective and subjective issues. Therefore, this stage may involve the use of multi-criteria analysis to bring the values together for each alternative to aid decision-making. Since criteria may be measured using different units, standardisation may be required to convert these criteria into a common basis (Janssen, 1992; Ding, 2008). As mentioned, the purpose of this research is to develop a mathematical model to produce a single index that allows alternatives to be ranked. The model for the sustainability index will be significant for the use of multi-dimensional approach in material evaluation

vii. Reaching a conclusion

Finally, a conclusion can be drawn and decisions made according to the score of each alternative. In accordance with the concept of the sustainability index, the higher the score the better will be the option of material selected. Evaluation may be considered as a continuous activity in a planning process as evaluation feedback loops can take place in different routes at different stages, providing further information to define alternatives and/or criteria to satisfy the ultimate objectives to be achieved.

4.4 Summary of chapter four

This section presented the literature review and a discussion on conventional single criterion models and the multiple dimensional approaches for building material evaluation. This section also presented a framework as adopted from Nijkamp *et al.*, (1990) for the conceptual development of a sustainability model that can be used to evaluate building material. This model is based on a multiple dimensional concept that encompasses economic, environmental and social/cultural aspects in the evaluation process. Combining these criteria into a single decision tool is fundamental to decision-making and will be the focus of investigation in chapter seven. The material selection model, as discussed in this section, represents a systematic and holistic approach to making a decision. It uses the concept of multi-criteria analysis and this concept will be further extended in the development of a sustainability index for project appraisal in the next chapter.

4.5 Conclusion of chapter four

This chapter summarised the aspects of environmental building material assessment methods that have been used by many countries to assess environmental performance of building material. The environmental building assessment methods have escalated from local programs into an international agenda. The importance of environmental building assessment is well recognised as a way for promoting environmental awareness among building professionals. However, as discussed in this chapter, the usefulness of assessment methods can be extended from a checklist-type single evaluation method, to a multiple criteria framework that includes physical quantification of criteria for material assessment.

This chapter also presented a conceptual framework for such a multiple criteria approach to material selection. The discussion in this chapter has laid down a platform for the development of a sustainability index, which will be discussed in detail in chapter seven. The next chapter now describes the research methodology adopted for the study.

CHAPTER 5: RESEARCH METHOD

5.1. Introduction

The effect of research method on the possible outcome of any research endeavour can never be overemphasised. When undertaking research it is important to choose the correct methodology, to ensure that the research objectives can be met and that the findings can be validated (Steele 2000; Fellows and Liu, 2003). This chapter discusses the research design and methodology including their strengths and weaknesses and highlights the general approach to the research. The choice of research methodology and the reasons for its selection are also provided and mapped out against research objectives and associated tasks along with research output in Table 5.5.

5.2 Research Approach

The nature of a research topic, its aims and objectives and the resources available largely determine its design (Creswell, 2003). These criteria largely informed the research method developed for carrying out this research. This research phase was achieved through deductive reasoning combined with extensive and critical reviews of a large body of literature, attendance of seminars and workshops, internet discussion forums and expert focus group approach. These helped to build up a theoretical background to the subject area, provided a foundation for achieving the research aim and insight into many of the major issues concerning the concept of sustainable development. The literature review in chapter two to four have reviewed the critical points of current knowledge including substantive findings as well as theoretical and methodological contribution to facilitate the aim of the research. A review of the literature covered the environmental impacts of architects' design decisions, concentrating on the selection of materials; and the situation in UK construction industry regarding designers' environmental awareness and related action.

The literature has revealed that the construction industry undoubtedly shares the responsibility of conserving natural resources and protecting the environment. The principle of sustainability has been advocated as the tragedy toward improving environmental impact of construction activities. The future direction for construction is a more responsible attitude and more environmentally friendly practices. The area of sustainable construction is one of increasing interest which has many levels and complex dimensions. The review has provided an overview of the wide range of environmental issues in the construction industry, while emphasizing the need for an integrated approach and understanding of the different components of a sustainable system. In order to achieve sustainability for society as a whole and for construction in particular, intelligent decision making is required which includes full consideration and knowledge of the many trade-offs and impacts associated with each building material available to be chosen. Sustainability is a desirable state towards which to strive, but the journey is not easy. The information provided in the literature review, provides the platform for further research on the need for improving understanding of sustainable construction and enhancing the effectiveness of actions to implement sustainable construction at the core of construction business process. In particular the literature review has opened up research questions that need to be addressed if the aim is to be achieved. The objectives posed a number of questions including:

a. Are architects and designers aware of the environmental implication of their design decision?

b. How important is environmental consideration at the conceptual stage of building projects?
c. To what extent are environmental issues considered in building projects?
d. Should environmental consideration be included in building material assessment?
e. Is sustainability assessment of building materials an important issue for building development?
f. Is there a correlation between awareness and implementation of sustainable practice in building projects?
g. To what extent are sustainable practices implemented in practice?
h. How important is material selection in achieving sustainable building?
i. Who are the principal stakeholders in building design and what influence do they have in material selection?
j. What are the criteria considered in the selection of sustainable materials for building projects?
k. How can the criteria be assessed for evaluating building materials?
l. What are the obstacles in the use of sustainable materials?
m. Does cost consideration affect sustainable material usage?
n. What are the existing building assessment techniques used by building professionals?
o. What are the perceived obstacles to the usage in practice?
p. Why are there problems in their use in practice?
q. How can the assessment techniques be improved for effective usage?

As a result of the multiplicity of the research questions and diversity in the types and sources of data required for answering these questions, it became apparent very early in the study that the data would be both qualitative and quantitative in nature. The next section reviewed research methods.

5.3 Review of research methods

Research design is the logical sequence that connects the generated empirical data to the initial research objectives of the study and ultimately to its conclusions (Yin, 1994). Although research is important in both business and academic activities, Amaratunga *et al.,* (2002) stated that there is no consensus in the literature on how it should be defined. Research is conducted in the spirit of inquiry, which relies on facts, experience and data, concepts and constructs, hypotheses and conjectures, and principles and laws. Additionally, they constitute the language of research, enabling precision in the use of words and communication among concerned (Amaratunga *et al.,* 2002). Table 5.1 illustrates how together these concepts of research form a symbolic and rational system of inquiry.

Table 5.1 Basic elements of scientific research methodology

Laws	Verified hypothesis; used to assert a predictable association among variables; can be empirical or theoretical
Principles	A principle is a law or general truth which provides a guide to thought or action
Hypotheses	Formal propositions which, though untested, are amenable to testing; usually expressed in causal terms
Conjectures	Informal propositions which are not stated in a testable form, nor is a causal relationship known or even necessarily implied
Concepts and constructs	Concepts are inventions of human minds to provide a means for organizing and understanding observations; they perform a number of functions, all of which are designed to form logical and systematic relationships among data. Constructs are theoretical creations that are based on observations but which cannot be seen either directly or indirectly; things such as IQ, Leisure Satisfaction etc., are constructs
Facts	Something that exists, a phenomenon that is true or generally held to be true
Data	The collection of facts, achieved either through direct observations or through garnering from records; observation is the process by which facts become data

Source: adapted from Buckley *et al.,* 1975; cited in Then, 1996.

There is a wide range of research methods and each can be used to elicit a specific type of information or combined to support and compliment one another (Kane, 1977; Frankfort-Nachmias, 1996). The review of research methodology indicated that opinion on the number of research methods ranges from five to seven. Yin (1994) suggested the following five: experiment, case study, survey, archival analysis and history. Steele (2000) argued the inclusion of two more methods, which are action research and process modelling. These various research methods fall into two classical and distinctive epistemological positions, which are qualitative and quantitative research methods. The combination of the two approaches is termed triangulation. This section provides a brief description of these research methods.

5.3.1 Quantitative research

Creswell (2003) defined quantitative research as *'an inquiry into a social or human problem, based on testing a hypothesis or theory composed of variables, measured with numbers, and analysed with statistical procedure to determine whether the hypothesis or theory hold true'* According to Brannen (1992), quantitative research is concerned with attitudes and large scale surveys rather than simply with behaviour and small-scale surveys.

The three types of quantitative research are experiments, quasi-experiments and surveys (SJI, 1999). The effectiveness of the selected types depends mainly on the nature of the research. The survey technique is the most widely use method in social science and also the most relevant to this study. It typically involves cross-sectional and longitudinal studies using questionnaires or interviews to collect large amount of data. The most common of this technique are mail, personal and telephone survey (Rubin and Babbie, 2010). Table 5.2 collates the advantages and disadvantages of these three data collection methods.

Table 5.2 Advantages and Disadvantages of Survey Methods

Types of Survey	Advantages	Disadvantages
Mail survey	• Cost is low compared to other methods • High degree of respondents anonymity • Wide geographical reach • Relatively low cost of processing	• Low rates of response • Require easily understood questions and instructions • Lack of chance to probe for further or clarity of answers • Greater respondents bias • High uncompleted questions
Personal survey	• Allows high flexibility in the questioning process • Interviewers have control of the interviewing situation • High response rate • Possibility of collecting supplementary information	• Higher cost than mail questionnaire • Potential interviewers bias due to high flexibility • Lack of anonymity; hesitant to disclose personal data • Time consuming
Telephone survey	• Moderate cost • Increase speed and time of data collection • High response rate • Increase quality of data	• Hesitancy to discuss sensitive data on phone • High chance of respondents terminating interview earlier • Less chance for supplement Information

Source: Adapted from Rubin and Babbie (2010)

5.3.2 Qualitative research

Miles and Huberman (1994) describe qualitative analysis as a continuous, iterative process that consists of the following concurrent flows of activity (see Figure 5.1):

- *data reduction*, which refers to the process of selecting, focusing, simplifying, abstracting and transforming the data;
- *data display*, which is an organised, compressed assembly of information that permits conclusions to be drawn and action; and
- *conclusion-drawing and verification*, which refers to the decision about what things mean and how the meanings that emerge from the data have to be tested for their validity.

Qualitative research consists of detailed descriptions of events, people, interactions and observed behaviours (Patton, 1992) and general opinion. It seeks to describe and explain both perspectives and behaviour of the people studied (Brannen, 1992).

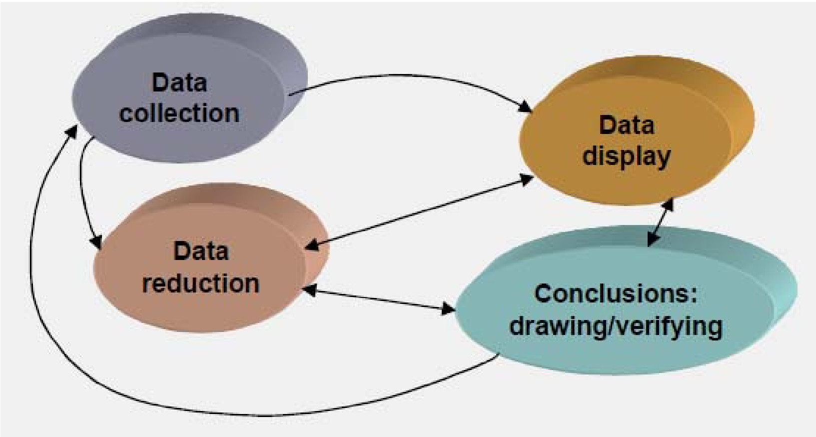


Figure 5.1 Components of qualitative analysis (Miles and Huberman, 1994)

Information gathered in qualitative research can be classified under two categories, namely exploratory and attitudinal research (Naoum, 1998). Exploratory research is used when the researcher has a limited amount of knowledge about the research topic. The purpose is closely linked with the need for a clear and precise statement of the recognised problem. Attitudinal research, on the other hand, is used to subjectively evaluate the opinion of a person or a group of people towards a particular attribute, variable, factor or a question. According to Hancock (1998), the main examples of methods of collecting qualitative data are individual interviews, focus groups, direct observation and case studies.

There are several advantages as well as disadvantages involved in using a qualitative research method. Among various advantages are it facilitates in-depth study, produces overwhelming detailed information with a smaller number of people and provides a great understanding of the topic under study (Amaratunga *et al.,* 2002). Flick (2009) listed few examples of disadvantages to include: it takes a great deal of time to collect data and the analysis requires some degree of interpretation, which may be subjected to bias and subjectivity. The comparison of both qualitative and quantitative research epistemology has been tabulated in Table 5.3

Table 5.3 Comparison between Qualitative and Quantitative Research

Point of comparisons	**Qualitative Research**	**Quantitative Research**
Alternative labels	Constructivist, naturalistic-ethnographic or interpretative.	Positivist, rationalistic or functionalist.
Scientific explanation	Inductive in nature	Deductive
Data classification	Subjective	Objective
Objective/purpose	To gain understanding of underlying reasons and motivations. To provide insight into the settings of a problem, generating ideas and /or hypothesis for later quantitative research. To uncover prevalent trends in thought and opinion.	To quantify data and generalise results from a sample to the population of interest. To measure the incidence of various views and options in a chosen sample.
Sample	Usually a small number of non-representative cases. Respondents selected to fulfil a given quota or requirement.	Usually a large number of cases representing the population of interest. Randomly selected respondents
Data collection	Participant observation, semi- and unstructured interview, focus groups, conversation and discourse analysis.	Structured interview, self administered questionnaires, experiments, structured observation, content analysis / statistical analysis
Data analysis	Non-statistical	Statistical usually in the form of tabulations. Findings are conclusive and usually descriptive in nature
Outcome	Exploratory and / or investigative. Findings are not conclusive and can not be used to make generalisations.	Used to recommend a final course of action.

Source: Amaratunga *et al.,* 2002

5.3.3 Triangulation

Combining both quantitative and qualitative research methods has proven to be more powerful than a single approach (Moffatt *et al.,* 2006) and very effective (Lee, 1991). Triangulation is a process of using more than one form of research method to test a hypothesis (Brannen *et al.,* 1992). This approach offers researchers a great deal of flexibility; whereby theories can be developed qualitatively and tested quantitatively or vice versa. The main aim of using triangulation method is to improve the reliability and validity of the research outcomes. Brannnen (1992) drawing on the work of Denzin (1970) argued that triangulation means more than just one method and data collection but also includes investigators and theories. He then outlined four different types of triangulation as follows.

- Multiple methods: can be a triangulation between methods and within methods.
- Multiple investigators: that is research is undertaken through partnership or by teams instead of a single individual.
- Multiple data sets- the gathering of different sets of data through the use of the same method but at different times or with different sources.
- Multiple theories: can be used in a single research.

5.4 Adopted research methodology

There is neither a fast rule to selecting research methods nor best research method, as the use of each research method depends on the form of research question, the research objectives and contextual situation (Yin, 1994). The selection of the most suitable research method depends largely on the intention of the research objectives and the type of data needed for the research. Because of the broad scope of the study and the industrial context of the research, a wide range of research techniques was adopted to achieve the research aim and objectives. To aid the selection process, Yin (1994) mapped out several research strategies against various possible situations as collated in Table 5.4 below

Table 5.4 Different Situations for Research Strategies (Yin, 1994)

Strategy	Form of research Question	Required control over behaviour events	Focus on contemporary events
Action research	Who, what, why, how many, how much?	Yes/No	Yes
Case study	How, why?	No	Yes
Survey	Who, what, where, how many, how much?	No	Yes
Archival analysis	Who, what, where, how many, how much?	No	Yes/No
Modelling	Who, what, how many, how much?	No	Yes/No
History	How, why	No	No
Experiments	How, why	Yes	Yes

This subsection discusses the overall research methods used for the study and justifies the reasons for using them. Table 5.5 presents the research road map. The table maps the research phases with the research objectives and tasks as well as the various research methods adopted. In addition, the table indicates the main research outputs, which consist of publication papers, sustainability index, material selection model and lastly the PhD thesis. Further information as regard to the research undertaken and outcomes are elaborated in Chapter 6 and 7.

5.4.1 Archival analysis

There is a wealth of literature on the concept of sustainable development and sustainable construction but to a varying degree of quality. The review of literature was extensively and critically undertaken throughout the study to build up a solid theoretical base for the research area and a foundation for addressing the problems and achieving the research objectives. Archival analysis is the most efficient, effective and cheapest method for gathering the existing wealth of literature on the subject matter to form a thorough understanding of the concept of sustainable development and sustainable construction (Adetunji, 2005). The review helped to identify gaps in knowledge and formed the basis for developing the framework to aid the implementation of sustainability in building material selection. Information was sought from various sources including industrial and academic publications, institutions and university databases, the Internet, seminars, workshops and conference notes attended. Moreover, information and knowledge was also gained by attending relevant courses.

PROJECT AIM: “ To develop a model to aid the implementation and integration of sustainability principles in building material evaluation and selection and to promote wider uptake of the concept in the construction industry”				
PHASE	OBJECTIVES	TASKS	METHOD	OUTPUT
……………………REVIEW……………………	1. Investigate the development impact on the environment	1. A review of related research in the field	AA	Paper 1
		2. Investigate the relationship between economic growth and the environment by looking at the extent in which economic growth promote resource depletion and damage to the environment.	AA	
		3. Review of historic context of sustainable development as a response to the destructive social and environmental effects of prevailing approach to “economic growth”.	AA	
		4. Investigate the root cause of the current poor progress in term of its practical application of the concept.	AA	
		5. Review of UK government measures in reducing impact of development on the environment by application of sustainable development strategies	AA	
	2. suggest ways to improve conventional decision methodology used in the development projects	6. Review the market based approach in decision making in development projects.	AA	
		7. Investigate the usefulness and limitations of environmental valuation techniques in incorporating environmental issues in decision making process	AA	
		8. Examine the usefulness and limitations of life cycle cost analysis as a decision making tool in development projects	AA	
		9. Review the usefulness of Multi criteria analysis as a non-monetary evaluation method to aid decision making when dealing with environmental sensitive projects	AA	
	3. Investigate the environmental impact of construction activities throughout their life cycle and to suggest strategies for sustainable construction implementation.	10. Investigate the environmental impact of construction activities on the environment	AA	
		11. Review themes of sustainable construction practices – principles, application in the UK construction, building materials and sustainability and barriers to the use of sustainable materials	AA	
		12. Establish strategies and approach for successful integration of sustainable development in the construction industry	AA	
………………SYNTHESIS………	4. Investigate environmental awareness of architects and designers and how it impact on their sustainability practices in building design and construction.	13. Prepare a detailed survey questionnaire to undertake a baseline review of UK architects and designer’s environmental awareness and their engagement with sustainable construction practices in building design and construction.	S	
		14. Gauge the industry response to the emerging concept of sustainable construction and its application in building material selection	S	
	5. Evaluate the principal sustainability criteria relevant to building materials for modelling decision-making in building projects	15. Determine the principal sustainability criteria for modelling decision making in building material evaluation.	AA, S	Paper 2
		16. Examine in detail and evaluate the criteria to be incorporated in developing sustainability index as a decision making tool for material selection	S	
		17. Present and discuss the conceptual framework of the sustainability index	A	Paper 3
…APPLICATION…	6. Develop a multi criteria assessment model for aggregating sustainability criteria into a composite index for building material selection	18. Discuss the development, role and limitations of current models in ascertaining building sustainability	A	Sustainability model
		19. Present the concept of developing a sustainability model for building material evaluation based on the multi dimensional approach discussed in chapter 2	A	
	7 Test the effectiveness and usefulness of the new decision model	20 apply the new decision model to a case study project	CS	PhD thesis
KEYS: AA (Archival analysis)		CS (Case study)	S (Survey)	

Table 5.5 Research road map

5.4.2 Survey

Survey is one of the most widely used methods in social sciences to provide a representative sample of the area of study and serves as an efficient and effective means of looking at a far greater number of variables than is possible with experimental approaches (Galiers, 1992; Czaja and Blair, 1996). It builds on previous work which has already developed principles, laws and theories that help to decide the data requirements of the particular research project (Fellows and Liu, 1997). Survey research involves eliciting information from respondents which can be achieved through questionnaires or structured interviews for data collection, with the aim of generalizing from a sample to a population (Babbie, 1990; Creswell, 2003). Although it also has limitations such as low response rates (for questionnaire surveys) and the risk of bias, this strategy offers the opportunity to explore a broad range of issues such as those envisaged in this research.

The survey research design was adopted to provide, as indicated by Creswell (2003), a quantitative description of trends, attitudes, or opinions of the population by studying a sample of that population. Specifically, a cross-sectional questionnaire survey of architects and designers was adopted with the questionnaire designed to:

- Investigate environmental issues awareness and sustainable practices of architects and designers and barriers towards implementing it, especially in the selection of building materials,
- Investigate factors driving sustainable construction practices of architects and designers.
- Assess the relative importance and prioritize the sustainability criteria responsible for selection of building materials as identified from the

literature review. These priorities are incorporated also into the sustainability index model for use in material selection.

5.4.2.1 Questionnaire development

A questionnaire survey is one of the most cost effective ways to involve a large number of people in the process in order to achieve better results, as recommended by McQueen and Knussen (2002). Questionnaire is a self-administrated measuring instrument comprising closed-ended (respondents choose from a given set of answers) and/or open-ended questions (respondents record their views and opinion in full). The accuracy and success of questionnaire surveys largely depend on the careful design of its content, structure and the response format. Hence, certain precautions must be taken in designing questionnaires (Hoinville and Jowell, 1978): the questions must be clear and easily understood by the respondents; should be easy to be administer by the interviewer; the recorded answers can be easily edited, coded and transferred onto a computer file for statistical analysis; and its flow, length and structure must motivate respondents to complete the questionnaire. Considerable effort was therefore devoted towards this endeavour. The traditional form of questionnaire survey is the postal questionnaire but the use of electronic mailed questionnaires over posted questionnaires is gaining momentum due to the increased speed and lower cost. The literature review in chapter two to four guided the formulation of a questionnaire which was used in the survey of architects and designers in the UK. The questionnaire was divided into three main sections for easy analysis and reporting.

1. Environmental Awareness and Related Actions: Exploring level of environmental awareness and attitude of architects and designers in building design and construction, solicit views on the adoption of environmental approaches during design, especially in the use of building materials. Investigate the basis of their design decisions to determine the level of importance accord to the environment in their normal operation.

2. Application of Sustainable Principles in Building Design and Material Selection Process: exploring the understanding of the concepts of sustainability, investigate commitment to sustainable design and construction practices, the drivers, barriers, source of information, use of building material assessment techniques and obstacles to successful usage. The section also establishes differences among groups.

3. Development of Material selection criteria: develop a holistic sustainable assessment criteria (SAC) set to assist in the selection of sustainable building materials for building project, investigate the importance of the criteria for material selection.

Survey questionnaire was used for Tasks 13, 14, 15 (see fig. 5.5). A questionnaire was used for these tasks because it is efficient and effective in sampling a large audience scattered over a wide geographical area. Also, it is a relatively inexpensive data collection and processing method. Once developed, the questionnaire was ready for testing.

5.4.2.2 Pilot survey

In order to evaluate the clarity and comprehensiveness of the questionnaire, as well as the feasibility of the survey as a whole, a pilot survey was conducted. Pilot study was also used to test the suitability of proposed sustainability criteria and respondents were invited to add new criteria if necessary. As argued by several researchers like Munn and Drever (1990), such test run surveys are necessary to demonstrate the methodological rigor of a survey. The sample used in this survey was drawn primarily from a Royal Institute of British Architects (RIBA) database of architects in the West Midlands. A total of 40 organisations were sent questionnaires to complete in this survey, taking into consideration the size, project type, annual turnover and age of organization. Of the 40 pilot questionnaires sent out to the selected sample, 13 were returned representing a response rate of 33%. This compares favourably with the 20% response rate achieved in the pilot survey reported in Xiao (2002).

As a result of the analysis of the pilot survey, the questionnaire was taken through a process of revision to make it more suitable for the main questionnaire survey. From the feedback provided by respondents, the average time taken to complete a questionnaire was approximately 20 minutes. It was therefore considered unnecessary to reduce the overall number of questions in the questionnaire to make it shorter. Some of the questions were also re-worded as the feedback from the respondents seemed to suggest that they found them ambiguous. Having satisfied the requirement to pre-test the questionnaire (Babbie, 1990; Munn and Drever, 1990; Czaja and Blair, 1996) and having completed the revision of the questionnaire, it was ready for deployment in the main survey.

5.4.2.3 Sampling for main survey

As indicated in Babbie (1990), sampling is necessary because of the constraints of time and cost. To achieve a thorough understanding of the specification process we need a better knowledge of the individuals who influence the selection of construction materials. This study aims at investigating two groups of the specifiers involved in the building process: the architects and designers. Architects and designers have traditionally been the major specifiers (Emmitt and Yeomans, 2008).

According to Architects Registration Board Register and the directory of Design Consultants, more than 33,000 architects and approximately 8,000 designers are employed in the UK, with around 80% working in private practice, mostly in small or medium-sized firms. Most of the remainder are employed either by commercial or industrial organizations (such as retail, finance or manufacturing companies) or by central or local government. Because it was impractical to collect data from all architects and designers in the population, sampling was necessary to make the survey possible.

Following the examples of Soetanto *et al.* (2001) and Xiao (2002), the sampling frame that was adopted for the selection of the sample was the list of architects registered with the Architects Registration Board (ARB), the Royal Institute of British Architects (RIBA) and the Directory of Design Consultants (DDC). In order to determine a suitable size for the sample, the following formula from Czaja and Blair (1996) and Creative Research Systems (2003) was applied:

$$ss = \frac{z^2 \times p(1-p)}{c^2}$$

...........Where:

.... ss = sample size

z = standardised variable

p = percentage picking a choice, expressed as a decimal

c = confidence interval, expressed as a decimal

As with most other research, a confidence level of 95% was assumed (Munn and Drever, 1990; Creative Research Systems, 2003). For 95% confidence level (i.e. significance level of α = 0.05), z = 1.96. Based on the need to find a balance between the level of precision, resources available and usefulness of the findings (Maisel and Persell, 1996), a confidence interval (c) of ±10% was also assumed for this research. According to Czaja and Blair (1996), when determining the sample size for a given level of accuracy, the worst case percentage picking a choice (p) should be assumed. This is given as 50% or 0.5. Based on these assumptions, the sample size was computed as follows:

$$ss = \frac{1.96^2 \times 0.5(1-0.5)}{0.1^2}$$

$$ss = 96.04$$

Therefore the required sample size for the questionnaire survey is 96 architects and designers. However, the figure requires a further correction for finite populations. The formula for this is given in Czaja and Blair (1996) as:

$$\text{new}\, ss = \frac{ss}{1 + \frac{ss - 1}{pop}}$$

Where:

$pop = population$

$$\text{new}\, ss = \frac{96.04}{1 + \frac{96.04 - 1}{176000}}$$

$$\text{new}\, ss = 95.99$$

The sample size still remains approximately 96. The UK construction industry is notorious for poor response to questionnaire surveys (Ankrah, 2007). 20 – 30% is believed to be the norm (Takim *et al.*, 2004). Based on this reasoning, it was necessary to adjust the sample size to account for non-response. Assuming a conservative response rate of 20%, the appropriate sample size to be surveyed was calculated as:

$$\text{survey}\,ss = \frac{\text{new}\ ss}{\text{response}\ rate}$$

$$\text{survey}\,ss = \frac{96}{0.20} = 480 \text{ architects and designers}$$

A random selection of architects and designers from UK Architects Registration Board register, the Royal Institute of British Architects Directory and the Directory of design consultants was thus made to provide a list comprising at least 480 architects and designers by generating random numbers in Microsoft Excel 2003. Random sampling is where each member of a population has a known and non-zero probability of being included in the sample. It was utilised because of the low cost involved, faster data collection and since data set is smaller, it is possible to ensure homogeneity and to improve accuracy and quality of data.

5.4.2.4 The main survey

The sample used in the survey was drawn from a database of architects and designers listed in the UK Architects Registration Board register, the Royal Institute of British Architects Directory and the Directory of Design Consultants. A total of 490 questionnaires were mailed out to participants for completion in this survey. The questionnaire was accompanied by a self-addressed envelope and a statement of the objective of the study to guide the respondents on the potential contribution they could make to good practice. For most of the questions, respondents were required to indicate the extent to which they agreed with a given statement, on a five point scale: ‘strongly agree’, ‘agree’, ‘neutral’, ‘disagree’, and 'strongly disagree'. For other questions, respondents were asked to rank some provided factors.

Three steps were followed in administering the survey to encourage a good response. The first involved a mail-out of an advance-notice letter to all the members of the sample notifying them of the questionnaire they were to be receiving shortly and encouraging their participation. The second step was a mail-out of the actual questionnaire with an accompanying personalised, signed cover letter and a self-addressed reply envelope (Babbie, 1990). This was undertaken on July 10, 2009, about one week after the advance-notice letter as recommended in Creswell (2003). The final step involved a mail-out of another set of questionnaires to all non-respondents, again with an accompanying personalised, signed cover letter and a self-addressed reply envelope. This was also undertaken, as recommended in Creswell (2003), about three weeks after the second step. Although the literature suggests two follow-up mail-outs to ensure high response rates (Babbie, 1990; Creswell, 2003), resource limitations meant that only one follow-up could be undertaken.

5.4.2.5 Response rate

Of the 490 questionnaires despatched to the selected sample, 99 were returned, a response rate of 20.2%. The response rate of 20.2% is acceptable and is in line with the opinions of Chinyio *et al.* (1999); Akintoye (2000); Dulami *et al* (2003) and Takim *et al.* (2004). They reported that the norm response rate in the construction industry for postal questionnaires is around 20-30 percent. Other sources that support this view include Black *et al.* (2000) which reported a response rate of 26.7% for a questionnaire survey conducted, stating that response rates in this region in construction industry surveys are not unusual at all. Ofori and Chan

(2001) received a 26 percent response rate, Vidogah and Ndekugri (1998) received a 27 percent response rate and Shash (1993) received a 28.3 percent rate

5.4.2.6 Margin of error

It is widely recognised and accepted that for inferential statistical analysis to be undertaken, a large sample is required. It is also generally accepted that as a rule of thumb, any sample with size greater than the threshold of 30 ($n > 30$) should be considered as a large sample (Munn and Drever, 1990; Sutrisna, 2004). Therefore the sample size of 99 obtained in this survey was considered adequate for the purpose of inferential statistical analysis. When the margin of error based on the 99 responses was computed, an estimate of 8.81% margin of error due to sampling was obtained at 95% confidence level. This can be interpreted as meaning that there is a 95% probability that results obtained from this survey lie within a ± 8.81% range. Analysis of the data was undertaken using SPSS v16.

5.4.2.7 Data editing

The responses received from participants contained some missing data. Indeed it is the exceptional study that has no missing data (LoPresti, 1998). Missing data can be problematic in analysis and occurs for many reasons. According to LoPresti (1999), in reputable studies, analysis of missing data is required to improve the validity of the study. Therefore to end up with a good data set and to be able to use all the data collected in the analysis, some time was spent investigating and resolving the missing data problem. The SPSS v.16 Missing Values Analysis option was used to analyse the patterns of missing data. It was decided after Hair *et al.* (1998), that where missing data levels were not excessively high (in the order of 50% or more) cases and variables would not be excluded from analysis. Where appropriate, the Replace Missing Values option was used to replace the missing values with the mean of all valid responses. Whilst several different options exist for replacing missing values, substitution with the mean is one of the most widely used (Xiao, 2002). This is so because it is considered as the best single replacement value (Hair *et al.*, 1998). Besides, it is easy to calculate and effect the replacement hence its use in this study. To check appropriateness of this approach, the *regression* method and the *estimation maximization* (EM) method were also used to estimate alternative replacement values. The series means calculated were consistent with these estimates, especially the regression estimates and were therefore accepted. Further editing of the data was also required to organise it in a format suitable for analysis.

5.4.2.8 Sample splitting

Because of the model development anticipated towards the latter phases of the data analysis, and the requirement for model validation prior to the drawing of conclusions (Good and Hardin, 2003), a proportion of the data collected was selected and held back for the purpose of the validation. This approach is in line with the second of the three approaches of validation described by Good and Hardin (2003) which specifies the splitting of the sample and using one part for calibration, and the other part for verification. This approach has been described as an effective method of validation when it is not practical to collect new data to test the model (Snee, 1977). In terms of how much is set aside for this purpose, the evidence from other research is rather mixed. Whilst Xiao (2002) set aside 12.20%, Omoregie (2006) set aside 9.03%. This appears to suggest that there is no fixed number or percentage required for validation. The recommendation however in Good and Hardin (2003) and Picard and Berk (1990) is that between a quarter

(1/4) and a third (1/3) should be set aside for validation purposes. 9% of the sample was therefore randomly selected in SPSS and excluded from the main analysis. The 9% was equivalent to 8 cases (Table 5.6). The data was now ready for analysis.

Table 5.6 Number of cases held back for validation

	Questionnaire received	%
Analysed sample	91	91
Held-back sample	8	9
Total	99	100

5.5 Method of data analysis

Data obtained for this research conformed to either the nominal or ordinal scale (Siegel and Castellan, 1988). Most of the responses were ratings measured on Likert scale. Such data cannot be treated using parametric statistics methods unless precarious and, perhaps, unrealistic assumptions are made about the underlying distributions (Siegel and Castellan, 1988). Ordinal scale data have been treated contentiously by previous research and, in some cases, large ordinal scales have been considered to be measuring continuous variables (Orme and Buehler, 2001), thus enabling parametric testing. In such cases, Siegel and Castellan (1988) claim that "they cannot be treated by parametric methods unless precarious and, perhaps, unrealistic assumptions are made about the underlying distributions." Therefore, despite the residuals of the dependent variables not breaching the normality assumptions, and previous research in this area using parametric techniques (Kelley and Margheim, 1990; Pierce and Sweeney, 2004; Otley and Pierce, 1996), it was was therefore found appropriate to analyze it using non-parametric statistics involving descriptive statistics analysis, relative index analysis, Kendall's Concordance, Spearman Rank Order Correlation test, Chi-square tests and Factor analysis. Non-parametric statistics was considered a conservative and acceptable approach because as Siegel and Castellan (1988) claimed "by using a parametric test, the researcher would 'add information' and thereby, create distortions which may be as great and as damaging as those introduced by the 'throwing away of information'."

In all these, the *Statistical Package for the Social Sciences (SPSS)* and *Microsoft Excel* for Windows application software package were employed.

5.5.1 Descriptive statistics analysis

Descriptive statistics are used to describe the main features of a collection of data in quantitative terms. This involved the use of frequencies, percentages and means for presenting description finding of the survey. These techniques were employed for analysing data related to the characteristics of the respondents, their organisations, and open ended questions/comments. They were also used for the initial analysis of rating score data of the various research variables. Graphical techniques utilised for presenting the results from these analyses include pie chart, bar chart and tables.

5.5.2 Relative index analysis

This technique was utilised to further analyse responses related to ratings of the research variables. The technique has been used extensively in similar types of Surveys (Olomolaiye *et al.,* 1987; Chinyio *et al.,* 1998[b]; Chan and Kumaraswamy ,1997; Adetunji et al., 2005; Braimah and Ndekugri (2009) and is recognised as an excellent approach for aggregating the scores of the variables rated on an ordinal scale by respondents (Chinyio *et al.,* 1998[b]).The SPSS was first used to determine the valid frequencies (in percentage terms) of the variables rated, which were then feed into Equation (5.1) to calculate the variables' respective rank indices (RIs).

$$RI = \sum \frac{w}{AxN} \text{ ....5.1}$$

where *w,* is the weighting as assigned by each respondent on a scale of one to five with one implying the least and five the highest. *A* is the highest weight (i.e 5 in our case) and *N* is the total number of the sample. Based on the ranking (*R*) of relative indices (RI), the weighted average for the two groups will be determined. The ranking index is labelled differently depending upon the context, e.g., "importance index", "awareness index", "frequency index" etc.

5.5.3 Kendall Coefficient of Concordance and Chi-square tests

To determine the degree of agreement among the respondents in their rankings, Kendall's coefficient of concordance (W) was used. This coefficient provides a measure of agreement between respondents within a survey on a scale of zero to one, with '0' indicating no agreement and '1' indicating perfect agreement or concordance. Using the rankings by each respondent, W was computed using Equation (5.2) below (Siegel and Castellan, 1988).

$$W = 12\sum \frac{R_i^2 - 3k^2N(N+1)^2}{k^2N(N^2-1) - k\sum T_j} \text{ ....5.2}$$

Where $\sum R_i^2$ is the sum of the squared sums of ranks for each of the *N* objects being ranked; k is the number of sets of rankings i.e. the number of respondents; and T_j is the correction factor required for the *j*th set of ranks for tied observations given by $T_j = \sum_{i=1}^{gj}(t_i^3 - t_i)$, where t_i is the number of tied ranks in the *i*th grouping of ties, and g_j is the number of groups of ties in the *j*th set of ranks.

To verify that the degree of agreement did not occur by chance, the significance of W was tested, the null hypothesis being perfect disagreement. The Chi-square (x^2) approximation of the sampling distribution given by Equation (5.3) with (N-1) degrees of freedom is used for testing this hypothesis at a given level, for N>7 (Siegel and Castellan, 1988). Calculated x^2 value greater than its counterpart table value implies that the W was significant at the given level of significance and as such the null hypothesis is not supported and thus has to be rejected.

$$x^2 = k(N-1)W \quad \text{..........} 5.3$$

5.5.4 Factor analysis

Factor analysis is a multivariate statistical technique for examining the underlying structure or the structure of interrelationships (or correlations) among a large number of variables (Hair *et al.*, 1998). This analysis yields a set of factors or underlying dimensions which, when interpreted and understood, describe the data in a parsimonious but more meaningful number of concepts than the original individual variables (Glynn *et al.,* 2009). This approach was utilised in the work of Fahy (2002) on sustainability. In the absence of any standard lists of Material selection criteria, there was a considerable risk of the analysis of the responses yielding diverse results. Thus, in establishing the list of criteria, it was considered important to ensure that the criteria are of adequate relevance and were also independent.

This analysis was performed with the assistance of SPSS Statistics v16. Kaiser–Meyer–Olkin (KMO) measure and Bartlett's Test of Sphericity were conducted to examine the sampling adequacy, ensuring that factor analysis was going to be appropriate for the research. Principal component analysis was then employed to extract six group factors with eigenvalues greater than 1, suppressing all other factors with eigenvalues less than 1 based on Kaiser's criterion (Kim and Mueller, 1994; Field, 2000). To interpret the relationship between the observed variables and the latent factors more easily, the most commonly used rotation method, varimax rotation, was selected.

5.6 Brief description of case study approach for sustainability index development

In relevant literature, opinion on what constitutes a case study varies (Gerring, 2007). Case study is an empirical (Gerring, 2007), in-depth and multifaceted inquiry (Orum *et al.,* 1991) that seeks to elucidate the dynamics (Stoecker, 1991) of a single contemporary social phenomenon (Orum *et al.,* 1991; Yin, 1994). A case study may combine a variety of data collection methods and research strategies (Fellow and Liu, 2003). It differs to other qualitative research studies in the sense that the focus of attention is on individual cases as opposed to the whole population of cases (Gerring, 2007). The individual case is chosen on the basis that they are representative of a sample group that can be used to demonstrate particular facets of topic of research (Fellow and Liu, 2003). Whilst most studies look for what is common and pervasive, in the case study the intent may not be generalisation but rather to understand the particulars of that case in its complexity (Key, 1997). Akin to most qualitative methods, case study is time consuming. As a result, data are collected from a smaller number of samples than would normally have been the case using a quantitative approach such as questionnaire survey (Gerring, 2007). The main advantages of a case study include richness of data and deeper insight into the phenomena under study (Hancock, 1998). Case study approach was used for Task 20 (see Table 5.5) to collate data from many construction companies and experts in the field of sustainable material selection.

An important objective of this research involves developing a sustainability index for material evaluation and selection. The research questions posed in Chapter One include identifying the fundamental criteria to be considered in material evaluation in order to ensure that building projects conform to sustainable practice. Identifying the essential criteria for material selection, using an extensive survey of architects and designers, was covered in the previous section. The objective of the case study was to collect data for the criteria identified for use in the sustainability index. A multi criteria decision analysis model will be used in aggregating the sustainability criteria into a composite index. Detail of the model development and data collection is covered in chapter 7 and 8

Case studies were chosen as the best means to explore sustainability relationships and dependencies of criteria in the sustainability index, and to show how the sustainability index works to rank building materials.

Case studies have previously been adopted as a relevant and adequate research methodology in planning, economic and political science (Gillham, 2000; Yin, 2003). They allow an empirical inquiry into the real-life context of research work. They are particularly useful when the research context is too complex for surveys or experimental strategies (Gillham, 2000). The results generated through these case studies are considered more compelling and more robust (Yin, 2003) and hence will be more useful in developing a sustainability index for material selection. In view of the complex nature of the research, case studies were deemed to be the preferable method to generate the essential data for analysis and to test the model robustness.

5.6.1 Data collection and analysis

Three commonly used roofing covering materials as shown in table 8.1, were chosen as the multiple case designs using an embedded approach. The number of materials to be included in the case studies is restricted by various constraints. The case studies involve quantifying the criteria identified as fundamental for enhancing sustainability in material selection. A multi criteria analysis method in the form of the Analytic hierarchy process (AHP) was employed to collect data for assessing the criteria. The data collection to quantify each criterion required comprehensive resources and the sample size needed to be a realistic and manageable size. The AHP questionnaires for evaluating the three roofing materials were sent to nine UK architects and designers Even though the sample size may seem small, it will not significantly affect the analysis as almost all relevant statistical techniques are applicable for samples of that size (Yin, 2003). The data collected were analysed using Expert choice 11 software and Microsoft Excel. Full description of the data collection and analysis is covered fully in chapter eight.

5.7 Summary of research method

This chapter has presented an outline of the research methodology adopted for carrying out this research. Combinations of methods are adopted to enable an in depth study of the sustainability phenomenon, which helped to achieve the research aim and objectives as summarised in the Research Road Map in Table5.5. This involved first, a comprehensive literature review followed by a pilot survey for fine-tuning the questionnaires for a subsequent nation-wide survey to investigate knowledge and awareness of architects and designers regarding the concept of sustainability as it affect building material selection and associated barriers towards implementing it. The data collected were analysed, with the aid of SPSS and Excel, using a variety of statistical methods including descriptive statistics, relative index analysis, Kendall's Concordance, Chi-square test, Spearman Rank Order Correlation test and Factor analysis.

Information gathered from literature review, the survey and subsequent interviews was used to: draw deductions and conclusions in respect of the research objectives; and developed a model for selecting sustainable building material. This model was validated via experts' review through survey. The next chapter outlines the research work undertaken and outcome using the adopted research methods.

Chapter 6: DATA ANALYSIS AND DISCUSSIONS

6.1 Introduction

This research employed a questionnaire survey in collecting data on environmental awareness and sustainability practices in building design and construction from architects and designers across the UK. Detailed information on the design of the questionnaire, research questions it addresses and sampling of the organisations are presented in Chapter 5. The questions contained in the questionnaire were informed by the review of the literature reported in Chapters 2, 3 and 4. This chapter presents the results and analyses the responses to individual questions in the light of comments made on sustainability practices and how this influences their design. The rest of this chapter was written, grouping these under the following headings: (i) analysis of demographic data (iii) environmental awareness and design practices (iv) consideration of sustainability in building design and construction (v) decision making in building material selection – stakeholder influence, source of information, drivers and obstacles, (vi) material assessment methods and obstacles to usage and (vii) development of sustainability criteria for material selection. This analysis is undertaken as a prelude to the development of the sustainability index model in chapter seven.

6.2 Analysis of the demographic data

Basic factual data was collected relating to the respondents personally as a professional designer/architect, and his/her organization. This data is presented in this section. The size of the response across available response categories is indicated in both percentage (%) and raw numeric terms.

6.2.1 Experience of respondents

Table 6.1 indicates most respondents (61.5%) have over 20 years experience working in the construction industry, 13.2% has industry experience ranging between 11 and 20 years, while 25.3% have at least 10 years or less. As the experience of the respondents is quite respectable, opinions and views obtained through the survey can be regarded as important and reliable. Majority of respondents had reasonable experience in sustainable construction which further shows that respondents are sufficiently experienced enough to provide data which are credible.

6.2.2 Organisation structure

Analysis of the returned questionnaire showed that 96.7% of respondents work in architectural and design office. Of this lot, 90.6% work in the private sector whilst 6.1% work in public sector (e.g. government agency). Response from the private sector predominated since more architects and designers are employed in the private sector than in the public sector. Therefore, the opinions obtained through this survey tend to be more representative of respondents working in the private sector.

Table 6.1 Summary of respondent's demographic data (architects and designers)

Variable	Number of respondents	Percentage (%)
Work experience		
<5 years	5	5.5
6-10 years	18	19.8
11-20 years	12	13.2
>20 years	56	61.5
Size of organisation (by staff)		
<10 staff	44	48.4
11-50 staff	17	18.7
51-249 staff	18	19.8
250-500 staff	5	5.5
>500 staff	7	7.7
Age of organisation (in years)		
<5 years	14	15.4
6-10 years	5	5.5
11-20 years	23	25.3
21-30 years	22	24.2
31-40 years	7	7.7
>40 years	20	22.0
Type of organisation		
Architecture/design	88	96.7
Education	2	2.2
Government agency	1	1.1
Area of Building project specialism		
Commercial	5	5.5
Residential	56	61.5
Institutional	29	31.9
Industrial	1	1.1
Organisation annual turn over (in £)		
>£5m	60	65.9
£6-£25m	16	17.6
£26-£100m	13	14.3
>£100m	2	2.2
Regular client type		
Public sector	9	9.9
Private sector	48	52.7
Public & Private	17	18.7
All	17	18.7

Source: analysis of surveyed data, 2010

6.2.3 Size of organization

Size of organisation was determined by asking respondents to indicate the number of employees in their organisation. Table 6.1 shows that majority (86.8%) of respondents worked in small to medium size organizations, with a small proportion (13.2%) working in large organizations with over 250 staff. The UK department of trade and industry categories small, medium and large organization as having employee of less than 49, 50-249 and over 250 respectively. However, small to medium sized organizations have contributed heavily in the UK, since they design and supervise the construction of most wide varieties of small and medium size residential and commercial building projects. Their inclusion and assessment in study has a great credibility.

6.2.4 Education

The result shows that 95 % of the survey participants have completed at least undergraduate degrees and 81% have additional postgraduate qualifications. The survey also shows that about half (50%) of the participants have experience in environmental design or environmental assessment of projects with 25% having more than 6 years experience working on environmentally sensitive projects. This means that the outcomes obtained from the survey represents the opinion of a group of architects and designers with a good educational background and sufficient knowledge of environmentally sensitive projects to provide a significant contribution in identifying criteria to be included in the decision-making model of a sustainability index.

6.2.5 Area of project interest

Within the combined valid response, residential building (61.5%) is the leading area of project specialism reported by respondents, with institutional (31.9%), commercial (5.5%) and industrial (1.1%) also making significant proportion. The larger numbers of residential respondents further reflect the intended focus of the research which is on residential buildings.

6.2.6 Annual turnover

Respondents were asked to indicate the annual turnover of their organization in the last five years (refer Table 6.1). Majority of respondents 83.5%indicated an annual turnover of £25m or less, 14.3% indicated an annual turnover of around £26m -£100m, and just 2.2% indicated an annual turnover of £100million or more. Rate of annual turnover further confirm majority of respondents as group of small to medium size organization in accordance with the department of trade and industry categorization of industries.

6.3 Environmental awareness and design practices

6.3.1 Environmental awareness and action

One of the purposes of this survey is to investigate the environmental awareness and attitudes of architects and designers to the environment. The responding architects and designers indicated that they were aware of the impact of construction activity on the environment: all the 91 respondents considered environmental assessment an important issue for building project and agree that the impact of environmental effects needs to be incorporated into the material selection process. Respondents also claimed to be aware of the effect of the utilization of materials on the environment. In table 6.2, almost all the respondents (95%) agreed or strongly agreed that the large amount of natural resources consumed in construction contributes to the negative impact on the environment.

Table 6.2 Construction impact negatively on the environment

Extent of agreement scale	Architects		Designers	
	Percent	Cumulative percent	Percent	Cumulative percent
Strongly disagree	0.0	0.0	0.0	0.0
Disagree	0.0	0.0	1.8	1.8
Neutral	5.0	5.0	9.9	11.7
Agree	14.4	19.4	12.7	24.4
Strongly agree	80.6	100.0	75.6	100.0
Total	100.0		100.0	

Source: analysis of surveyed data, 2010

6.3.2 Consideration of environmental issues at conceptual stage

Most commentators have argued that the more effective way of achieving sustainability in a building project is to consider and to incorporate environmental issues at an early stage of building project. To investigate the extent to which this practice is observed by respondents were asked to score their level of agreement with the proposition:*" it is important to consider and include environmental issues at the conceptual stage of building project";* using a 5-point Likert scale (where '1= disagree' to '5 =agree').

Table 6.3 Proposition of environmental issues inclusion at conceptual stage

Extent of agreement scale	Architects (N=60)		Designers (N=31)	
	Percent	Cumulative percent	Percent	Cumulative percent
Strongly disagree	0.0	0.0	0.0	0.0
Disagree	0.1	0.1	0.0	0.0
Neutral	7.6	7.7	4.7	4.7
Agree	35.4	43.1	21.7	26.4
Strongly agree	56.9	100.0	73.6	100.0
Total	100.0		100.0	

Table 6.3 shows the results, which suggest that over 92% of respondents agreed or strong agreed that the best stage at which to consider incorporating environmental issues is the conceptual stage. This is in line with other studies (Crawley and Aho, 1999; Soebarto and Williamson, 2001; Ding, 2008) that observe that the more effective way of achieving environmental sustainability in a project is to consider and to incorporate environmental issues at the conceptual stage. BRE and

CyrilSweett (2005) and Elhag and Boussabaine (2001) explained that the significance of the consideration of sustainability early in a project life cycle was likely to result in less of an increase in capital costs as compared to projects in which environmental issues where considered at a later stage. These results indicate without doubt that environmental issues are important, they should be part of the building material selection process, and they have to be introduced at an early stage. The previous work made the case that there is a clear need to develop a more reliable early stage building material selection model for sustainable housing projects in the UK.

6.3.3 Environmental design in practice

An attempt was made to assess respondent's views on the adoption of environmental approaches during design, especially in the use of building materials. The results are shown in Table 6.4-6.6. To investigate the extent to which this practice is observed by, respondents were asked to score their level of agreement using a 5-point Likert scale (where '1= strongly disagree' to '5 = strongly agree'). The results, suggest that on all the three propositions, most respondents (95%) agreed or strongly agreed that it is important for architects to understand the environmental impacts of their design decisions; be conscious of the environmental implications of their design decisions as they relate to the selection of materials and consider the life cycle environmental impacts of materials.

Table 6.4 Important to understand the environmental impacts of design decisions

Extent of agreement scale	Architects (N=60)		Designers (N=30)	
	Percent	Cumulative percent	Percent	Cumulative percent
Strongly disagree	0.0	0.0	0.0	0.0
Disagree	0.2	0.2	0.6	0.6
Neutral	2.1	2.3	5.3	5.9
Agree	8.5	10.8	12.8	18.7
Strongly agree	89.2	100.0	81.3	100.0
Total	100.0		100.0	

Table 6.5 Important to be conscious that some of the materials have an impact on the environment

Extent of agreement scale	Architects (N=61)		Designers (N=30)	
	Percent	Cumulative percent	Percent	Cumulative percent
Strongly disagree	0.0	0.0	0.0	0.0
Disagree	0.0	0.0	0.0	0.0
Neutral	0.5	0.5	0.0	0.0
Agree	4.9	4.9	7.5	7.5
Strongly agree	94.6	100.0	92.5	100.0
Total	100.0		100.0	

Table 6.6 Important to consider the full range of environmental impacts of construction materials by assessing their entire life cycle

Extent of agreement scale	Architects (N=61)		Designers (N=30)	
	Percent	Cumulative percent	Percent	Cumulative percent
Strongly disagree	0.0	0.0	0.0	0.0
Disagree	0.0	0.0	0.0	0.0
Neutral	1.9	1.9	1.2	1.2
Agree	16.4	18.3	15.7	16.9
Strongly agree	81.7	100.0	83.1	100.0
Total	100.0		100.0	

Source: analysis of surveyed data, 2010

6.3.4 Priorities in building design

The results of the survey present so far show that architects and designers are aware of the need for them to adopt environmentally sound design practices. This preliminary finding was further investigated by examining the basis of their design decisions. The respondents were asked to rank the importance of their project objectives in order to gauge the level of importance architects and designers accord to the environment in their normal operations. A number of authors have listed objectives considered important in construction projects, mostly from the point view of clients need. It is obvious that if these objectives are achieved, the project is claimed to be successful (Stuckenbruck, 1981; Bennett, 1983; Walker, 1990 in Ofori, 1992). Many of theses hinge on cost, time and quality aspects, and hence the three objectives were chosen for investigation to see if they impact on architects design decisions. Two more objectives, building regulation and project environmental impact were included to see if they will change the conventional project priorities from the architect's and designers perspective

Using Relative index analysis techniques, the respondents were asked to rank the level of their project objective on a five-point scale from "very low" (=1) to "very high" (5).

Table 6.7 Ranking of project objectives

Project objectives	Architects		Designers		Overall	
	RI	Rank	RI	Rank	RI	Rank
Minimize cost	0.94	1	0.96	1	0.95	1
Building regulation	0.84	2	0.88	2	0.86	2
Project deadline	0.78	3	0.83	3	0.81	3
Building quality	0.72	4	0.75	4	0.74	4
Minimize project environmental impact	0.72	4	0.69	5	0.71	5
Test statistics						
Kendall's W=0.337						
χ^2 critical(=0.05)=11.07; df=5; *χ^2 sample=455.2*						

Source: analysis of surveyed data, 2010

Table 6.7 shows the rating of project objectives. The overall ranking in descending order is: cost; building regulation; project deadline (time); quality; and environmental considerations. The results show that the conventional project priority of cost is still held by architects and designers in the UK, with environmental considerations trailing in the fifth and last place. Test statistics was applied to these rankings in order to test the significance of these findings. The

Kendall's coefficient of concordance (W) value obtained was 0.337, which was significant at 95% confidence level. There is thus significant degree of agreement between architects and designers as to the ranking of project objectives.

The ranking of cost as the most important is not unexpected as clients greatest financial obligation for a project, construction cost is frequently the central concern of design and construction, as such costs must be monitored and controlled, whether from the point of view of the owner, or the designer. Buildings are very expensive, and owners rarely have infinite funds with which to pay for them. Fixed budgets create clear and definite obligations for the architect and designers. Meeting those budgets is a high priority for every member of the project team (Demkin, 2008).

Building regulation was ranked second with RI of 0.86. The design and construction of buildings is conditioned, in part, by legal requirements itemised in the building regulations that, in the English context, seek to ensure 'the health and safety of people in and around buildings by providing functional requirements for building design and construction' (ODPM, 2005). The high importance given to regulation is not unexpected as design and construction of all buildings and the use of building materials have to adhere and comply with building regulations as recommended by the department of communities and local government.

The Third and fourth project objective rated was project deadline (RI 0.81) and building quality (RI 0.74) respectively. Like cost, Meeting project deadlines and quality has been identified as a problematic issue for many project groups. Timely completion of a construction project and its result quality are frequently seen as a major criterion of project success by building stakeholders (Chinyio *et al*, 1998c;

Rwelamila and Hall, 1995). Newcombe *et al.* (1990) note that there has been universal criticism of the failure of the construction industry to deliver projects in a timely way. NEDO (1983) states that a disciplined management effort is needed to complete a construction project on time, and that this concerted management effort will help to control cost which is important to clients. The importance of quality on the other hand has been gaining momentum following the publication of Rethinking Construction (Egan, 1998). Interest in the quality of building design has been heightened – especially in the public sector – with the need for a better understanding of the use of buildings and a new enthusiasm for delivering 'best value'.

Minimizing project environmental impact was rated last with RI 0.71. This showed that, despite the respondents' indication of their high level of awareness and conviction of the merits of considering the welfare of the environment in their design decisions, they placed environmental considerations low among their project objectives. Other studies have found the objectives of construction clients when they launch projects to be similar to those identified by the respondents (Chinyio *et al*, 1998c; Holt *et al,* 1994). Thus, responding architects and designers may be influenced by their clients' objectives. The findings also confirmed those of authors in other countries such as Melet (1999); Ofori *et al.* (2000) and Chan *et al.* (2009), who found that few clients are committed to sustainable design despite the examples of others, and evidence that it makes commercial sense (Zeiher, 1996; Edwards, 1999).

6.4 Consideration of sustainability in building design and construction

Environmental concern has broadened to include fundamental questions about sustainability, and so the concept of sustainable construction has evolved to cover ecological, economic and social responsibilities. Until recently, considerations of sustainability have not been included in the design decision processes. One of the problems encountered in the word of Ugwu and Haupt (2007) is the task of understanding and translating strategic sustainability objectives into concrete action plan at project specific level. This could indicate a problem in levels of knowledge, skills, or both as recognized by Egan (2004). Sha *et al.* (2000); Edwards (2006) and Lam *et al.* (2010) repeated that a lack of practical understanding of sustainability has hampered the effective implementation of the concept in the construction process. The process has been exacerbated by multi-dimensional perspectives of sustainability such as economy, society, environment, combined with lack of structured methodology, tool and access to sustainability information. There is therefore dire need to investigate these challenges.

6.4.1 Knowledge in sustainable design

To successfully implement sustainability in building design, the knowledge of architects and designers is indispensable and the results of the survey on their knowledge are shown in Table 6.8.From the survey, 96.4% of respondents claim they have sufficient to excellent knowledge of sustainable concepts especially in the selection of building materials. 2.6% reported an insufficient knowledge and 1.1% undecided. An explanation for this 1.1% could be that they haven't handled project in which sustainability was part of the project criteria and are rather ignorant about the importance of sustainability practices as shown in table 6.9 when asked to recall the percentage (%) of project they have handled with sustainability consideration. It was surprising to know that over 53% of respondents stated that projects they handled with sustainability consideration are less than 10%.

Table 6.8 Knowledge in sustainable design

Rate of knowledge scale	Architects (N=61)	Designers (N=30)		
	Percent	percent	Valid Percent	Cumulative percent
Excellent	16.1	8.8	24.9	24.9
Good	27.5	7.7	35.2	60.0
Sufficient	23.1	13.2	36.3	96.3
Insufficient	1.4	1.2	2.6	98.9
Don't know	0.0	1.0	1.1	100.0
		Total	100.0	

Source: analysis of surveyed data, 2010

Table 6.9 Project with sustainability consideration

Percentage of project	Architects (N=61)	Designers (N=30)		
	Percent	percent	Valid Percent	Cumulative percent
<10	36.3	17.6	53.9	53.9
10-20	12.1	2.2	14.3	68.2
21-30	9.9	11.0	20.9	89.0
>30	8.8	2.2	11.0	100.0
		Total	100.0	

Source: analysis of surveyed data, 2010

Although most respondents were aware and have certain knowledge of sustainable construction, implementation is a different matter. Majority respondents believed that the level of implementation of sustainable practices is either low or at a moderate level. On the low implementation observed, respondents stated that they do not feel the urgency to adapt to this practice. They believe their interest on this matter will improve when there is a demand for it. Presently, this issue is not on their priority list as it lacks publicity and the interest of clients.

However, this perception differs among those who have applied this concept. Respondents from big and well-established architectural and design companies rated their implementation of sustainable practices as high or excellent. They can appreciate the merits of this and will continue pursuing it. They believed that by responding to the need to protect the environment and addressing social needs, they can generate more profit. It is a good move as it adds value to the project and projects a good image of the designer.

6.4.2 Sustainability assessment consideration

The study further examines the respondent's perception on the importance of sustainability assessment in the design and construction process in particular in the use of building materials. Respondents were asked if sustainability assessment of building material is an important issue in building development. The importance accorded to sustainability was high, with 95.6% saying sustainability assessment as an important issue in material selection, 3.3% did not believe it is important while 1.1%were undecided. One possible reason for the negative response from a few respondents in the word of Boyle (2000) is the believe that sustainability is not an issue that should affect business –in this case building project- and will pose an unacceptable cost to business.

Table 6.10 sustainability assessment consideration

Level of importance	Architects (N=61)	Designers (N=30)		
	Percent	percent	Valid Percent	Cumulative percent
yes	62.6	33.0	95.6	95.6
no	3.3	0.0	3.3	98.9
Don't know	1.1	0.0	1.1	100.0
		Total	100.0	

Source: analysis of surveyed data, 2010

Respondents were asked which categories of client are more likely to consider sustainability in building project. The result in table 6.11 shows that sustainability consideration is more prevalent in public building projects (50.6%), private building projects (11%), with 30.8% of respondent seeing no difference in consideration between private and public client. With the low private client consideration, it seems they are still weighing the costs of sustainability against its economic benefits for individual projects. This again calls for a methodology that can be used to assess building projects without incurring further cost to the client.

Table 6.11 Stakeholders attuned to sustainability consideration

Stakeholders scale	Architects (N=61)	Designers (N=30)		
	Percent	percent	Valid Percent	Cumulative percent
Public	31.9	18.7	50.6	50.6
private	7.7	3.3	11.0	61.6
No difference	23.1	7.7	30.8	92.3
Cant tell	4.4	3.3	7.7	100.0
		Total	100.0	

Source: analysis of surveyed data, 2010

6.4.3 Sustainable construction practices for designers

It is appreciated that a number of Sustainable Construction Practices (SCPs) has been adopted by designers to manifest the extent of commitment or comprehensiveness towards sustainable construction. In line with the developments in the literature, 11 sustainable construction practices have been identified as shown in Table 6.12. Data are collected through the questionnaire survey on whether or not the designers had implemented these practices, or to what extent. Table 6.12 depicts two basic statistics (i.e. Mean values and Standard Deviation) of the each sustainable construction practice.

It is interesting to note that according to the respondents, 17 (13.82%) designers had not undertaken any practice. Only 3 (2.439%) undertake all the mentioned SCPs. On average, 4.959 SCPs are adopted among the surveyed designers. The practice presenting the highest frequency is “Having obtained the ISO 14001certification - SC[1]” by comprising 69.92% of the sample, followed by "comprehensive material saving plan - SC^5", implemented by 65.85% of designers. While, only 18.70% of designers reported having implemented "comprehensive waste abatement plan - SC^{10}"

Table 6.12 Descriptive statistics of the variables.

Variable	Mean values	Std. dev.	Description of the practice
SC^1	0.6892	0.4604	Having obtained the ISO 14001certification
SC^2	0.4473	0.5009	Having obtained the code for sustainable homes standard
SC^3	0.2189	0.4256	Investing on R&D for implementing sustainable construction
SC^4	0.4460	0.5003	Investing resources for improving sustainable equipment and technology
SC^5	0.4310	0.5000	Implementing comprehensive energy-saving plan (CESP)
SC^6	0.6584	0.4679	Implementing comprehensive material saving plan (CMSP)
SC^7	0.5377	0.5000	Implementing comprehensive water saving plan (CWSP)
SC^8	0.3495	0.4859	Implementing comprehensive land saving plan (CLSP)
SC^9	0.6259	0.8290	Implementing comprehensive noise controlling (CNCP)
SC^{10}	0.1869	0.3989	Implementing comprehensive waste abatement plan (CWDP)
SC^{11}	0.3980	0.4943	Implementing comprehensive air pollution controlling plan (CACP)

Source: analysis of surveyed data, 2010

6.5 Factors affecting designers' sustainability practice

During the last decade, sustainable development issues have been gradually adopted in the UK construction industry, changing the traditional methods and technology. Part of this study therefore investigates the different factors forcing architects and designers to adopt sustainable construction practices (listed in previous sub section). To understand the relationship between the factors and adoption of sustainable construction practices, a theoretical framework was designed and three hypotheses proposed as shown in Fig. 6.1. The theoretical model introduces the driving forces that trigger sustainable construction practices and a hypothesis is proposed for addressing the relation between driving factors and sustainable construction practices.

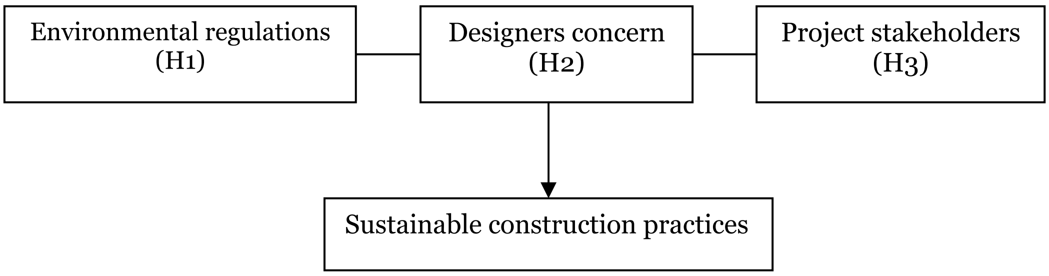


Figure 6.1 Theoretical model of sustainable practices

The factors as shown in Figure 6.1 include environmental regulation (Fergusson and Langford, 2006; Blayse and Manley, 2004); Designers concern (Bansal and Hunter, 2003; Spangenberg *et al.,* 2003; Fergusson and Langford, 2006) and Project stakeholders pressure (Adetunji *et al.,* 2003; Walker, 2000; Zhang *et al.,* 2008). Based on the understanding of sustainable construction practices and their factors, the following hypotheses have been introduced:

Hypothesis 1: There is a positive relationship between government environmental regulations and the adoption of sustainable construction practices

Hypothesis 2: There is a positive relationship between designer's environmental concerns and the adoption of sustainable construction practices

Hypothesis 3: There is a positive relationship between project stakeholder pressures and the adoption of sustainable construction practices

6.5.1 Assessment Measures

Measures for assessing the relationship between driving factors and sustainable construction practices are identified under three groups: pressure imposed by environmental regulations (ER); designers environmental concern (DEC), and pressure from project stakeholders (PPS). According to previous studies (Eiadat *et al.,* 2008; Zeng *et al.,* 2008), the following five factors are identified to measure the pressure of environmental regulation (ER):

1. Regulations for sustainable construction are stringent (RSCS);

2. The need to meet Regulation is increasing client demand for sustainable home (RSCP);

3. Regulations for sustainable construction have a considerable impact on design practice (REIM);

4. Regulations for sustainable construction can effectively deal with issues regarding the sustainability of construction process (RSCC); and

5. The sustainable construction laws are appropriate for UK construction industry environment (REAP).

With references to the previous studies, such as Walker (2000), Revell and Blackburn (2007) and Williams and Dair (2006), stakeholders' pressures (PPS) are contributed by the following four factors:

6. Designers faced with pressure from client (PCL);

7. Designers faced with pressure from community (PCOM);

8. Designers faced with pressure from environmental NGO (PEN); and

9. Designers faced with pressure from colleague (PC).

Similarly, with referring to previous studies on the designers environmental concerns for implementing sustainable construction (DEC) (Fergusson and Langford, 2006; Williams and Dair, 2006; Eiadat *et al.,* 2008), the typical factors contributing to designers environmental concerns are identified as follows:

10. Sustainable construction is an important component of the firm design practice (DSFP);

11. Designers conceive sustainable construction as an effective strategy (DSCS);

12. Sustainable construction is necessary for improving environmental performance (DSCE); and

13. Designers pay considerable attention to "sustainability" issues in the construction process (DSCP).

6.5.2 Relationship and reliability of the factors

There are in total 13 factors affecting designers' sustainability practices. The relative importance of these factors was measured through the questionnaire survey based on a five-point Likert scale ranging from "strongly disagree"1 and "neutral"3 to "strongly agree"5. Respondents were invited to indicate the relative importance of each factor in order to identify the significant ones driving sustainable construction practices. Factor analysis was then employed to analyze the structure of interrelationships among the variables. Before the factor analysis, validity test for factors was conducted according to the method by Kaiser (1974). By Kaiser Method, a value called eigenvalue under 1 is perceived as being inadequate and therefore unacceptable for factor analysis. Based on Kaiser's eigenvalue rule, factor analysis is performed and the retained factor requires the eigenvalue to be larger than 1. After the primarily factor analysis, Varimax rotation method was used to look for a linear combination of the original factors, such that the variance of the loadings is maximized. The final factor analysis results are shown in Table 6.13. It can be appreciated that three retained factors resulted with eigenvalues greater than 1, capturing 61.9868% of variance.

Table 6.13 Result of factor analysis

Items	Cronbach α	F1-designers concern (DEC)	F2- Regulatory pressure (ER)	F3- Stakeholders pressure (PPS)
DSFP	0.831	0.9046	0.119	-0.0289
DSCE		0.9266	0.0150	0.0790
DSCP		0.9137	0.109	0.1430
DSCS		0.8192	0.0836	0.1032
RSCS	0.803	0.189	0.7374	0.1131
RSCP		0.344	0.7290	0.1339
REIM		0.1569	0.7024	0.1377
RSCC		0.0740	0.8139	-0.0120
REAP		0.0490	0.7880	-0.1990
PCL	0.711	0.0350	-0.1201	0.7331
PCOM		0.1190	0.1100	0.5599
PEN		0.270	0.1619	0.5574
PC		0.152	0.0450	0.6103
Variance (initial factors loading matrix)		4.31301	2.25160	1.49491
Variance (rotated factors loading matrix)		3.48312346	2.9400026	1.64687
Variance explained percentage (rotated factors loading matrix)		26.80298	22.6159	12.5701
Cumulative variance percentage (rotated factors loading matrix)		0.2790182	0.489778	0.621109
Kaiser-Meyer –Olkin (KMO)		0.8019		

Source: analysis of surveyed data, 2010

The value of KMO is 0.8019, which is well above Kaiser's (1974) specification of 0.5. Moreover, Hinkin (1998) stated that the cut-off point of the Cranach's of each factor set is 0.7, and that Cranach's a greater than 0.7 provide evidence for composite reliability. Therefore, the results shown in Table 6.13 proved that all the three factors presented an adequate reliability. The three factors (i.e. F1-designers concern (DEC); F2-Regulatory pressure (ER); and F3-Stakeholder pressure (PPS) extracted from the factor analysis can be used as a multidimensional measure for internal and external forces affecting designers' sustainable construction practices SCPs. The factor scores were generated by using the Bartlett method, which calculates for each response architect's and designer's, the 'weighted sum' of their standardized value for every variable multiplied by the corresponding factor loading of the variable in Table 6.13

6.5.3 Regression model

For the regression analysis, it is considered that the importance between individual SCPs is equal and therefore they adopt the same weights. In other words, there is no distinction between the effects of alternative practices (Khanna *et al.,* 2007). According to Winkelmann (2008), the Poisson Regression Model is the benchmark model for 'count data', almost in the same way as the normal linear model is the benchmark for 'continuous data'. Typical count econometric models are based on Poisson's distribution and these generally include standard Poisson Regression Model (PRM) and Zero-Inflated Poisson Regression Model (ZIP) (Khanna *et al.,* 2007). ZIP is used when zero counts are greater than expected for a Poisson distribution. Thus, the Poisson Regression Model is used for estimating the expected number of SCPs as a function of factor scores. Scores for each factor were entered jointly into the model as independent variables that together comprised the multidimensional measure for the factors influencing architect's and designer's to adopt SCPs. Two dummy variables SIZE2 and SIZE3 (SIZE2 representing middle size designers and SIZE3 representing large size designers) were introduced into feasible regression models to reflect the effect of different organizations size on designers sustainable construction practices. For robust principle, two Poisson regression analysis results are reported (i.e. PRM and ZIP) and the Vuong statistic was used to test the validity of the ZIP vs. PRM model.

6.5.4 Result analysis

Table 6.14 presents the results of two models explaining the factors for adopting SCPs. It presents the results of PRM and ZIP models explaining the forces for adopting SCPs. Both models examined the effects of designers concern (DEC), regulatory pressure (ER) and project stakeholder pressures (PPS) on the different SCPs. In order to examine the effect of different organization sizes on the implementation of SCPs, two dummy variables were introduced, namely SIZE2 and SIZE3 in the two regression models.

Table 6.14Result of three models

Independent variable	PRM	ZIP
DEC	0.5904002	0.4201225
	(0.080809)	(0.0891096)
	(0.000***)	(0.000***)
ER	0.1361293	0.3257712
	(0.0572014)	(0.0571002)
	(0.018**)	(0.017**)
PPS	0.0811190	0.0721154
	(0.0566112)	(0.05677732)
	(0.160)	(0.250)
SIZ2	0.3782466	0.37887061
	(-0.1000567)	(-0.1004645)
	(0.000***)	(0.000***)
SIZ3	0.3682231	0.3671228
	-0.1009199	-0.1004221
	(0.000***)	(0.000***)
CONS	1.584875	1.725766
	(0.0790120)	(0.0812786)
	(0.000***)	(0.000***)
Vuong statistic	3.69	

*N=91 for all regressions. Standard errors (upper) and p-value (lower) are in parentheses. *Statistically significant at the 10% level; **statistically significant at the 5% level; ***statistically significant at the 1% level.*

Source: analysis of surveyed data, 2010

From Table 6.14, we find that both of the ZIP model and the PRM model provide consistent results. 3.69 is the resulted Vuong statistic value as presented in Table 6.14. According to Long (1997) if Vuong statistic value is greater than 1.96, it is considered statically significant. Thus, the ZIP model is considered appropriate when compared to the standard Poisson model. It is also appreciated that DEC have a positive and statistically significant effect on SCPs in the Poisson models and ZIP model (from PRM: $p < 0.001$; from ZIP: $p < 0.001$), which supports Hypothesis 2. The regression coefficient of DEC indicates that one standard deviation change in DEC score, the difference in the log of SCPs number is expected to change by 0.5904002 in Poisson Regression Model (PRM) and by 0.4201225 in Zero-Inflated Poisson Regression Model (ZIP), while the other independent variables in the model remain constant. This can be explained by the following two reasons: (1) sustainable construction practices require the collaboration and coordination of different departments and this is easier to manage when such practices are endorsed from the top management level; (2) the resources required for the implementation of the sustainable construction practices will be more easily available for those in charge of these practices.

The two models have also shown consistent evidence on the effect of ER on SCPs (from PRM: $p<0.05$; from ZIP: $p<0.05$). This means the stringency (RSCS), client demand (RSCP), impact (REIM), effectiveness (RSCC) and applicability (REAP) of sustainable construction regulations have a comprehensive effect on the adoption of SCPs, which supports Hypothesis 1. The results obtained from this analysis are consistent with previous empirical findings by Adetunji *et al.*, (2003); Revell and Blackburn (2005), who stated that regulatory pressures are associated with firms' decisions to implement sustainable construction practices.

The importance given to regulation as Nakao *et al* (2007) cited in Lopez-Gamero *et al;* (2010) suggest could be as a result of tightening environmental regulations enforcement and increasing awareness of environmental issues in recent years.

Building practitioners are being compelled to spend large amounts on environmental protection through such measures as investing in environmental equipment and developing and specifying environmentally friendly products. Authors such as Buysse and Verbeke (2003); Cabugueira (2004) suggest that environmental regulation may be a tool which helps organizations to implement sustainability in building projects. Opponents of regulation however argued that more building regulations means that houses are built uniformly and firms compete on price alone, leading to increased risk in the adoption of new innovation such as the use of new building materials (Tatum, 1987; Wubben, 1999; Dewick and Miozzo, 2002). Wubben (1999) suggest that Private firms will naturally oppose increased environmental regulation since the direct costs are clear whilst the potential future savings are unknown. However, Porter *et al.,(*1995); Dean and Brown (1995), observed that regulations are in place to protect the environment, to maintain minimum quality standards, to provide a level playing field for firms to compete and to provide a buffer for innovative firms until new technologies are proven and economies of learning reduce their costs.

It is interesting to note that there is no support on the effect of project stakeholder pressures on the adoption of SCPs therefore Hypothesis 3 is rejected. Both regression models used in this study have provided consistent evidence that firms with larger size are statistically more likely to implement SCPs. In Table 6.14, it is appreciated that when the firm size changes from small size to medium size, the difference in the log of SCPs number is expected to change by 0.3782466 in Poisson Regression Model (PRM) and by 0.37887061 in Zero-Inflated Poisson Regression Model (ZIP). Similar results are obtained when changing from medium size firms to lager size firms. On one hand, this can be explained as large companies have more resource availability to devote to environmental management (Sharma, 2000; Gonzalez-Benito, 2006), small firms may have more difficulties to adopt environmental friendly practices, because of lack of resources to do it (Barney, 1991); on the other hand, large contractors receive more pressure from their social and economic environment and frequently these are the primary target of local governments and Environmental NGOs on forcing to adopt sustainability practices (Zeng *et al.,* 2007; Li *et al.,* 2010).

Based on the findings from the above analysis, the following discussions can be elaborated: First, construction firms aiming to improve their environmental performance by the adoption of SCPs need to have designers who have knowledge and concern about environmental issues. Second, there is need to for a decision making method that can help designers in incorporating and implementing sustainability in the building design and construction process.

Having discussed and investigated the environmental awareness of architects and designers and the driving factors influencing sustainability practices, the next section investigate decision making involved in the application of the concept to building material assessment and selection.

6.6 Decision making in material selection practices

The choice of building material has been described as an important design variable that can significantly affect the performance of the building (Nassar *et al,* 2003). Architects and Designers therefore have a decisive role to play in helping to implement sustainability in building project focussing on material selection. In order to maximise their influence, they need to understand the issues, constraints and opportunities related to sustainability application and the practical means by which improvements can be achieved.

6.6.1. Influence of stakeholders in material selection

The building process includes all processes that lead to, or are conditions for, a finished building. The material selection procedure is a part of the building process, but also includes stakeholders that are not traditionally regarded as a part of the process. In parallel with the growing trend in society towards greater participation in decision making there has been a trend towards a wider view of people with an interest or 'stake' in organizations – the stakeholders (Mitroff, 1983; Freeman, 1984; Harrison and Caron, 1998). Surprisingly little is reported on the pragmatic influence of project stakeholders on selection of materials for building project. A review of the literature revealed stakeholders involved in influencing material selection. Respondents were thus asked to rank the level of involvement of relevant stakeholders on a five-point scale from "very low" (1) to "very high" (5), as it affect their material selection. Table 6.15 gives a summary of the result of respondents. Test statistics was applied to these rankings in order to test the significance of these findings. The (W) value obtained was 0.328, which was significant at 95% confidence level. There is thus significant degree of agreement between architects and designers as to the ranking of stakeholders influence.

Table 6.15 Stakeholders influence in material selection

Stakeholder influence	Architects		Designers		Overall	
	RI	Rank	RI	Rank	RI	Rank
Client	0.75	1	0.76	1	0.76	1
Technical consultants	0.65	2	0.67	2	0.66	2
Quantity surveyors	0.58	3	0.60	3	0.59	3
Site Managers	0.57	4	0.57	4	0.57	4
Contractors	0.58	3	0.52	5	0.55	5
Project Managers	0.41	7	0.52	5	0.52	6
Product manufactures	0.47	5	0.41	6	0.44	7
Product suppliers	0.46	6	0.40	7	0.40	8
Test statistics						
Kendall's W=0.328						
x^2 *critical*(=0.05)=14.07; *df=7;* x^2 *sample=792.5*						

Source: analysis of surveyed data, 2010

As expected, client has the highest degree of involvement, followed by technical consultant, quantity surveyor, site manager, contractor, project manager, product manufacturers and suppliers in that order. The client involvement is understandable as the client is legally responsible for the project, and carries the initial risk for the costs of the project. The importance of the client can further be reflected by the various ways they influence the adoption of innovation strategy (Chinyio, 1998c; Shen and Tam, 2002; Ling *et al.,* 2007). The client is vital for whether or not environmental goals are included in the project and exerts pressure on project participants to improve buildings' lifecycle performance (Gann and Salter, 2000). Further, the client is responsible for setting priorities and evaluating the actions throughout the production process. Some clients have a clear idea of a program, budget, and other project objectives, including the final appearance of the building. Others look to their architect to help them define the project objectives and to design a building that meets those objectives. In both cases the effectiveness of the relationship between client and architect is a major factor in making and implementing design decisions throughout the project. This demonstrates the important role of clients in influencing designer's environmental strategies.

6.6.2 Source of material information and advice

Paramount in making informed decisions about sustainability issues related to material is the manner in which information is collected, formatted and structured. Architects and designers need information about different kind of building materials, so as to be able to evaluate and select building materials during the design process. According to van Kesteren (2008), selecting materials can be considered as a problem solving activity in part because many new products of different qualities are entering into the market at an increasing pace. This increases the workload and responsibilities of the specifiers who have to evaluate and select the building materials needed. Problem solving demands a large and constant flow of information (Pahl and Beitz, 1996; van Kesteren 2008). The issue of accessing up-to-date information through different steps of the construction process, what the sources are and how they are obtained is one of the most discussed topics in the Architecture community at the moment (Tas *et al.,* 2008). To select materials, information is needed about these materials; what are their properties and performances? What is their price? More importantly, do these materials provide what designers are looking for, on environmental, technical and aesthetic aspects? With appropriate information, architects and designers can compare materials candidates within the project requirements.

To investigate the source of information used in evaluating and selecting building materials, respondents were asked to rank the extent of use of information source as identified from the literature using the 5-point scale from "low"(=1) to "high"(=5). A summary of the result is presented in table 6.10. The degree of agreement (W) between the groups in ranking was computed as 0.497 which was significant at 95% confidence level. There was thus significant degree of agreement between architects and designers on the source of information used in evaluating building materials.

Using the Relative index analysis, the overall ranking in descending order (see table 6.16) is web based (RI 0.94); Catalogue/Brochures (RI 0.79); Colleagues (RI 0.75); Trade Journal/Magazines (RI 0.71) Exhibitions and fairs (RI 0.68) and lastly trade representatives (RI 0.67).

Table 6.16 Source of material information

Information source	Architects		Designers		Overall	
	RI	Rank	RI	Rank	RI	Rank
Web based	0.93	1	0.95	1	0.94	1
Catalogue/Brochures	0.77	2	0.80	2	0.79	2
Colleague	0.73	3	0.77	3	0.75	3
Trade journal /Magazines	0.70	5	0.71	4	0.71	4
Exhibitions and fairs	0.71	4	0.64	6	0.68	5
Trade representatives	0.64	6	0.69	5	0.67	6
Test statistics						
Kendall's W=0.497						
x^2 *critical*=(0.05)=11.07; *df=5*; x^2 *sample=773.5*						

Source: analysis of surveyed data, 2010

According to Tas *et al* (2008), the building material information exists generally in paper form (e.g. brochures and catalogues) rated second by respondents, but paper-based information becomes quickly obsolete if their updates do not keep pace with the speed with which new building materials appear on the market. The paper-based information is quickly being replaced by the information that serves the users by taking advantage of online web-based tools (such as Greenspec, Sweets Construction etc), which was rated first by respondents. Since the quality and reliability of the information are as important as its accessibility, the key factor for the construction sector, it should be accessed easily and timely of which web based source offer.

6.6.3 Obstacles in the use of sustainable material

Constraints are a reflection of the real world in which building professionals operates. They usually have a major effect on design decisions and, consequently, a clear understanding of these constraints will assist architects and designers in producing a better architectural design (Williams and Dair, 2007). An attempt was made therefore to identify obstacles perceived by the architects and designers as they sought to apply sustainable design, especially in their selection of materials. Using the 5-point likert scale from "low" (=1) to "high" (=5), respondents were asked to rank the obstacles that affect their sustainable practices in building material selection. A summary of the result is presented in table 6.10. The degree of agreement (W) between the groups in ranking was computed as 0.222 which was significant at 95% confidence level. There was thus significant degree of agreement between architects and designers on the perceived obstacles.

The results are presented in Table 6.17. The biggest concern in specifying sustainable material is the perception that sustainable material cost more, with relative index of 0.77 for both set of respondents. This was closely followed by lack of adequate information (RI 0.74); lack of comprehensive method and data to compare material alternative (RI 0.72); perception of extra time been incurred (0.71) and Maintenance concern (RI 0.70) making the top five. Summary discussions of the top five obstacles are discussed below.

Table 6.17 Perceived obstacles in sustainable material selection

Obstacles	Architects		Designers		Overall	
	RI	Rank	RI	Rank	RI	Rank
Lack of sustainable material information	0.72	2	0.76	2	0.74	2
Uncertainty in liability of final work	0.66	7	0.63	8	0.65	8
Maintenance concern	0.71	3	0.70	6	0.70	5
Building code restriction	0.64	6	0.59	11	0.62	9
Lack of comprehensive tools and data to compare material alternatives	0.69	5	0.75	3	0.72	3
Perception of extra cost being incurred	0.75	1	0.78	1	0.77	1
Perception of extra time being incurred	0.70	4	0.71	5	0.71	4
Perception that sustainable materials are low in quality	0.47	11	0.62	9	0.55	11
Aesthetically less pleasing	0.47	11	0.53	13	0.50	12
Possible project delay due to sustainability requirement	0.54	9	0.61	10	0.58	10
Limited availability of supplier	0.68	6	0.71	5	0.69	6
Low flexibility of alternatives or substitutes	0.68	6	0.64	7	0.66	7
Unwilling to change the conventional way of specifying	0.53	10	0.57	12	0.55	11
Test statistics						
Kendall's W=0.222						
x^2 *critical*=(0.05)=14.07; *df=7*; x^2 *sample=781.6*						

Source: analysis of surveyed data, 2010

Perception of extra cost been incurred

This was rated first by both architects and designers. Infact, cost figured prominently as a barrier to achieving sustainability in most literatures (Meryman and Silman, 2004; Kunzlik, 2003; Ofori and Kien, 2004; Williams and Dair, 2007). In most cases, there is a limit to the funds available for a building project. Once defined, this limit has a major influence on subsequent design decision such as material selection. Williams and Dair (2006) in a survey of designers involved in a development schemes in England observed that in many instances, although cost differentials had not been thoroughly investigated, designers were certain that anything other than 'business as usual' would be more expensive. Speculative designers are quick to point out that the cost of providing sustainable buildings is significantly higher than for standard schemes and most were not convinced there is a widespread demand for such buildings. However, The Construction Industry

Environmental Forum (CIEF, 2005) suspected that practice still finds it problematic to know how much more it will cost to build in a sustainable manner. The research study of BRE and Cyril Sweett (2005) asserted that it would cost somewhere between 1 and 3 per cent extra to achieve a rating of "very good" on the EcoHomes system for a sustainable house. A similar study by Davis Langdon, a leading international cost consultancy, showed that some measures of sustainability had a zero cost premium (CIEF, 2005). Upon analysis it was found that the assessment for these studies focused heavily on environmental issues rather than the broader social and economic aspects of sustainable construction. However, there is a lack of agreement on the anticipated costs of sustainability features in a building project as for instance the Royal Institute of British Architects (RIBA, 2005) found that sustainable construction features can have only minimal cost implications.

Lack of access to sustainable material information

The identification of lack of information as one of the biggest obstacle to specifying sustainable products and materials for both architects and designer respondents is notable in light of the current proliferation of documentary resources relating to selection of sustainable materials. Architects and designers have a duty to stay up to date with current regulations and codes, current building practices and development in materials both new materials innovation and existing ones. In practice, it presents a series of challenges, as building practitioners try to stay up to date with material information from a variety of sources (see section 6.6.2). Respondents have difficulty identifying what sustainable materials are available, and from what sources; Technical product-material information; and the environmental credentials of sustainable materials. Lack of access to information is a reflection of the real world in which architects operates. They usually have a major effect on design decisions. In some cases, they lacked the information they needed to make choices about which material options would be more or less sustainable. In other cases they were unaware of sustainable options or lacked expertise to implement them. Where designers lacked information, they usually opted for a 'safe' solution (Williams and Dair, 2006). In situation were information on sustainable material is not available, designers do carry on with conventional materials they are familiar with. Without readily available information, respondents reported that many sustainability objectives simply fell by the wayside. This barrier suggests there is clearly need for more information to push the use of sustainable materials forward.

Lack of comprehensive tool and data to compare material alternatives

The consideration of building material issues when material choices are being made identified the extent of required environmental impact attributes. There are already a number of tools for evaluating the environmental profile of building materials (see chapter 4). As noted by Alwaer *et al.* (2008), many existing evaluating methods and selection models are perceived to be either lacking in comprehensiveness or difficult to manipulate. Evaluation of the methodology of the tools exposed lack of comprehensive requirements in terms of criteria and indicators relating to building materials. The lack of inclusion of criteria reflecting sustainability advantages or disadvantages of different building material options means designers have little reason for choosing a material over another. Also, some researchers criticise the existing evaluation methods for being fraught with problems of fairness and being partially subjective, because some important elements did not receive sufficient emphasis and less important elements are ignored (Weaver and Rotmans, 2006). Consequently, difficulty arises on how best to apply them.

Perception of extra time been incurred

Another design constraint is time. Good design, in all of its creative aspects, take time- and sufficient time is not always available to satisfy the inner needs of the architect. Chan and Kumaraswamy (2002) stated that time serves as a benchmark for the performance (including cost) of building project. Regardless of building type, size and complexity of the design, each project will have some form of time constraint imposed on it. Usually, the client requires a completed building for a particular date, a date that will influence the amount of time allocated to different phases of the project. This imposes time constraints that have to be accommodated into overall programming of resources, thus limiting the amount of time available for producing the requisite information. Adequate time is required to consider appropriate products and set performance standards, co-ordinate information provided by others, write specification and check the project documentation for constituency and errors. Time constraints also influence the uptake sustainable material as demonstrated by Mackinder (1980 cited in Emmitt and Yeomans, 2008). When a project had to be completed quickly, there was an increasing tendency to stick to materials used on previous projects, thus eliminating the time needed to search for sustainable alternatives.

Maintenance concern

Maintenance was ranked third and sixth by architects and designers respectively and ranked fifth overall as a barrier for sustainable material uptake. It was clear from the research that there is perception of ambiguity surrounding the long term maintenance of sustainable material. A similar study reported by Joseph and

Tretsiakova-McNally (2010), found that extensive maintenance involved in the use of sustainable material still persist in the mind of building stakeholders. This is not entirely a surprise given that maintenance free buildings are increasingly sought by clients, anxious to minimise the running costs associated with buildings. It is clear that maintenance has a considerable impact on the performance of a building and that maintenance related problems that occur during the lifetime of a building can be minimized by using materials that require less maintenance and have lower replacement costs over the life of the building.

6.6.4 Material assessment techniques used by building professionals

Part of the survey also included questions to explore the techniques that building professionals use when assessing building materials for building projects. Using Relative index analysis techniques, respondents were thus asked to rank the rate at which they use the techniques on a five-point scale from "very low" (=1) to "very high" (5). A summary of the result is presented in table 6.18. The degree of agreement (W) between the groups in ranking was computed as 0.433 which was significant at 95% confidence level. There was thus significant degree of agreement between architects and designers on the rate of use of the tools in evaluating and assessing building materials.

Table 6.18 Tools used by building professionals

Type of tools	Architects		Designers		Overall	
	RI	Rank	RI	Rank	RI	Rank
Multi-criteria analysis	0.35	3	0.29	3	0.32	3
Building for Environment and economic sustainability (BEES)	0.36	2	0.33	2	0.35	2
BRE environmental assessment methods (BREEAM)	0.68	1	0.65	1	0.67	1
ATHENA impact estimator for buildings	0.24	7	0.25	6	0.25	7
Environmental Preference Method (EPM	0.25	7	0.23	7	0.24	8
Building Environment assessment tool (BEAT 2001)	0.28	6	0.23	7	0.26	6
Leadership in energy and and environmental design (LEED)	0.34	4	0.26	5	0.30	4
Building environmental performance assessment criteria (BEPAC)	0.29	5	0.28	4	0.29	5
Test statistics						
Kendall's W=0.433 x^2 *critical*=(0.05)=14.07; *df*=7; x^2 *sample*=774.2						

Source: analysis of surveyed data, 2010

The result indicates that architects and designers mostly use BRE environmental assessment methods (BREEAM) and Building for Environment and economic sustainability (BEES) as a decision making tool, followed by Multi-criteria analysis. BREEAM and BEES are techniques that have been widely used in the construction industry and are designed to help construction professionals understand and mitigate the environmental impact of development they design and build. However, they are not useful for evaluating the tradeoffs (environmental, social-economic, technical & resource consumption) between material alternatives within the context of a specific project.

The survey responses show that there are only a few participants who have heard about multiple criteria analysis (MCA), as this method is mainly used for urban planning, infrastructure and environmental assessments but is seldom used to help decision making in construction (Voogd, 1983; Nijkamp *et al;* 1990; Janssen, 1992). Most material assessment techniques focus on single criterion such as energy usage, but MCA allows multiple criteria to be considered and combined to aid decision making. This powerful method is widely used in other areas for decision making e.g. environmental management and urban planning (Voogd, 1983; Nijkamp *et al;* 1990; van Pelt, 1993; Triantaphyllou, 2000). This approach again provides the methodological framework for the development of the sustainability index.

6.6.4.1 Perceived obstacles to usage

From table 6.19, it is obvious that the usage of material assessment techniques (MAT) is low among respondents judging by the low rating given to them. Some commentators have sought to explain the relatively low use of some MATs by pointing out perceived obstacles to their successful usage. To investigate the validity of these commentaries respondents were asked to score the perceived obstacles on the frequency with which they are encountered in practice on a 5-point Likert scale (where "1= not frequent" to "5 =very frequent"). Respondents were also asked to add and rate any other relevant obstacles not included in the listed. Table 6.14 shows the rankings of the obstacles obtained from analysis of the results. As indicated by the test statistics, the degree of agreement among the respondents in their ranking was strong and significant.

Table 6.19 obstacle to usage of material assessment techniques

Obstacles to usage	Architects		Designers		Overall	
	RI	Rank	RI	Rank	RI	Rank
Lack of familiarity with the tools	0.80	1	0.74	1	0.77	1
High cost involved in its use	0.71	5	0.72	2	0.72	4
High time consumption in its use	0.72	4	0.67	4	0.70	5
Lack of skill in using the tools	0.76	2	0.71	3	0.74	2
Lack of clear and simple assessment method(Complexiity)	0.73	3	0.74	1	0.73	3
Poorly updated programmes	0.61	7	0.61	5	0.61	7
Lack of adequate project information	0.64	6	0.60	6	0.62	6
Test statistics						
Kendall's W=0.089						
x^2 *critical*=(0.05)=14.07; *df=7*; x^2 *sample=613.4*						

Source: analysis of surveyed data, 2010

Lack of familiarity with existing tool; Lack of skill in using the tools and complexity of MATs were the top 3 obstacles given by respondents. This is supported by Pediaditi *et al* (2010) who observe that tool developers commented that they had to spend a lot of non-accounted time explaining the methodology of tools and the meaning of results to building designers when demonstrating their systems. This indicates the need for clarity, simplicity in developing building material assessment method.

6.7 Development of sustainable material selection criteria

One of the main objectives of the research was to develop a holistic sustainable assessment criteria (SAC) set to assist design team members in particular architects and designers in the selection of sustainable building materials for building project during early project stages. As a result, the likelihood of sustainable construction is enhanced, both to meet society's environmental goals and account for the social and economic impacts of building project.

6.7.1 Criteria development

A wide scope review of literature revealed that there was no comprehensive list of assessment criteria developed specifically for material selection in building projects. In trying to develop a set of criteria, Foxon *et al.* (2002) proposed the consideration of two key factors. What use will be made of this set of criteria? To what extent can any set of criteria encompass the range of issues to be considered under the heading of 'sustainability'? Some of these issues have been considered in approaches developed by other researchers. The following set of guidelines has been developed to aid the choice of criteria to assess the options under consideration:

(1) Comprehensiveness

The criteria chosen should cover the four categories of economic, environmental, social and technical, in order to ensure that account is being taken of progress towards sustainability objectives. As noted in chapter 2, the UK government interprets sustainable development as meeting social, economic and environmental objectives at the same time. The criteria chosen need to have the ability to demonstrate movement towards or away from sustainability, according to these objectives.

(2) Applicability

The criteria chosen should be applicable across the range of options under consideration. This is needed to ensure the comparability of the options.

(3) Transparency

The criteria should be chosen in a transparent way, so as to help stakeholders to identify which criteria are being considered, to understand the criteria used and to propose any other criteria for consideration.

(4) Practicability

The set of criteria chosen must form a practicable set for the purposes of the decision to be assessed, the tools to be used and the time and resources available for analysis and assessment. Clearly, the choice of sustainability criteria will influence the outcome of the decision being made, as will the method of comparison or aggregation chosen. The above factors provide initial guidance in the choice of criteria. Combined with sustainable concerns and requirements of project Stakeholders, such as clients, a list of assessment criteria (see table 6.18) were developed. These criteria are identified under three categories:

- Environmental;
- Technical; and

- Socio-economic.

These categories aim to encapsulate the economic, environmental and social principles of sustainability, together with technical criteria, which relate primarily to the ability of buildings and its component system to sustain and enhance the performance of the functions for which it is designed. For any decision process, the selected criteria must be broadly applicable to *all* of the options if comparative evaluation is to be achieved.

Based on the derived criteria, an industry questionnaire survey was designed which aims at investigating the perspective of architects and designers on the importance of the criteria for material selection. Respondents were thus asked to rate the level of importance of the derived criteria based on a scale of 1–5, where 1 is 'least important', 2 'fairly important', 3 'important', 4 'very important', and 5 'extremely important'. To ensure a better understanding of the criteria, definition of each criterion was clarified and guidance on completion was given in the questionnaire. At the same time, respondents were encouraged to provide supplementary criteria that they consider to influence building material selection but were not listed in the provided questionnaire (refer to Appendix A for questionnaire details).

6.7.2 Criteria importance rating

To ensure that the rating scale (1–5) for measuring the criteria yields the same result over time, a reliability analysis using the internal consistency method was first examined. Cronbach's alpha was calculated to test the internal consistency reliability of the generated scale. The alpha reliability coefficient normally ranges between 0 and 1. The closer alpha is to 1 the greater the internal consistency reliability of the criteria in the scale. Cronbach's alpha values for economic criteria, social criteria, environmental criteria, and all criteria are 0.834, 0.836, 0.941, and 0.939, respectively. All alpha values are greater than 0.7, indicating that all reliability coefficients are acceptable and the internal consistency of the criteria included in the scale is excellent.

In order to identify the relative importance of SACs based on the survey data, ranking analysis was performed. It must be noted that the ratings in the scale indicate only a rank order of importance of the criteria, rather than how much more important each rating is than the other. Relative index analysis (see section 6.2) was used to rank the criteria according to their relative importance.

Five important levels are transformed from Relative Index values: High (H) ($0.8 \le RI \le 1$), High–Medium (H–M) ($0.6 \le RI < 0.8$), Medium (M) ($0.4 \le RI < 0.6$), Medium–Low (M–L) ($0.2 \le RI < 0.4$), and Low (L) ($0 \le RI < 0.2$).

Recognizing that the derived SACs are likely inter-related through an underlying structure of primary factors, and to obtain a concise list of SACs under these circumstances, a factor analysis was also utilized. Factor analysis is an effective statistical method used to describe variability among observed variables in terms of fewer unobserved variables (latent variables) called factors. In other words, it reduces variables with similar characteristics together into a smaller set of uncorrelated dimensions or factors, which are capable of explaining the observed variance in the larger number of variables (Chen *et al;* 2010).

Kaiser–Meyer–Olkin (KMO) measure and Bartlett's Test of Sphericity were conducted to examine the sampling adequacy, ensuring that factor analysis was going to be appropriate. The principal component analysis was chosen to extract the latent factors based on the criterion that the associated eigenvalue should be greater than 1. To interpret the relationship between the observed variables and the latent factors more easily, the most commonly used rotation method, varimax rotation, was selected.

Overall, as shown in Table 6.20, a total of 24 SPCs were selected for building material assessment, with 7 SPCs in socio-economic criteria, 6 SPCs in technical category, and 11 SPCs in environmental criteria, respectively. To better understand the criteria, definition of each criterion was provided in the questionnaire. These can be used as the basis to assess the building material option to know if moving towards or away from sustainability.

Table 6.21 show the ranking results for each criteria category (e.g., environmental) by using the relative index analysis in Eq.(1) (see section 6.2). Based on these ranking results, twelve criteria were highlighted to have "High" importance levels in evaluating building material with an RI value between 0.808 and 0.898. These twelve criteria are "Environmental statutory compliance (E7)", "minimize pollution (E8)", "aesthetics (S4)", "ease of construction (S3)", "health and safety (S2)", "material availability(S6)", "first cost(S1)", "maintainability(T1)", "energy saving(T6)", "life expectancy(T5)", "fire resistance(T4)", and "resistance to decay(T3)".

Table 6.20 Sustainable criteria for building material selection

	Environmental criteria	Social –economic criteria	Technical criteria
Focus of architects & designers	E1:Potential for recycling and reuse E2:Availability of environmentally sound disposal options E3:Impact of material on air quality E4:Ozone depletion potential E5:Environmental Impact during material harvest E6: Zero or low toxicity E7: Environmental statutory compliance E8: Minimise pollution (e.g. air, land) E9:Amount of likely wastage in use of material E10: Method of raw material extraction E11:Embodied energy within material	S1: disposal cost S2:Health and safety S3: Maintenance cost S4: Aesthetics S5: Use of local material S6: Initial (acquisition cost) S7: Labour availability	T1: Maintainability T2: Ease of construction (buildability) T3:Resistance to decay T4: Fire resistance T5:Life expectancy of material (e.g. strength, durability etc) T6: Energy saving and thermal insulation

Table 6.21: Rank of sustainable criteria for building material selection

Sustainable performance criteria	Valid percentage of score of (%)					Relative index	Ranking by category	Overall ranking	Importance level
	1	2	3	4	5				
Environmental criteria									
E7: Environmental statutory compliance	4.4	1.1	13.2	29.7	51.6	0.846	1	7	H
E8: Minimize pollution	1.1	1.1	18.0	46.1	33.7	0.820	2	10	H
E6: Zero/low toxicity	3.3	2.2	22.2	38.9	33.3	0.793	3	13	M-H
E4: Ozone depletion potential	3.3	8.8	19.8	39.6	28.6	0.763	4	15	M-H
E1: Recyclable/reusable material	1.1	7.7	29.7	38.5	23.1	0.749	5	17	M-H
E9: Amount of likely wastage in use	3.3	7.7	29.7	39.6	19.8	0.729	6	18	M-H
E11: Embodied energy in material	1.1	9.9	28.6	47.3	13.2	0.723	7	19	M-H
E2: Environmental sound disposal options	1.1	10.1	36.0	34.8	18.0	0.717	8	20	M-H
E3: Impact on air quality	4.4	8.8	35.2	39.6	12.1	0.692	9	21	M-H
E5: Impact during harvest	4.4	15.4	31.9	37.4	11.0	0.670	10	22	M-H
E10: Methods of extraction of raw materials	5.5	19.8	45.1	20.9	8.8	0.615	11	24	M-H
Technical criteria									
T1: Maintainability	0.0	0.0	3.3	47.3	49.5	0.892	1	2	H
T6: Energy saving and thermal insulation	0.0	0.0	3.2	50.4	46.2	0.886	2	3	H
T5: Life expectancy (e.g. durability)	0.0	0.0	4.4	50.5	45.1	0.881	3	4	H
T4: Fire resistance	0.0	0.0	13.2	44.0	42.9	0.859	4	5	H
T3: Ease of construction/buildability	0.0	0.0	9.9	53.8	36.3	0.853	5	6	H
T2: Resistance to decay	1.1	1.1	28.6	48.4	20.9	0.774	6	14	M-H
Socio-economic criteria									
S4: Aesthetics	0.0	0.0	10.1	30.3	59.6	0.898	1	1	H
S3: Maintenance cost	0.0	0.0	12.1	56.0	31.9	0.839	2	8	H
S2: Health and safety	1.1	3.4	15.9	40.9	38.6	0.825	3	9	H
S6: First cost	0.0	5.5	14.3	49.5	30.8	0.810	4	11	H
S1: disposal cost	1.1	0.0	22.0	47.3	29.7	0.808	5	12	H
S5: Use of local materials	3.3	5.5	23.1	48.4	19.8	0.752	6	16	M-H
S7: Labour availability	5.5	16.5	39.6	29.7	8.8	0.639	7	23	M-H

Source: analysis of surveyed data, 2010

“Aesthetics” was ranked as the first priority in the socio-economic category with an RI value of 0.898, and it was also the highest among all criteria and was highlighted at “High” importance level; “Maintainability” which was a concern among architect and designers in section 6.6.4 was also rated high in importance among the selection criteria. It was clear from the research that there is a perception of ambiguity surrounding the long term maintenance of sustainable material. This is not entirely a surprise given that maintenance free buildings are increasingly sought by clients, anxious to minimise the running costs associated with buildings. “First cost” have been, and will continue to be, major concerns for building designers, as well as important traditional performance measures; “ease of construction”, the extent of the facility of construction, basically, has close relationships with time, cost, and quality performance. Among the top twelve criteria, it is observed that only two criteria from the environmental category out of 11 listed are rated high among the selection criteria. This again suggests that environmental issues are not strongly considered despite the high environmental awareness claimed by the respondents.

According to Table 6.21, a total of 12 criteria, consisting of 9 environmental criteria, 1 technical criteria, and 2 socio-economic criteria, were recorded to have “High–Medium” importance levels. Although these 12 criteria were in the same importance level category, the socio-economic criteria (average RI=0.695) were considered to be less important compared to the technical criteria (average RI=0.774) and environmental criteria (average RI=0.716). However, it should be noted that environmental criteria account for 39.2% in this importance level. The result is an example of evidence pointing to the trend that environmental aspects are no longer the least important factors for material selection in building project.

Some criteria in the three categories were ranked relatively higher in the "High–Medium" level. For example, "zero/low toxicity (E6)" was rated as third in the environmental subcategory, and ranked as first in the 12 criteria with an RI value of 0.793. Material toxicity issues are of paramount importance to all project participants. Volatile organic compounds (VOCs) and other hazardous chemicals are contained in many construction materials. Products with high levels of VOC's pose a health risk to the occupant and construction workers alike. Using low VOC materials for new construction and remodeling projects can significantly reduce the emission volatile organic compounds and has been acknowledged by the industry as a crucial component to any successful project. It has also been hailed as an important step in sustainable construction.

From the results in Table 6.21, an interesting observation is that none of the criteria fall under the medium and other lower importance level. This clearly shows how important the sustainability criteria are to building designers in evaluating building materials. All criteria were rated with "High" or "High–Medium" importance levels. Respondents asserted that the criteria with low RI did not mean they were not important for selecting materials, but rather they wanted to highlight the relative importance of criteria from their vantage point.

6.7.3 Factor analysis

Although the most significant criteria were identified using ranking analysis, some of them are likely to be inter-related with each other through an underlying structure of primary factors. In order to obtain a concise list of SPCs, a factor analysis was performed.

For the socio-economic criteria, the analysis results showed that the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was 0.606, larger than 0.5, suggesting that the sample was acceptable for factor analysis. The Bartlett Test of Sphericity was 96.100 and the associated significance level was 0.000, indicating that the population correlation matrix was not an identity matrix. Both of the tests showed that the obtained data in socio-economic category supported the use of factor analysis and these could be grouped into a smaller set of underlying factors. Using principal component analysis, the factor analysis extracted two latent factors with eigenvalues greater than 1.0 for the 7 socio-economic criteria, explaining 53.7% of the variance. The rotated factor loading matrix based on the varimax rotation for the two latent factors is shown in Table 6.22.

Table 6.22 Factor loadings for socio-economic criteria after varimax rotation

Observed socio-economic variable	Latent socio-economic factors	
	Life cycle cost	Social benefit
S3: Maintenance cost	0.757	
S6: First cost	0.693	
S1: Disposal cost	0.576	
S4: Aesthetics		0.830
S5: Use of local material		0.759
S2:Health and safety		0.579
S7: Labour availability		0.556
Eigenvalues	1.556	2.205
Percentage of variance (%)	22.234	31.502
Cumulative of variance (%)	22.234	53.736

Source: analysis of surveyed data, 2010

The component matrix identifies the relationship between the observed variables and the latent factors. The relationships are referred to as factor loadings. The higher the absolute value of the loading, the more the latent factor contributes to the observed variable. Small factor loadings with absolute values less than 0.5 were suppressed to help simplify Table 6.22. For further interpretation, the two latent factors under the socio-economic category (shown in Table 6.22) are given names as: Factor 1: life cycle cost; and Factor 2: socio benefit. Similar factor analyses were performed to identify the underlying structures for technical and environmental categories. For Environmental category, both the KMO measure of sampling adequacy test (0.801) and Bartlett's sphericity (p=0.000) were significant, which indicated that factor analysis was also appropriate. Three factors under environmental category were extracted from the factor analysis, namely, Factor 3: environmental impact; Factor 4: Resource efficiency; and Factor 5: waste minimization. Along with rotated factor-loading matrix, the percentage of variance attributable to each factor and the cumulative variance values are shown in Table 6.23. From the table, it can be seen that the three factors accounted for 71.3% of the total variance of the eleven environmental criteria.

Table 6.23 Factor loadings for environmental criteria after varimax rotation

Observed environmental variable	Latent environmental factors		
	Environmental impact	Resource efficiency	Waste minimization
E7: Environmental statutory compliance	0.882		
E6: Zero or low toxicity	0.824		
E4:Ozone depletion potential	0.719		
E8: Minimise pollution (e.g.water, land)	0.586		
E3:Impact of material on air quality	0.557		
E10: Method of raw material extraction		0.893	
E9:Amount of likely wastage in use of material		0.773	
E11:Embodied energy within material		0.588	
E5:Environmental Impact during material harvest		0.546	
E2:Availability of environmentally sound disposal options			0.912
E1:Potential for recycling and reuse			0.871
Eigenvalues	5.505	1.216	1.116
Percentage of variance (%)	50.048	11.057	10.149
Cumulative of variance (%)	50.048	61.105	71.254

Source: analysis of surveyed data, 2010

In the technical category, the results for the factor analysis showed that the KMO measure was 0.804 and the Bartlett's test (p=0.000) was also significant, which indicated that the factor analysis was also appropriate in identifying the underlying structure of the technical category. The results of the analysis are presented in

Table 6.24 Just one factor named Factor 6: performance benefit was extracted, explaining 50.3% of the total variance of the six technical criteria.

Table 6.24 Factor loadings for technical criteria after varimax rotation

Observed technical variable	Latent technical factors
	Performance capability
T4: Fire resistance	0.799
T3:Resistance to decay	0.740
T6: Energy saving and thermal insulation	0.724
T5:Life expectancy of material	0.712
T2: Ease of construction	0.658
T1: Maintainability	0.604
Eigenvalues	3.016
Percentage of variance (%)	50.264

Source: analysis of surveyed data, 2010

Overall, a total of five latent factors were extracted to present the underlying structure of the criteria used for selecting material for building project. Two factors were under environmental category, two factors belong to socio-economic category, and one factor for the Technical dimension. Descriptions of the six latent factors are presented in the next chapter (7).

6.8 Summary

This chapter has presented the results of a questionnaire survey of architects and designers aimed at ascertaining current practice in sustainable design and construction, especially in the selection of building materials; highlights drivers and obstacles of sustainable design implementation and determine principal sustainable development criteria for modelling decision making material selection. The survey questionnaires were distributed to 490 architects and designers across UK and received an overall response rate of 20.2%. The respondents were mostly from small to medium construction organizations with considerable experience in material selection.

Various statistical tests including frequencies, relative indices, Kendall's Concordance, Chi-square tests and factor analysis were used to analyse the survey data. There was a considerable corroboration between the study results and the findings of the literature review. A summary of the findings of the survey is as follows:

a. Gaps existing between the awareness and the implementation/application levels of sustainable construction practices, have led to failure of realizing the benefits of a sustainable approach to construction projects. The study confirmed previous findings that architects in UK claim to have a high level of awareness and knowledge of the adverse environmental impact of construction and how their design decisions contribute to this. However, the findings of the study showed a discrepancy between what architects claim to be convinced about, and knowledgeable in, and their commitment and practices; architects seem to be unable to translate their environmental awareness and knowledge into appropriate design decisions. For example, respondents ranked environment-related measures lowly among project objectives. Moreover, when selecting materials, they give low weightage to such environmental issues.
b. Architects and designers agreed that sustainability consideration should be included in building design and construction process. General opinions towards sustainable building material use were similar among group of respondents.
c. The influence of designers concerns, environmental regulations, and stakeholder pressures on the adoption of sustainable construction practices from the designers' perspective has been evidenced in this study. According

to the results analysis, it is found that designers concerns and regulatory pressures are the two most important driving forces for their adoption. However, it appears that project stakeholder pressures have not much significant effect on sustainable construction practices. The results highlight the importance of designer's personal value and belief for how they consider environmental issues.

d. The result reveals that the clients have the greatest involvement and influence in building design and material selection. The influence of clients defines the overall context within which materials selections are made, vital for whether or not environmental goals are implemented in a project thereby constituting a pragmatic 'starting point' for design decision making. The stakeholder with the lowest influence and involvement is the material/product suppliers.

e. Barriers to incorporating sustainable materials in design decisions became apparent through the survey. "Cost" was a reoccurring factor in designer's ability to implement sustainable construction. Respondents also acknowledged that their lack of detailed understanding of sustainable design concept and lack of sustainable material information makes it difficult to evaluate material alternative and to educate their clients.

f. The Research demonstrates the current UK emphasis on sustainable building material use and identified six dimensions of sustainable assessment criteria assisting building designers in selecting appropriate building material. The proposed criteria based on the sustainable triple bottom line include both "hard and soft" factors which may capture the potential assessment of building materials better, as opposed to the traditional measures of cost, time and quality. This will allow project teams to have an appropriate balance between economic, social, technical and environmental issues, changing the way construction practioners think about the information they use when selecting building materials for building project. Additionally, the list of criteria also appropriately captured the concerns of different stakeholders involved in material selection. Most importantly, the adoption of these criteria requires only a minimum of information, usually available in the early stages of conceptualization, and thus enables quick and easy data collection. This lays the ground work for the development of sustainability index based on the derived criteria to help improve the decision making process for appropriate material selection for building projects.

g. Given the international focus on sustainability in recent years, the research shows that there is a dire need for a simple and efficient method that would facilitate sustainability assessment in building process and decision making at the various project level interfaces as the research has shown that the current assessment tools are undermined by usage issues such as lack of familiarity, skill involved in their use and lack of clear and simple assessment method (complexity).

The main challenge now is how architects and designers can evaluate building material options by aggregating performance along various sustainability criteria. Such material evaluation and assessment would contribute to making better sustainability driven decisions at the project levels. The next chapter is designed to make a substantial contribution by addressing this identified research gap. It presents a methodology and computational processes (analytical models) that address the existing problem of designing for sustainability in building projects.

CHAPTER 7: DEVELOPING A SUSTAINABILITY INDEX FOR SELECTION OF BUILDING MATERIALS

7.1 Introduction

As discussed in the previous chapters, in order to protect the environment, sustainable development is essential for building design and construction. The principal sustainability criteria for material selection have been identified using a questionnaire to elicit the opinions of professionals in construction (details refer to Section 6.7). With reference to the survey analysis (in chapter 6), the participants' opinions are statistically significant as they represent the views of practising architects and designers with academic qualifications in building development, practical experience in construction work, and specialist knowledge in designing and constructing environmental projects. Therefore, their opinions have provided a broad spectrum of knowledge, experience and expertise in terms of economic, social, technical and environmental issues and will be valuable in developing a multiple criteria decision-making model for material selection. This will challenge the predominantly conventional economic view currently used in material selection.

The opinions obtained from the questionnaire allow the criteria requiring consideration in the sustainability index to be ranked. This chapter examines, in detail, the criteria to be incorporated in developing the sustainability index as a decision-making tool for material selection. The assessment approach and the benefits of using an index system in material selection will also be discussed. Finally, the conceptual framework of the sustainability index is presented and discussed. The framework of the sustainability index developed in this chapter lays down the foundation work for assessing the practical application of the index in chapter 8.

7.2 The derived material selection criteria

Following the results of the survey in chapter 6, the 24 criteria identified as being important components of material selection are analysed and ranked according to respondent's opinions as shown in Section 6.7. The 24 criteria were further compressed into six of assessment criteria factors of - environmental impact, resource efficiency, waste minimization, life cycle cost, performance capability and social benefit - for easy evaluation and are, therefore, the key areas to be assessed in the model. Consequently, the sustainability index includes the following criteria factors:

- environmental impact;
- resource efficiency;
- waste minimization;
- life cycle cost;
- performance capability and
- social benefit.

These six criteria factors are brought together in developing an index system to aid decision-making. The six criteria in the derived sustainability index are measured using MCA. Since these criteria are derived from the survey through expert opinion, they symbolise the sustainable criteria that promote socio-economic, technical and environmental consideration in building material assessment and selection. Consideration of these six criteria in material selection will ensure sustainable development in building design and construction.

7.3 Rationale of material selection criteria

Since the essential components of material selection have been identified, it is important to ensure that the decision-making model is not confined to evaluating a material cost implications and environmental impact, but is used to aid decision-making in selecting a sustainable material option from the alternatives. This section is devoted to discussing the nature of these criteria in order to establish the methodological framework for their assessment and the sustainability index.

Factor 1: Life cycle cost

The first assessment focuses on the "life cycle cost". Life cycle cost includes criteria such as initial cost (purchase cost), maintenance cost and disposal cost. Construction clients ask for high quality building with lower cost and shorter lead-time. Buildings represent a large and long-lasting investment in financial terms as well as in other resources (Oberg, 2005). Improvements of cost effectiveness of buildings is consequently of common interest for all stakeholders. With increasing pressure to provide environmentally responsible buildings, stakeholders are putting significant foci on the early identification of financial viability of building projects. Goh and Yang (2009) observe that traditionally, there has been an imbalance between sustainable measures and project budget. They observe that historically, decisions concerning the design and construction of building projects have been based largely on the first-cost mentality approach. On the other, environmental experts and technology innovators often push for the ultimately sustainable building without much of a concern for cost. This situation is being quickly changed as the industry is under pressure to continue to return profit, while better adapting to current and emerging global issues of sustainability (Goh and Yang, 2009).

The concept of sustainability as applied to the construction of buildings is intended to promote the utmost efficiency and to reduce financial costs (San-Jose Lombera and Garrucho Aprea, 2010). Sustainability has become one of the prime issues that the current construction industry needs to respond to. Although the sustainability concept is important to building development, the financial constraint is still one of the prime concerns to many building clients, when they contemplate sustainability initiatives in building projects (section 6.6.4) and because of the huge capital requirement for building construction. While minimizing cost is the main concern in building material selection, clients, architects and designers have realised that the selection of the lowest initial cost option may not guarantee the economical advantage over other options for a building project. In order to ensure that these objectives are achieved, the concept of life-cycle costing analysis (LCCA) will play significant roles in the economics of a building project. Life cycle cost analysis (LCCA) is an economic assessment approach that is able to predict the costs of a building from its operation, maintenance, and replacement until the end of its life-time.

According to List (2007), life-cycle cost analysis (LCCA) helps to ensure that these objectives are achieved. LCCA makes it possible for decision makers to evaluate competing initiatives and identify the most sustainable growth path for the common building project (Goh and Yang, 2009). A cost analysis study by Abraham and Dickson (1998) shows that the cost of operating a building can be quite significant and may often exceed the initial costs. Thus, decisions based solely on initial cost may not turn out to be the best selection in the long term and this method can be effectively utilized to realize the benefits of long-term cost implications of sustainable development in building project. Accordingly, consideration should not only be given to the economic requirement in the project design phase but also throughout the entire life-cycle of the building.

<u>Factor 2: performance capability</u>

Factor 2 is labeled "performance capability" and is associated with fire resistance, resistance to decay, energy saving and thermal insulation, life expectancy of material (durability), ease of construction and maintainability. One of the aspects of building design is to find trade-offs that satisfy a multitude of performance objectives. The performance concept provides a rational framework for building design and construction that is flexible and amenable for accommodating innovations and change (Becker, 1999). A large set of literature have made several attempt with measuring and assessing the performance of building systems with respect to different performance criteria like energy saving and thermal insulation, maintainability and so on (the literature here is extensive but a good review can be found in (Gero and Tyugu, 1994; Kalay, 1999; Nassar *et al.,* 1999 and 2003; Zhou *et al.,* 2009; Wang *et al.,* 2009).

When applied systematically throughout the building process, the performance concept is supposed to enable the design and execution of buildings that are highly suitable for the functions and activities of their occupants, provide thermally, acoustically and visually comfortable and healthy internal conditions while conserving energy and the environment, are pleasant and harmless from the tactile point of view, are sufficiently safe under regular and extreme loads that may occur during the life expectancy of the building, do not compose a fire hazard to their surroundings and are sufficiently safe when a fire starts within their spaces, are easy to evacuate upon emergency, do not leak and are not inflicted by moisture, condensation or mold, are free of cracks and frequent mechanical damage, do not have any of the symptoms of the sick building syndrome, are maintenance friendly and can easily be modified in order to cater for new demands (Becker, 1999). According to Wong and Li (2008), a building that fails to recognize the significance of performance criteria and systems interface may lead to system incompatibility, malfunctioning, and risk of obsolescence. If the building systems malfunction, it affects the business operations of occupants. The maintenance cost and the cost associated with a potential plunge in revenue arising from loss of tenants have an adverse effect on the financial viability of the building (Wong and Li, 2008; Clements-Croome, 2001). The failure to match occupants' and clients' expectations may eventually lead to disenchantment and a serious decline in interest and confidence in a building. Based on these problems, the analysis of performance requirements of building material options during the design stage is considered important.

All these qualities are expected to be realized during the service life of the building without excessively increasing its life-cycle cost. It seems, therefore, that it should be the long-term task of the architects and designers to provide the reliable means and tools for reaching this target by considering performance criteria in building design and material selection.

Factor 3: Resource efficiency

Variable loading on latent Factor 3 focus on Resource efficiency such as method of raw material extraction, environmental impact during harvest, amount of likely wastage in use of material and embodied energy. "Resource efficiency" means achieving more with less: 'resource efficiency is the process of doing more with less-using fewer resources (or less scarce resources) to accomplish the same goals (Wilson *et al.,* 1998). The concept has become a major issue in debates about sustainable development. Halliday (2008) observe that certain resources are becoming extremely rare and the use of remaining stocks should be treated cautiously. He called for the substitution of rare material with less rare or renewable materials.

Bold statements about the need for radical improvements in the use of materials and energy resources have achieved recognition in policy circles. The argument is that productivity improvement is necessary to minimize impacts on the capacity of natural systems to assimilate waste materials and energy (Halliday, 2008). According to Graham (2003), the construction industry is a major consumer of natural resources, and therefore many of the initiatives pursued in order to create ecology sustaining buildings are focusing on increasing the efficiency of resource use. He stated that the ways in which these efficiencies are sought are varied. He cited examples ranging from the principles of solar passive design which aim to reduce the consumption of non-renewable resources, the consumption of energy production, life cycle design and design for construction. Methods for minimizing material wastage during construction process and providing opportunities for recycling and reuse of building material also contribute to improving resource consumption efficiency. Calls to be resource efficient have been born from concern for increasing depletion of non-renewable natural resources.

Factor4: Environmental impact

The fourth factor is related to environmental impacts such as environmental statutory compliance, toxicity, ozone depletion potential, pollution and air quality. Since building materials have considerable impacts on the environment, it has become necessary to pay more attention to environmental issues in their selection and use. Environmental criteria are essential to guide design decisions and choices in this regard, and should complement overall environmental goals. Based on the environmental material criteria established for a building project, the selection of a sustainable building material can be accomplished. Cole (1998) observed that the range of environmental criteria that are relevant to building material is potentially enormous, and any attempt to generate design guidelines or undertake a comprehensive assessment must be preceded by a declaration and characterization of this range. Whereas it is relatively straightforward to simply list environmental criteria, organizing them into useful, related categories and prioritizing them for either design or assessment is far more problematic. The number, organization of criteria and rigour applied to the formulation in assessment methods are influenced by:

i. the practicality and cost of making an assessment - the greater the number of criteria, the greater the effort required to collect and analyse the results;
ii. the ability to make assessments repeatedly and reliably by trained assessors or through self-assessment. The credibility of an assessment method within the market-place is, in part, dependent on the consistency of the results, i.e. different assessors of the same building should produce essentially the same performance evaluation. Greater differences can be expected if the assessment methods includes a large number of qualitative criteria involving personal judgement on the part of the assessor; whether there is general agreement over the criteria, and therefore confidence, as to their significance. Although some aspects of building performance are widely accepted as critical environmental concerns and have clearly defined performance indicators, e.g. greenhouse gas emissions, others such as

embodied energy or design for deconstruction are less well understood at this time;

iii. the ability of users to fully comprehend to the results of the assessment. Clearly the comprehensiveness of an assessment is improved by increasing the number of assessment criteria which are included. However, the ability of building owners, users and the public to interpret the results of an assessment diminishes with each additional criterion.

Environmental criteria for building design must also, of course, be accommodated within a broad spectrum of other design issues and constraints. No environmental approach to building design can be successful that addresses any issue or principle exclusively and in isolation of other considerations. While improved building performance can occur more easily and readily in some areas than in others, it is the integration of all issues into comprehensive design strategies that will constitute the basis of successful environmental principles. A building and its impact on, and integration with, the external environment must be viewed as a total system and design must focus on the successful integration of criteria and strategies rather than instituting the assemblage of a series of discrete techniques for conserving or optimizing resource use (cole, 2005).

Factor 5: Waste minimization

Waste minimization criteria in this cluster include availability of environmentally sound disposal option and potential for recycling and reuse. Waste in the construction industry is important not only from the perspective of efficiency, but also concern has been growing in recent years about the adverse effect of the waste of building materials on the environment. Building materials waste is difficult to recycle due to high levels of contamination and a large degree of heterogeneity

(Bossink and Brouwers 1996), and often there is insufficient space for its disposal in large cities. In Scotland, the Scottish ecological design association stated that the landfill situation is now critical, with local authorities having to resort to transporting waste further and further afield or else burning it and releasing pollution into the air.

Wyatt (1978) stressed the consequences of high levels of waste, both in reducing the future availability of materials and energy and in creating unnecessary demands on the transportation system. In fact, some building materials and components use large amounts of non-renewable sources of energy, as well as resources that are in danger of depletion, such as timber, sand, and crushed stone (Osmani, 2008).

The construction industry has become increasingly aware of the importance of waste reduction in the construction process. In many respects, achieving sustainability is closely linked to the manner in which waste are dealt with. Visions of what constitutes an ecologically sustainable system for waste treatment have been suggested (Osmani, 2008). It is also apparent that the mass of waste products released to the atmosphere as 'molecular-waste' in the industrialised countries, greatly exceeds the amount of solid waste generated per capita. A study, made by the World Resource Institute of material flows in a number of industrialised countries, showed that one half to three quarters of the annual material input to these societies was returned to the environment as waste within a year (Hutter, 2000).

It is therefore important for the designer to align all parties to the design intent of waste minimization, in order to optimize the benefits. The designer's role is to turn requirements that may be explicit or implicit in the brief into effective full life cycle strategies and, at least in capital construction stages, quantifiable outcomes and reporting requirements (Khasreen *et al.,* 2009). Tiberg (1993) stated that Design for sustainability can close the waste loop in two ways; firstly by re-using existing construction elements where practical and secondly by encouraging the designed elements to be re-used easily and locally.

Osmani *et al* (2008) listed the benefits of waste minimisation for designers to include design finesse relating to a more informed relationship between good design and materials and products selection. It also improves the collaborative relationship between designers and suppliers, which, in turn, greens the supply chain and minimises local impacts and compliance costs. Improving the waste efficiency can generate economic benefits. In addition to potential economic benefit implementing waste reduction, avoidance and management strategies can generate cost savings, and can result in resource conservation, pollution and emissions prevention, reduced costs for waste disposal, and less time spent on dealing waste (Hylands, 2004; Osmani *et al.*, 2008).

Consideration of waste efficiency of building material not also reduces environmental impacts but also raises awareness and generates behaviour change across industry groups. This may include improving an individual's understanding of the waste implications of design decisions, not only related to their professional activities, but also to building material selection. For building owners, waste avoidance, reduction and management at the operational phase have long-term implications in terms of building maintenance and service life. Similarly, disposal of waste is a problem in the absence of any environmentally sound means.

Factor 6: Socio benefit

The sixth factor concern aesthetics, use of local materials, labour availability and health and safety. Social benefit is much more difficult to quantify and as such have not received much attention in the architecture literature (San-Jose *et al.,* 2007). The multifaceted dimensions of the sustainability concept are evident in the definition of Sustainable Development given by the "International Council for Local Environmental Initiatives" in 1994: "*Development that delivers basic social, economic and environmental services to all without threatening the viability of the natural, built and social systems upon which these services depend*". Thus, the social aspect may be included as a further component in sustainable environment, as it indirectly generates employment through building activity, and directly generates employment in those buildings that will eventually house a productive industrial process.

Use of local material is a further aspect, which due to increasing awareness of its ramifications is often thought to be synonymous with employment generation (Behm, 2005). Building aesthetics as stated by San-Jose and Garrucho (2010) is a further value to bear in mind, with a view to conserving the architectural asset that blends in with the built environment of the local area or promotes a company image. They went on to say that the aesthetic aspect should be an implicit part of the construction and should not be sacrificed for greater productive capacity. A company will often promote the construction of its buildings with a corporate image, which identifies it and gives it greater prestige and by doing so, it is emphasizing the aesthetical requirement as a sustainable aspect.

Further factor to consider is health and safety which is of great importance to the final cost of the building. Health and safety are defined as the degree to which the general conditions promote the completion of a project without major accidents of injuries (Bubshait and Almohawis 1994). Research and practice (Behm, 2005; Frijters and Swuste, 2008; Ikpe, 2009) have demonstrated the benefit of health and safety consideration in building design to include reduced insurance premiums of constructors form injuries and accidents, which translate into lower costs to the project. Therefore, design professionals (i.e. architects and designers) are in a position for decision-making and influencing to help improve construction safety, by addressing safety during material selection, hazards will be eliminated or reduced during construction, thus improving the safety performance of the constructor (Behm, 2005).

The sustainability requirements envisaged in a building are to a greater or lesser extent interrelated. The challenge for new sustainable studies is to bring together these different sustainability requirements in innovative ways. These sustainability requirements will be applicable throughout the different stages of the building life cycle, from its design, during its useful life, up until management of the building waste in the demolition stage.

7.4 Conceptual framework of sustainability index for material assessment and selection

7.4.1 Background

The economic approach to decision-making has dominated material selection in building design and construction. In many cases, little or no consideration was made for assessing building material based on its sustainability. Socially, the overall objective of assessing building material may be the one with the least cost to the client, their performance characteristics with little regard to environmental protection and minimal use of natural resources. It may no longer be acceptable to make decisions about building material by only considering the costs and its performance alone. A range of social, technical and environmental effects must also be considered and encompassed within the selection process.

It may be difficult, or even impossible, to improve social welfare in a society if the natural environment continues to be abused and depleted. Indeed, within the economic evaluation framework, environmental issues are ignored or under-estimated as there are often considerable difficulties in measuring all relevant impacts of building material in money units (Abelson, 1996). Furthermore, since the media and general public constantly focus on ecologically sustainable development, intangibles and externalities have become major issues in material selection (Joubert *et al.,* 1997; Bentivegna *et al.,* 2002). There is concern about the potential impact of a building material on the man-made and natural environments. The externalities, risks and spill-overs generated by building material preclude a meaningful and adequate use of market approach methodology (Krotscheck and Narodoslawsky, 1996). When the analysis turns to such effects as environmental quality, or loss of biodiversity due to building, it is rarely possible to find a single variable whose direct measurement will provide a valid indicator (Mitchell *et al.,* 1995). Although many efforts have been undertaken to arrive at values for intangibles and externalities it is, in practice, almost impossible to place anything more sophisticated than subjective numerical values on such effects. The requirement for incorporating environmental issues into building design and material assessment process becomes wider and wider; the imputation of market prices more and more questionable.

Alternatives have been researched and suggested to completely replace the traditional market approach with techniques that not only identify environmental issues, they do not require valuation since they are difficult, or even impossible to assess (see Chapter Two). Cost effectiveness analysis (CEA) and environmental impact assessment (EIA), are leading in this respect (Abelson, 1996; Postle, 1998). Other researchers have suggested supplementing LCCA with a technique to measure environmental costs in other than monetary terms (Nijkamp *et al.,* 1990; Hanley, 1992; van Pelt, 1993; Abelson, 1996). Multiple criteria analysis (MCA) is also a widely accepted tool to aid decision-making in building project (van Pelt, 1994). Building materials are better assessed by non-monetary techniques, which mean we can contemplate environmental costs in a more relevant manner.

The research has made the beginning with the identification of sustainability criteria. The criteria have been developed specifically for the material selection in building design and construction. Generally, it is quite difficult to evaluate the performance of building material on the large number of sustainability criteria. Integration of key sustainability criteria is quite essential for decision making. This could be done by aggregating sustainability criteria into a composite index which can address the sustainability of building materials along all the four pillars of sustainability – economic, technical, social and environmental.

7.4.2 Composite sustainability indices

Any alternative methods to a market-based approach are still problematic and do not fully consider environmental issues (Curwell *et al.,* 1999). It is necessary to consider different building materials and their long-term impact on the environment. Simply using a non-monetary approach to replace or to complement the monetary approach in material assessment is inadequate. A new approach is required to incorporate the strengths of both market-based and non-monetary approaches that embrace the key elements of sustainable development in order to choose sustainable material option from competing alternatives (Munda *et al.,* 1998).

A number of different approaches have been developed to measure sustainability. Developing criteria has becomes one of the instruments to consider environmental effects and to move toward more sustainable practices (Mitchell *et al.,* 1995; Sands and Podmore, 2000; Dale and Beyeler, 2001). Curwell *et al.* (1999) state that "it is necessary to use composite criteria, that is, a small number of factors that are used to indicate the performance over a whole basket of issues". Indeed, the ultimate objective for developing a decision-making tool is to provide a single tool that can demonstrate the sustainability of building material while not undermining the clients economic objectives. These criteria may be combined together into a single decision model. Developing a more comprehensive and holistic methodology will ensure that sustainability is taken into account when evaluating building material alternatives that may affect current and future generations (Woolley *et al.,* 1999). Achieving sustainable development requires the material assessment methodology to take into account the full range of socio, economic, technical and environmental issues raised.

7.4.2.1 Gross domestic product (GDP)

Various types of environmental indices have been developed as tools to aggregate and simplify diverse information into a useful and more advantageous form. The gross domestic product (GDP) indicator of economic welfare has been frequently used as a proxy measure of quality of life since the 1940s (Lawn and Sanders, 1999; Chambers *et al.,* 2000). GDP is an aggregate statistical measure that adds up different goods and services so that they are expressed as a monetary unit. Since the 1970s, there has been growing criticism as to the usefulness of GDP as an indicator for economic growth (Stockhammer *et al.,* 1997). It was argued that GDP does not reveal anything about human welfare or unpaid services such as housework, community service and volunteer work. Social activities and recreation are also excluded from GDP calculations (Chambers *et al.,* 2000). In addition, GDP does not take into account the depreciation to the economy affected by the consumption of natural resources (Castaneda, 1999; Chambers *et al.,* 2000). High GDP growth is necessarily to have higher welfare when unpaid services and the contribution of the natural capital are taken into consideration.

However, even though GDP fails to be used as a measure of sustainable economic welfare, it is still widely used as the key indicator for economic policy (Stockhammer *et al.,* 1997). Since the late 1960s, many discussions have taken place about the links between economic growth, social welfare and the environment as economic growth is restricted by the availability of natural resources and the level of pollution in the environment (Castaneda, 1999). Attempts, therefore, have been made to account for depletion of both natural and man-made capital, and defensive expenditures. Daly and Cobb developed the Index of Sustainable Welfare (ISEW) in 1989 as a better means of measuring welfare changes in an economy (Lintott, 1996; Hanley *et al.,* 1999; Chambers *et al.,* 2000). ISEW takes into account GDP and includes adjustments to value housework, social costs, environmental damages, resource depletion and income distribution. In addition, it also adjusts for defensive and non-defensive expenditure that does not necessarily contribute to economic welfare (Herendeen, 1998). Nevertheless, Castenada (1999) states that ISEW cannot be used for international comparisons due to the methodological insufficiency. Calculating defensive expenditure is very limited to local effect only, which lacks the proper approach to extrapolate for the rest of the country or world.

7.4.2.2 Environmental Sustainability Index

The Environmental Sustainability Index (ESI) which was a composite index tracked 21 elements of environmental sustainability. The 21 indicators are again derived from 76 variables. It was superseded by the Environmental Performance Index in 2006.The "ESI score quantifies the likelihood that a country will be able to preserve valuable environmental resources effectively over the period of several decades" (Esty *et al.,* 2005). For normalization the standard deviation is calculated of each (normal distributed) variable. The three aggregation steps consist of arithmetic means with equal weights (Bohringer and Jochem, 2007).

7.4.2.3 Environmental Performance Index

Complementary to the ESI which focuses on the environmental dimension of sustainability, "the EPI addresses the need for a gauge of policy performance in reducing environmental stresses on human health and promoting ecosystem vitality and sound natural resource management. The EPI focuses on current on-the-ground outcomes across a core set of environmental issues tracked through six policy categories for which all governments are being held accountable" (Esty *et al.,* 2005). The EPI is based on a proximity-to-target approach which measures country performance against an absolute target established by international agreements, national standards, or scientific consensus (Esty *et al.,* 2005).

7.4.2.4 United Nations Development Programme (UNDP)

In 1990, the United Nations Development Programme (UNDP) launched the Human Development Index (HDI) which aims towards a more comprehensive measure of human development. It brings the indexes for income, longevity and education into a simple arithmetic average to measure human development. This system is appropriate for comparing developed and developing countries, but it fails to investigate the affect on the natural system by activities that potentially contribute to national income (Herendeen, 1998; Neumayer, 2001).

7.4.2.5 Farmer sustainability index (FSI)

In Malaysia, an index has been developed for the cabbage farming industry. The farmer sustainability index (FSI) was developed to accumulate a series of scores assigned to specific responses to questions from a survey in accordance with their intrinsic sustainability, by looking at the organisational affiliation, self-identification, or key practice such as use, or non-use of synthetic agricultural chemicals (Taylor *et.al,* 1993). The FSI combines 33 different practices used to control insects, diseases, weeds and soil erosion, and to maintain and enhance soil fertility, into a composite index to measure sustainability. The higher the FSI, the greater the sustainability of the practice. It has been proved to be successful, reflecting the degree of sustainable practice among individual farmers (Taylor *et al.,* 1993). The FSI as developed by Taylor *et al.* (1993) has been extended to evaluate cabbage and potato farming in Indonesia (Norvell and Hammig, 1999).

7.4.2.6 European sustainability index

An index has also been developed to rank the sustainability of European cities. This index involves 12 European cities, the goal being to develop a system of indicators that can be used in cities throughout Europe. The European sustainability index describes the situation in view of the development of the city by means of a number of representative elements and compares this with the situation in previous years. It offers a compact index that is flexible, adjustable and intended for general application at the local level, and for comparisons at the international level (Deelstra, 1995). A similar type of index, based on the quality of life indices derived from investigating the weighted mean of a set of amenities to rank cities in Canada, has also been developed and used (Giannias, 1998).

7.4.2.7 Other indices

Other similar index systems have been developed, such as the Sustainable Process Index for measuring the areas needed to provide the raw materials and energy demands and to accommodate by-product flows from a process (Krotscheck and Narodoslawsky, 1996). Other indicators or indexes used to indicate the performance of the economy in everyday life include the bank interest rate, rainfall, temperature, unemployment figures and the FT100 share index (Mitchell *et al.,* 1995).

7.4.2.8 Sustainability index

A sustainability index can also be developed to model the most significant criteria in a construction-related decision. The sustainability index captures the complexities of the ecosystem, yet remains simple enough to be used. A sustainability index can provide direction to strategic planning and can make a process more understandable and help to make the choice among alternatives more amenable to rational discussion in society (Krotscheck and Narodoslawsky, 1996).The development of a sustainability index combines objective factors, that is costs (Life cycle cost) together with subjective issues such as resource efficiency, performance benefit, waste efficiency, social benefit, and environmental impact.

Developing a sustainability index is a reflection of the integral concept of sustainable construction that involves evaluating competing material option, investigating their environmental impact and assessment of sustainability. The comparative assessment of sustainability indicates which of the acceptable material alternatives may be selected by screening out the unsustainable options. The sustainability index also provides a means to aggregate information into a single framework of relative performance. The purpose of the sustainability index is to ensure that the important aspects of the ecosystem, the economy, material property and society are included, and that everyone can find a measure that applies. These criteria comprise Life cycle cost, resource efficiency, performance benefit, waste efficiency, social benefit, and environmental impact. All the criteria very important today, as the supply of natural resources is under serious threat.

When all six criteria are combined, an indexing algorithm is created to rank options of building materials on their contribution to sustainability. The algorithm is termed the 'sustainability index'. Each criterion is measured and combined using a multi criteria assessment method to give an overall index score as shown in Figure 7.1. The higher the index, the more sustainable is the outcome.

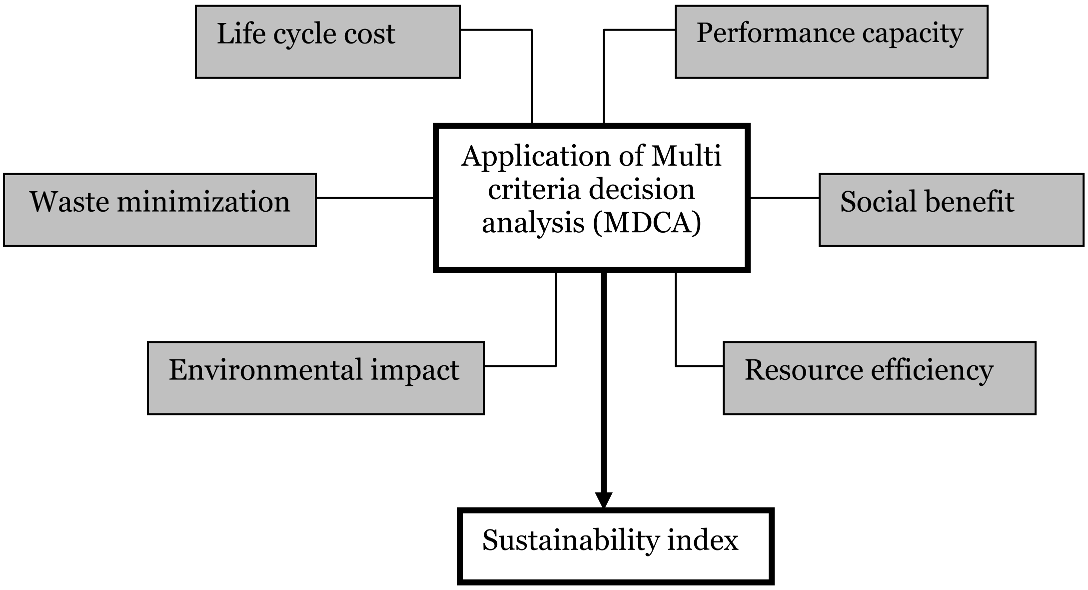


Figure 7.1 Sustainability index using Multicriteria decision analysis

7.4.3 Multi-criteria decision models for sustainable material selection

Statistical procedures provide a set of tools that enable researchers to sum up their empirical findings in a manner that can be easily presented to the intended audience and understood by them without difficulty. Researchers have found sole reliance on univariate and bivariate analyses to be inadequate and opted for multivariate analysis (Singh *et al.,* 2007; 2009).

As the name indicates, multivariate analysis comprises a set of techniques dedicated to the examination of relationships between more than two variables, which are random but interrelated so that their different effects cannot meaningfully be interpreted separately (Rencher, 2002; Singh *et al.,* 2007). Two approaches are currently under debate; on the one hand all impact should be translated into financial terms, which is often understandable by decision-makers. On the other hand, it is difficult, if not impossible, to place an economic value on all environmental and social impacts, and a qualitative route with decision analysis techniques, could be used. In some cases, combinations of these two approaches have been proposed. The important principle in formation of an index is that sum total of the variable must yield an interpretation that is unidirectional. That is 'code' must be the same (Singh *et al.,* 2007).

In a composite index somewhat disparate variables are clubbed together. The final index must have a magnitude and direction, so that the index can be uniquely interpreted. Recently, a family of novel and somewhat controversial analytical methods has been gaining attention within the academic literature as a viable and more complete alternative to evaluation (Ducey and Larson, 1999; Mendoza and Prabhu, 2003). These methods described generally as multi-criteria analysis (MCA), which have their foundations in operations research, have suggested a theoretical framework capable of capturing the essence of sustainable development, while still being operational and implementable (Munda *et al.,* 1994; Mendoza and Prabhu, 2003).

There is a criticism, that MCA methods lack an absolute objectivity and leaves a problem with no defined mathematical solution. Nonetheless, the multi-faceted nature of sustainable development, its wide spatial scale and the multiple issues it encompasses defy attempts to analyze it using precise methodologies (Singh *et al.,* 2007). Thus, in spite of the disquiet of economists, MCA methods remain a most constructive framework for evaluating sustainable development and developing sustainability index.

However, the issue remains as to which of these MCA methods are suitable as a theoretical framework for the construction of a composite criterion. The selected method for composite criteria formulation must allow for the weighted aggregation of quantitative individual indicators, which requires that the method is utility or value based, quantitative in format and provides a cardinal measurement of the weighted differences amongst indicators and not merely ordinal difference (Nijkamp *et al.,* 1990). Transparency is also important in composite criteria so that the method of construction can be disseminated for robustness (OECD, 2003). Importantly, transparency is achieved when the method formalizes explicitly the logical thought processes that are implicitly carried out by the stakeholders when coming to an evaluation problem.

Numerous techniques for multi-criteria or multiattribute decision-making have emerged. Some of the simpler and more useful techniques include Scoring Multi-Attribute Analysis (SMAA), Multi-attribute utility theory (MAUT), Multiple Regression (MR), Linear programming (LP), Cluster analysis (CA), Multivariate discriminant analysis (MDA), Weighted sum method (WSM) and the Analytical hierarchy process (AHP)

No uniform agreed MCA methodology exists for aggregation of composite criteria for sustainability evaluation (Singh *et al.,* 2007; Zhou *et al.* 2010). Weights heavily influence a composite set of criteria. The factors considered in the selection of a MCA method include internal consistency, flexibility of methodology and easy to use. Selection of appropriate MCA methodology can be guided by a trade-off between its objectivity and comprehensiveness (Janssen, 1991). Detail description of the tools is not within the scope of this chapter; literature abounds for thorough investigation of this subject where necessary (e.g Wang *et al.* 2009; Lakhmi and Chee, 2010; Zeiler *et al.,* 2010).

Scoring Multi-Attribute Analysis (SMAA)

This is a technique for evaluating multi-criteria decision problems to identify the best decision alternative from several well-defined alternatives (Finlay, 1994). Anderson *et al.* (2005) have spelt out the analysis involved in this technique in clear steps as follows:

Step1. Develop a list of the criteria to be considered. The criteria are the factors that the decision maker (DM) considers relevant for evaluating each decision alternative.

Step 2. Assign a weight to each criteria that describes the criterion's relative importance. Let w_i = the weight of criterion *i*.

Step3. Assign a rating for each criterion that shows how well each decision alternative satisfies the criterion. Let r_{ij} = the rating for criterion *i* and decision alternative *j*.

Step 4. Compute the score for each decision alternative as follows:

$S_j = \sum w_i r_{ij}$; where S_j is the score for decision alternative j....................7.1

Step 5. Order the decision alternatives from the highest score to the lowest score to provide the scoring model's ranking of the decision alternatives. The decision alternatives with the highest score is the recommended decision alternative.

The simplest form of SMAA is expressed as $S_j = \sum r_{ij}$ (i.e. without any weightings (W_i)) and is termed simple scoring MAA (Holt, 1998). This has major weakness as r_{ij} is often a very subjective measure. The purpose of the weighting indices is to heighten the aggregated scores of the various alternatives in commensuration of their satisfaction in relation to the various criteria. The W_i may be a function of (Holt, 1998): sole practitioner experience/predilection; group consensus opinion and survey and analysis of data, from a sample pertinent to the selection setting in which the model will be applied.

Multi-attribute utility theory (MAUT)

This technique is similar to SMAA except that it uses "utility" to quantify the subjective components of the attributes. The term "utility" is used to refer to the measure of desirability or satisfaction of an attribute of the alternative under consideration. It gives an abstract equivalent of the attribute being considered from natural units such as years, or £ into a series of commensurable units (utiles) on an interval scale of zero to 1 (Holt, 1998). As in SMAA, utility values can be used in conjunction with weightings, W_i, to give a more reliable aggregate score for the various alternatives. MAUT is expressed mathematically as:

$$S_j = \sum_{i=1}^{n} W_i U_{ij};\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.2$$

Where U_i represents the abstract equivalent expressed in utiles for the *i*th attribute of the *j*th alternative and n is the attributes considered by the decision maker.

Multiple Regression (MR)

This is a statistical technique used to develop a model for observing and predicting the effect of a number of independent variables upon a dependent variable. In general, a MR model for predicting an outcome *Y*, a function of independent variables, $X_1, X_2, \ldots X_n$ is given by equation of the form:

$$Y = a + b_1(X_1) + b_2(X_2) + \ldots + b_n(X_n)\ldots\ldots\ldots\ldots\ldots\ldots 7.3$$

Where *a* is the constant representing the y-axis intercept of the regression line; $b_1, b_2, \ldots b_n$ are the partial regression coefficients representing the amount the dependent variable *Y* changes when the corresponding independent variable changes 1 unit and *n* is the number of independent variables. In applying MR as a decision-making technique, the various attributes or criteria will be represented as independent variables and the dependent variable will represent the total score obtained by each alternative. Associated with multiple regression is R^2, *coefficient of determination*, representing the percent of variance in the dependent variable explained collectively by all of the independent variables. The higher it is, then the more accurate the model is able to predict. The difference between the actual values of Y and those predicted by the model is known as residuals.

Linear programming (LP)

LP is an optimizing tool for identifying maximum or minimum value of a linear function, $f(x_1, x_2, \ldots x_n)$ called an objective function, subject to a number of linear constraints of the form $A_x + B_y + C_z + \ldots \leq N$ or $A_x + B_y + C_z + \ldots \geq N$. LP is thus a MOA technique. The largest or smallest value of the objective function is called the optimal value, and a collection of values of $x, y, z, \ldots$ that gives the optimal value constitutes an optimal solution. The variables $x, y, z \ldots$ are called the decision variables.

Cluster analysis (CA)

Cluster analysis is a tool for grouping objects (people, things, events, etc) of similar kind into respective categories or classification (Gaitani *et al* 2010). By this, any associations and structure in a data, which hitherto were not evident, may be discovered. It has thus been a very useful too for developing taxonomies or classification system. Hennig (2008) listed three main types of CA: *Joining (Tree Clustering)*, *Two-way Joining (Block Clustering)*, and *k-Means Clustering*. Although CA is generally meant for solving classification problems, it has been used widely as a decision tool (Holt, 1998). In this application, a classification algorithm is first used to group the given number of alternatives into a number of clusters such that alternatives within classes are alike and unlike those from other clusters. This reduces the original set of alternatives into manageable sub-sets of like characters. These sub sets are then analyzed considering their attributes to identify the best alternatives.

Multivariate discriminant analysis (MDA)

MDA is also a statistical analysis technique concerned with separating distinct set of objects (or observations) based upon their observed independent variables (Klecka, 1980). The technique begins by finding the most discriminating variable, which is then combined with each of the other variables in turn until the next variable is found which contributes most to any further discrimination between the groups. The process continues in a similar manner until such time as very little discrimination is gained by inclusion of any further variable (Holt, 1998). The criteria which best discriminate between groups and which are most similar is confirmed by computing the ratio of between-group variation to within-group variation, simultaneously for all the independent variables (Klecka, 1980). The discriminate factors are then used to develop a linear discriminate function of the form:

$$Z= C_0 + C_1 V_1 + C_2 V_2 + \ldots\ldots C_n V_n \quad\ldots\ldots 7.4$$

Where Z is the score of the discrimant function; V_n is the nth discriminating variable; C_n is coefficient of V_n and C_0 is a constant.

Weighted sum method (WSM)

The Weighted sum method often called the decision matrix approach is perhaps the earliest and the most commonly used approach, especially in single dimensional problems. This evaluates each alternative with respect to each criterion and then multiples that evaluation by the importance of the criterion. This product is summed over all the criteria for the particular alternative to generate the rank of the alternative. Mathematically (Bhushan and Rai, 2004),

$$R_i = \sum_{j=1}^{N} a_{ij} w_j \text{ ....7.5}$$

where R_i is the rank of the *i*th alternative, a_{ij} is the actual value of the *i*th alternative in terms of the *j*th criterion, and w_j is the weight or importance of the *j*th criterion. Difficulty with this method emerges when it is applied to multi-dimensional decision-making problems. In combining different dimensions, and consequently different units, the additive utility assumption is violated (Solnes, 2003; Pohekar and Ramachandran, 2004).

Analytical hierarchy process (AHP)

Analytical Hierarchy Process (AHP) is perhaps the most commonly used for prioritization of decision alternatives. Developed by Saaty (1980), the essence of the process is decomposition of a complex problem into a hierarchy with goal (objective) at the top of the hierarchy, criterions and sub-criterions at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy. Elements at given hierarchy level are compared in pairs to assess their relative preference with respect to each of the elements at the next higher level. Ratio scale and the use of verbal comparisons are used for weighting of quantifiable and non-quantifiable elements. The method computes and aggregates their eigenvectors until the composite final vector of weight coefficients for alternatives is obtained. The entries of final weight coefficients vector reflect the relative importance (value) of each alternative with respect to the goal stated at the top of hierarchy. A decision maker may use this vector due to his particular needs and interests.

One of the major advantages of AHP is that it calculates the inconsistency index as a ratio of the decision maker's inconsistency and randomly generated index. This index is important for the decision maker to assure him that his judgments were consistent and that the final decision is made well. The inconsistency index should be lower than 0.10 (Saaty, 1980). Although a higher value of inconsistency index requires re-evaluation of pair wise comparisons, decisions obtained in certain cases could also be taken as the best alternative

Table 7.1 gives a summary of the various tools based on the levels of information on the decision-making environment and the nature of output results as described by Holt (1998) and Greening and Bernow (2004).

Table 7.1 Characteristics of decision-making tools (Holt, 1998; Greening and Bernow, 2004)

Technique	Nature of input data	Nature of output
Scoring multiattribute analysis	Interval and ordinal but Subjective	Numeric score and ranks and hence rank amongst alternatives
Multi-attribute utility theory	Raw data is often qualitative, utility achieves interval data	Numeric score and ranks and hence rank amongst alternatives
Multiple regression	Interval predictive	Numeric; further value
Linear programming	Value judgement on the importance of an over-all objective	Maximisation of objective function
Cluster analysis	Multivariate	Group membership/group characteristics
Multivariate discriminant analysis	Multivariate	Group membership/group characteristics
Weighted sum method	Interval and ordinal but Subjective	Numeric score and ranks and hence rank amongst alternatives
Analytical hierarchy process	Raw data is often qualitative, utility achieves interval data	Numeric score and ranks and hence rank amongst alternatives

7.4.4 The technique adopted for the sustainability index development

In this work, the AHP model was adopted, as it offered a logical and representative way of structuring the decision problem and deriving priorities. The method is a theoretically sound and practicable approach for selecting, weighting, standardizing and aggregating individual criteria into a composite index (Singh *et al.,* 2007). The technique allows both quantitative and qualitative criteria to be entered into the model and offers an overall solution for the model (Singh *et al.,* 2007). AHP explicitly ranks tangible and intangible factors against each other for the purpose of resolving conflict or setting priorities. AHP compares decision factors by pairs and assigns weights to reflect their relative importance (Saaty, 1986).

Singh *et al.* (2007) describe AHP method as a multiple step analytical process of judgment, which synthesizes a complex arrangement into a systematic hierarchical structure. It allows a set of complex issues that have an impact on an overall objective to be compared with the importance of each issue relative to its impact on the solution of the problem (Raisinghahi and Meade, 2005). It is designed to cope with the intuitive, the rational, and the irrational when making multi-objective, multi-criterion and multi-actor decisions—exactly the decision-making situation found with material selection.

While AHP is conceptually easy to use, it is decisionally robust so that it can handle the complexities of real world problems. AHP models a decision-making framework that assumes a unidirectional hierarchical relationship among decision levels (Presley, 2006). The top element of the hierarchy is the overall goal for the decision model. The hierarchy decomposes to a more specific attribute until a level of manageable decision criteria is met. The method's fundamental rationality is decomposing a dataset into smaller constituent elements and then eliciting pair-wise comparisons (e.g. "how important is indicator *i* relative to indicator *j* ?), by using a fundamental (1–9) scale developed by Saaty (1980) to determine their specific priorities. Thus, although the hierarchical structure of the AHP method does facilitate analysis (by making a complex evaluation into smaller more manageable sub-evaluations), it is the method's ability to measure and synthesize the multitude of factors within the developed hierarchy that truly sets the method apart (Singh *et al.,* 2007).

The hierarchical approach allows AHP to investigate the interrelationships amongst sustainability criteria. This is important as the various aspects and criteria pertaining to sustainable development are often linked together (Singh *et al.,* 2007). Thus because interrelationships can be deciphered the AHP method allows different criteria to overlap or to be strongly interrelated, which while having possible limitations with double-counting is both more appropriate for evaluating the holistic nature of the sustainable development concept and thus does not necessitate the need for the very strong assumption of mutual independence.

Another advantage with AHP method is that it does not require the very strong assumption that the stakeholders make absolutely no errors in providing preference information. The ability to deal formally with judgment error is distinctive of the AHP method. The AHP method provides the objective mathematics to process the unavoidably subjective preference inherent in real-world evaluations (Saaty, 2007).

The AHP has been accepted as a leading multiattribute decision model both by practitioners and academics (Presley, 2006; Saaty, 2007). In this research, it is tested to derive weights of criteria by the prioritization of their impact to overall sustainability assessment. AHP has been adopted mainly because of its inherent capability to handle qualitative and quantitative criteria important for sustainable material selection. AHP can help to improve the decision-making process. Furthermore, it can be easily understood and applied by architects and designers. The AHP model can enable all members of the evaluation team to visualize the problem systematically in terms of criteria and sub-criteria (Harker and Vargas, 1987 cited in Singh *et al.,* 2007). Figure 7.2 shows the conceptual framework for the application of AHP model in the selection of sustainable building material.

The AHP model is based on a basic set of four axioms (Saaty, 2007). The first axiom states that given any two evaluation elements, stakeholders must be able to provide a pair-wise comparison. The second axiom requires that when comparing any two elements, stakeholders should never decide that one indicator is infinitely superior to another. The third axiom states that the evaluation must be formulated as hierarchy. Finally, the fourth axiom states that all elements, that is, sustainability criteria must be represented in the hierarchy (Saaty, 2007).

A decision model that encapsulates these sustainability criteria would enable designers to consider a wide range of options (both conventional and innovative materials) before committing to a particular option. The ensuing section discusses computational methods for sustainability assessment. The underpinning mathematical model encapsulates the sustainability criteria (SC) for computational analysis and decision making in building material selection.

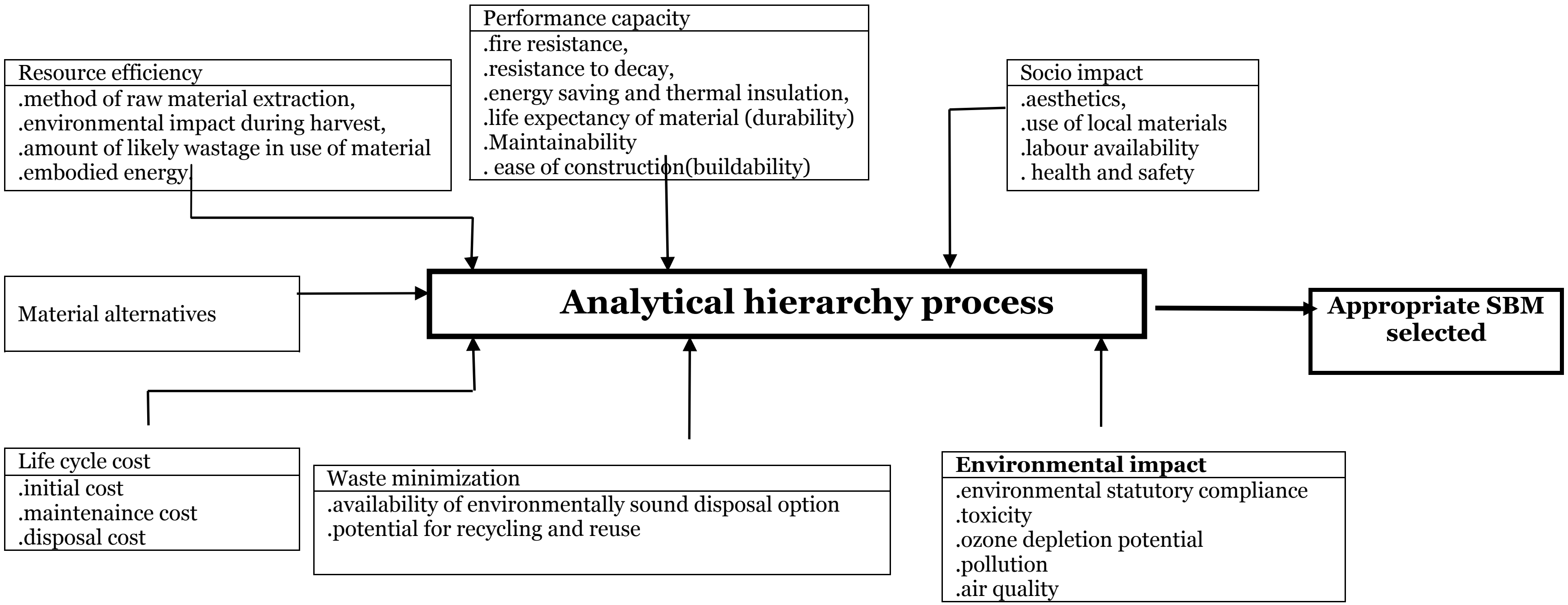


Figure 7.2 Conceptual Framework for the selection of SBM

7.5 Sustainable material selection: procedures and computational methods

The computational assessment procedure used in this study follows that of the AHP technique described in section 7.4 and that of material assessment model described in chapter 4. Evaluating the sustainability of different material alternatives using the AHP numerical analysis involves three main steps. The process steps include:

(i) determining the relevant applicable criteria and alternative material options in the form of a hierarchy of objectives. The hierarchy is structured on different levels: from the top (i.e. the goal) through intermediate levels (criteria and sub-criteria on which subsequent levels depend) to the lowest level (i.e. the alternatives); ,

(ii) assigning numerical values (i.e., weights) to measure the relative importance of these criteria for a given material alternative. For this purpose, AHP uses simple pairwise comparisons to determine weights and ratings so that the analyst can concentrate on just two factors at one time and

(iii) processing the numerical values (i.e., computational analysis) to determine the ranking of material alternative options along the various main sustainability criteria.

However, there exist very significant gaps between the theory and practice of sustainability and sustainable development at the project level (Ugwu *et al.,* 2006). The foundations for sustainable development are already encapsulated in the definition given in the seminal Brundtland report (WCED, 1987). This most quoted definition states that it is, "*development that meets the needs of present generation without compromising the ability of future generations to meet their own needs*". However, Ugwu *et al.* (2006) stated that the all-inclusive definition sounds abstract, and it needs hierarchical transformation to operational decision-making variables. There is now broad recognition of the requirement for quantitative transformations, vis-a-vis integrated holistic approaches in evaluating the sustainability of building material, as a part of wider sustainable development agenda. Researchers working on the evolving discipline of *Sustainability Science* now recognize that the success of implementation at the project levels hinges on several contributors. These include: (i) the development of criteria that transform macro-level policies and national sustainability goals to project level decision-making variables; (ii) the development of decision models, computational frameworks, and assessment methods for sustainability assessment of building material; and (iii) the development and implementation of integrated decision support tools to facilitate decision making by various stakeholders.

A mathematical model and computational algorithmic procedures would provide a basis for computing the *sustainability index* of material alternatives, within an integrated decision-support framework and tool(s). Such a crisp value index would facilitate comparison of different material alternatives along various dimensions of the sustainability envelope: economy, environment, resource efficiency, performance, waste minimization, and socio benefit. A mathematical model is therefore an essential requirement of the MCDM problem. Such a model is required for sustainability quantification in decision-making. The ensuing section focuses on the analytical (numerical) computation of "sustainability index" using the data described in steps (i) and (ii). It describes the mathematical/decision model for sustainable material assessment and selection. Further details on the mathematical model formulation and validation in a case study building project are discussed in chapter eight.

7.5.1 Mathematical model formulation

This section formulates the mathematical model for computing the sustainability index (SI) using the Analytical hierarchical process. The SI is defined as a crisp value that is an aggregated measure of material alternative along various sustainability dimensions (socio-economic, environment, technical). The sustainability index utilises the multi-criteria evaluation methods based on discrete problems to investigate a number of choice possibilities in the light of conflicting priorities (Voogd, 1983; Nijkamp *et al.,* 1990). The underlying assumption here is the additive utility function. The contextual translation means that the total utility of a given material proposal (as measured by the sustainability index) depends on its individual utilities in the various decomposed elemental sustainability criteria (SC). This assumption holds for most extant theories of utility and is particularly true of the concept of "generalized additivity" (Ugwu *et al.,* 2006). Also the use of AHP model assumes that the decision criteria can be expressed in the same unit of measure. This is achieved by using dimensionless numerical scores (i.e., scalar quantity) in the sustainability assessment process.

Let SI_i (for $i = 1, 2, 3 \ldots N$) represent the final sustainability index (a crisp value), of material alternative M_i when all the decision criteria $d_{i,j}$ are considered. The next problem is how to compute SI_i. This work uses the AHP framework because it is the most widely used MCDM method. It is also considered sufficient for formulating an underpinning mathematical model for quantitative sustainability assessment. The decision is further buttressed by the fact that a review of some completed case study major projects and the application of MCDM techniques in practice indicates that the AHP is widely used for practical decision making in real life situations. It is therefore considered valid enough to develop a mathematical foundation for sustainability.

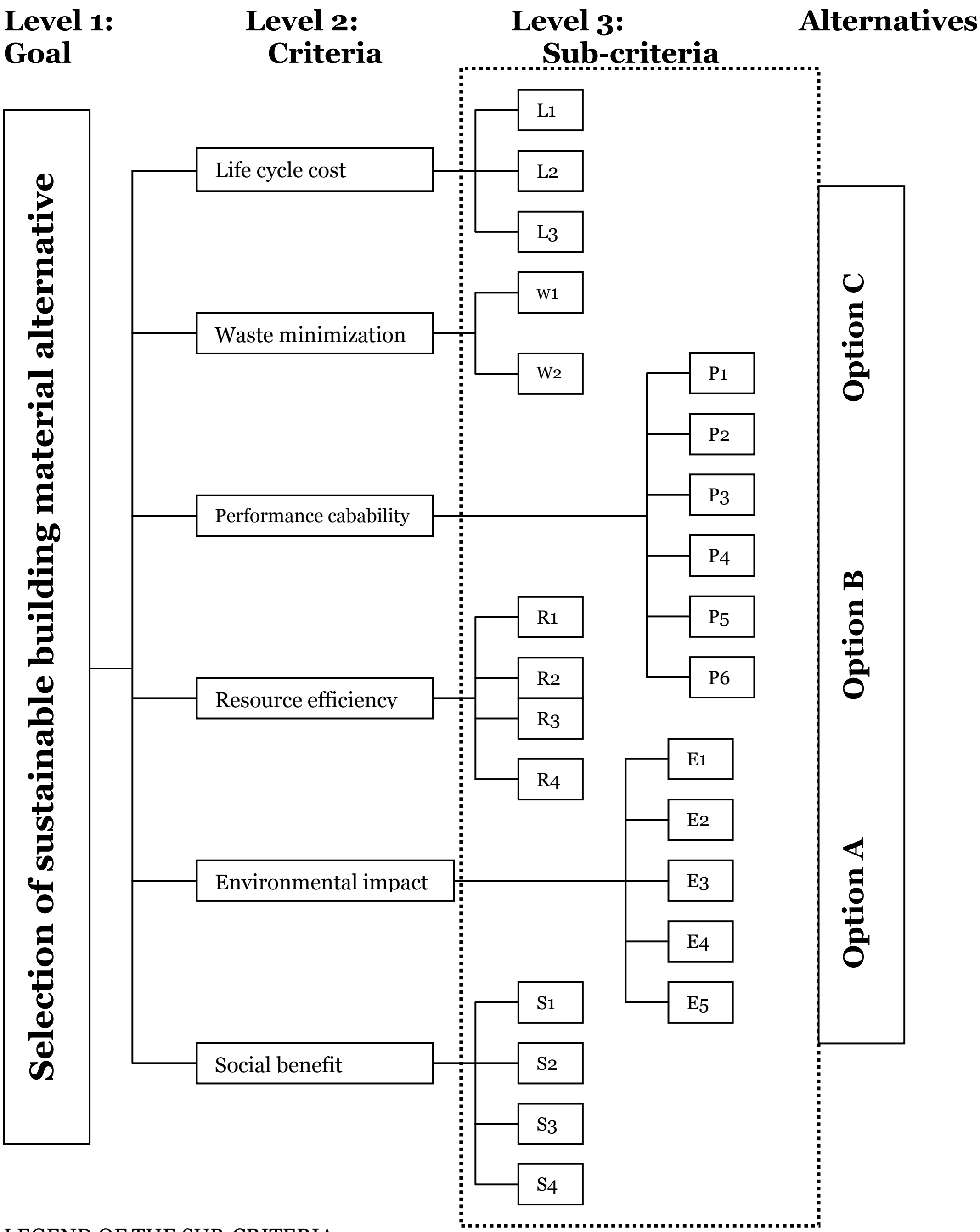
Detailed description of the main steps contained in the model formulation is described below.

Step 1: Establishment of a structural hierarchy

Constructing the hierarchical structure is the most important step in AHP. There is no specific procedure for constructing a hierarchy, and the approach depends on the kind of decision to be made. The hierarchy should be constructed so that elements at the same level are of the same magnitude and must be capable of being related to some or all elements in the next higher level. In a typical hierarchy, the alternatives are at the bottom; the next higher level would consist of the criteria for judging the alternatives. These criteria could be clustered within high-level criteria, where the clusters would be linked to the top single element, which is the objective or the overall goal. It begins by considering sustainable material selection as a decision-making problem with M material alternatives, and N criteria. The objective or the overall goal of the decision is represented at the top level of the hierarchy. The criteria and sub-criteria contributing to the decision are represented at the intermediate levels.

According to Saaty (2008), a hierarchy can be constructed by creative thinking, recollection and using people's perspectives. He further notes that there is no set of procedures for generating the levels to be included in the hierarchy. Zahedi (1986) comments that the structure of the hierarchy depends upon the nature or type of design decision. Also, the number of the levels in a hierarchy depends on the complexity of the problem being analyzed and the degree of detail of the problem that an analyst requires to solve (Zahedi, 1986). Fig.7.3 shows the decision hierarchy used in the study

The first step sets the problem as a hierarchy, where the top most node is the overall objective of the decision, while subsequent nodes at lower levels consists of the criteria used in arriving at this decision. The second step requires pair-wise comparisons to be made between each pair of criteria (of the given level of the hierarchy).



LEGEND OF THE SUB-CRITERIA

L1-Initial cost
L2- Maintenance cost
L3-Disposal cost
W1-Eenvironmentally sound disposal option
W2 -Recycling and reuse.
P1 -Fire resistance,
P2-Resistance to decay,
P3-Energy saving and thermal insulation,
P4-Life expectancy of material (durability)
P5-Maintainability
R1-Method of raw material extraction
R2- Embodied energy
R3-Amount of likely wastage
R4- Environmental impact during harvest
E1-Environmental statutory compliance
E2-Toxicity
E3-Ozone depletion
E4-Pollution
E5-Air quality
S1-labour availability
S2- Aesthetics
S3-Use of local material
S4-health & safety

Figure 7.3 The decision hierarchy for selecting sustainable material

Step 2: Pairwise comparisons and computation of the criteria weights

After arranging the problem in hierarchical terms, the next step is to determine the relative importance of each criteria and sub-criteria, using a pairwise comparison technique as suggested by Saaty (1986). Comparisons are performed between pairs of elements within each branch of each level of the hierarchy to determine the relative worth of one element as compared with another in relation to the element directly above. For example, a question that may be asked of a decision maker is “How much more important is initial cost than disposal cost in predicting the life cycle cost of a building material?” The comparison is done by utilizing a preference scale (Saaty, 1980) as shown in table 7.2.

Table 7. 2 Comparison scale adapted from (Saaty, 1980)

Degree of importance	Definition
1	Equal importance of elements
3	Importance of one element over another
5	Strong importance of one element over another
7	Demonstrated or very strong importance of one element over another
9	Absolute importance of one element over another
2,4,6,8	Intermediate values between two adhacent degrees of importance

The pairwise comparisons from each branch at each level of the hierarchy are entered into a matrix and used to determine a vector of priority weights. Only those elements that pertain to a common objective are compared against one another. Breaking a complex system into a set of pairwise comparisons is a major feature of AHP. Judgements are often established by an open group process; therefore, dynamic discussion is used for setting priorities by mutual agreement and for revision of views among group members.

We use the following notation:

w_i = weight for attribute i, i=1,..,n where n = number of attributes

$a_{ij} = w_i / w_j$ = the result of a pairwise comparison between attribute i as compared to attribute j

A = matrix of pairwise comparison values, aij

A set of pairwise comparisons can therefore be represented as:

	w_1/w_1	w_1/w_2	w_1/w_n
	w_2/w_1	w_2/w_2	w_2/w_n
A=	.	.	.
	.	.	.
	w_n/w_1	w_n/w_2	w_n/w_n

..........................7.6

where w_1/w_2 is the importance of attribute *1* as compared to attribute *2*. Since the direct result of a pairwise comparison is aij, where a_{12} is equal to w_1/w_2, matrix A becomes:

	a_{11}	a_{12}	...	a_{1n}
	a_{21}	a_{22}	...	a_{2n}
A=	⋮	⋮	⋮	⋮
	a_{n1}	a_{n2}	...	a_{nn}

.................................7.7

The goal of AHP is to uncover the underlying scale of priority values w_i. In other words, given a_{ij}, find the "true" values of w_i and w_j.

This A matrix has some special properties. First, A is of rank one. If we look at each column of A, we have:

		w_1		w_1		w_1
A=	w_1^{-1}	w_2	,w_2^{-1}	w_2	,...,w_n^{-1}	w_2
		⋮		⋮		⋮
		w_n		w_n		w_n

..................7.8

Each column of A differs only by a multiplicative constant, w_i^{-1}. If the A matrix is consistent only one column is required to determine the underlying scale ($w_1,\ldots,w_n$). The same evaluation could be undertaken in a row-wise fashion with the same result.

Second, if B is x times more important than C, then it follows that C is 1/x times as important as B. In other words, a_{ji} is the reciprocal of a_{ij} such that $a_{ij} = 1/a_{ji}$. This assumes the decision maker is consistent with respect to individual pairwise comparisons and is a fundamental assumption made by the AHP. With this assumption, matrix A is be reduced to:

	1	a_{12}	a_{13}	…	a_{1n}
	$1/a_{12}$	1	a_{23}	…	a_{2n}
A=	$1/a_{13}$	$1/a_{23}$	1	…	a_{3n}
	⋮	⋮	⋮	⋮	⋮
	$1/a_{1n}$	$1/a_{2n}$	$1/a_{3n}$	…	1

………………7.9

As seen in Equation 7.9, when a criterion is compared with itself each criteria has equal weight. This makes the diagonals equal to unity (i.e. $w_1/w_1 = 1$). The entries below the diagonal are reciprocal of those entries above the diagonal. The above reduction means that only $\frac{n(n-1)}{2}$ pairwise comparisons need to be solicited from decision makers as compared with n^2 total entries in the completed A matrix. If the assumption that the decision maker is consistent with respect to individual pairwise comparisons does not hold, in other words if $a_{ij} \neq 1/a_{ji}$, then $(n^2 - n)$ pairwise comparisons would be required.

Deriving Weights

Once pairwise comparisons have been elicited from the decision maker, the next step is to use this matrix to estimate the underlying scale of preferences. In other words, given a_{ij}, find w_i and w_j. Because of the "random" error inherent in human judgment, even professional judgment, it can not be expected the true values of wi and wj can be found. The user will need to be content instead with good estimates of w_i and w_j (Fichtner, 1986). Several methods have been proposed to estimate weights from matrices of pairwise comparisons. The two most common methods of deriving attribute weights are the eigenvector and the logarithmic least squares methods.

It can be shown by algebraic manipulations of the pairwise definitions that attribute weights can be obtained by finding the eigenvector corresponding to the largest eigenvalue of the A matrix. The eigenvector method was originally proposed by Saaty (1980) and is one of the most popular methods of calculating preferences from inconsistent matrices of pairwise comparisons. Equation 7.9 showed a consistent matrix of pairwise comparisons. When this matrix is consistent it is of rank one, meaning that only one column or one row is necessary to derive the underling scale, w_i, of weights. When inconsistency is introduced into pairwise comparisons, more than one row or column of A is desired in order to derive a good estimate of the underlying scale of weights. The largest eigenvalue of A, λmax, is used in consistency calculations (discussed below in Consistency) and its corresponding eigenvector, normalized such that its components sum to one represents the vector of attribute weights.

Elements of the eigenvector are normalized to sum to one as opposed to setting the largest element of the eigenvector equal to one. This is required in order to give the potential for equal weighting between branches of the hierarchy where the number of elements being compared may be different. This normalization ensures the weights within each branch of the hierarchy sum to one no matter the number of elements or the relationships between the elements of a branch. Assume a hierarchy with two branches with two and six sub-objectives, respectively. If the vector of weights were normalized such that the largest element is equal to one, the branch with six sub-objectives would be given more weight in total than the branch with only two sub-objectives. Likewise, a branch where there is little preference for one element over another would be given a higher total weight over a branch with the same number of elements but with larger differences in preferences between the individual elements.

Following the definition of $a_{ij}=w_i/w_j$ and $a_{ij}=1/a_{ji}$

$$a_{ij}a_{ji} = a_{ij}\frac{1}{aij} = a_{ij}\frac{1}{\frac{w_i}{w_j}} = a_{ij}\frac{w_j}{w_i} = 1 \text{....................} 7.10$$

If follows that in the consistent case:

$$\sum_{j=1}^{n} a_{ij}\frac{w_j}{w_i} = n \qquad i=1 \text{ to } n \text{..................} 7.11$$

Or, stated another way, multiplying equation 7.11 through by w_i:

$$\sum_{j=1}^{n} a_{ij}w_j = nw_i \qquad i=1 \text{ to } n \text{..................} 7.12$$

These statements are equivalent to the matrix notation Aw = nw. If the goal is, given a positive reciprocal matrix A, to find w, the problem becomes (A - nI) w = 0. This is a classical eigenvector problem and is non-trivial if and only if *n* is an eigenvalue of A. This method for deriving a vector of weights from a positive reciprocal matrix of pairwise comparisons uses the largest eigenvector, also termed the principal right eigenvector, and its corresponding eigenvalue.

Measurement of consistency

Deviations from both ordinal and cardinal consistency are considered, and to a certain extent allowed, within AHP. Ordinal consistency requires that if *x* is greater than *y* and *y* is greater than *z*, then *x* should be greater than *z*. Cardinal consistency is a stronger requirement stipulating that if *x* is 2 times more important than *y* and *y* is 3 times more important than *z*, then *x* must be 6 times more important than *z*. If A is cardinally consistent, then $a_{ij}a_{jk} = a_{ik}$. Using the previous definition of a_{ij} we can see that this is true:

$$a_{ij}a_{jk} = \frac{w_i}{w_j}\frac{w_j}{w_k} = \frac{w_i}{w_k} \text{......................7.13}$$

If the relationship $a_{ij}a_{jk} = a_{ik}$ does not hold than A is said to be cardinally inconsistent. AHP has been designed to deal with inconsistent matrices (both cardinal and ordinal inconsistency), thus the problem becomes:

$$\frac{w_i}{w_j}\varepsilon_{ij} \bullet \frac{w_j}{w_k}\varepsilon_{jk} = \frac{w_i}{w_k}\varepsilon_{ik} \text{.......................7.14}$$

where $\varepsilon_{ij} > 0$ and represents some perturbation causing A to be inconsistent, producing an A matrix that looks like the following:

$$A = \begin{matrix} 1 & \varepsilon_{12}a_{12} & \varepsilon_{13}a_{13} & \ldots & \varepsilon_{1n}a_{1n} \\ {}^1/\varepsilon_{12}a_{12} & 1 & \varepsilon_{23}a_{23} & \ldots & \varepsilon_{2n}a_{2n} \\ {}^1/\varepsilon_{13}a_{13} & {}^1/\varepsilon_{23}a_{23} & 1 & \ldots & \varepsilon_{3n}a_{3n} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ {}^1/\varepsilon_{1n}a_{1n} & {}^1/\varepsilon_{2n}a_{2n} & {}^1/\varepsilon_{3n}a_{3n} & \ldots & 1 \end{matrix} \quad \ldots\ldots\ldots.7.15$$

Various methods have been devised to deal with inconsistency. Saaty (1977) suggests using the following consistency index (CI):

$$CI = \frac{(\lambda \max - n)}{(n-1)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.7.16$$

where λmax is the largest eigenvalue of A and n is the number of elements within a branch being compared. If A is perfectly consistent (cardinally) than λmax will be at a minimum and equal to n, producing a CI equal to zero. As inconsistency increases λmax will become increasingly large, producing a larger value of CI. This consistency index can also be expressed as a consistency ratio:

$$CR = \frac{CI}{RI} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.7.17$$

where RI is a known random consistency index obtained from a large number of simulation runs and varies depending upon the order of matrix. Tables 7.3 shows the value of the random consistency index (RI) for matrices of order 1 to 10 obtained by approximating random indices using a sample size of 500 (Saaty, 2000).

Table 7.3 Average random index for corresponding matrix size (Saaty, 2000)

Matrix size (n)	1	2	3	4	5	6	7	8	9	10
Random index	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The acceptable CR range varies according to the size of matrix i.e. 0.05 for a 3 by 3 matrix, 0.08 for a 4 by 4 matrix and 0.1 for all larger matrices, n>= 5 (Saaty, 2000, Cheng and Li, 2001). If the value of CR is equal to, or less than that value, it implies that the evaluation within the matrix is acceptable or indicates a good level of consistency in the comparative judgements represented in that matrix. In contrast, if CR is more than the acceptable value, inconsistency of judgements within that matrix has occurred and the evaluation process should therefore be reviewed, reconsidered and improved. An acceptable consistency property helps to ensure decision-maker reliability in determining the priorities of a set of criteria.

Step 3: Scaling Attributes

After pairwise comparisons have been made and priority weights calculated for each element within the hierarchy, the input data for each alternative must be transformed to a usable value before alternatives can be compared. A major strength of AHP is its ability to incorporate attributes that are measured on a number of different scales, at different intensities, and can include both numeric, descriptive, and categorical data.

AHP allows for a high degree of flexibility in the treatment of input data. This is achieved by converting all values to relative data. Relative values can be created by either comparing attribute values to other alternatives being compared or by comparing attributes to an “ideal” alternative. The choice of treatments will be dependent on the type of problem and available data.

When Saaty (1980) conceived AHP he carried pairwise comparisons through to the alternatives, termed relative scaling. Relative scaling has generated a large amount of criticism (see Belton and Gear 1983, 1985 and Millet and Saaty 1999) and will generally not be appropriate for the sustainable index development or any other problem where more than a small number of alternatives are considered.

An alterative method proposed by Saaty for dealing with alternatives is the absolute, or ideal, mode of AHP. In the absolute mode, for a given attribute, each alternative is compared with an “ideal” alternative to determine its weight, termed “scoring.” The score for each attribute of each alternative will range between zero and one. A common scoring technique involves dividing each attribute value by the maximum value for that attribute present among the alternatives. This assumes the decision maker’s preference for that attribute is linear. Non-linear preferences can also be accommodated within AHP. These functions may be the result of scientific study, expert judgment, or pairwise comparisons between categorical variables.

We have now moved through the construction of the problem as a hierarchy, presented a technique of pairwise comparisons to estimate user preferences, and have discussed method to convert attribute data into a relative form. What remains is the synthesis of the information generated in the first three steps to develop a ranked list of alternatives.

Step 4: Synthesizing Priorities – calculating the sustainability index

Once relative values have been calculated for each criteria of each alternative, these criteria scores are combined with the criteria weights from pairwise comparisons to determine the overall ranking of each alternative. The normalized local priority weights of dimensions of sustainability are obtained and are combined together in order to obtain the global composite priority weights, termed the sustainability index of all sustainability criteria used in the third level of the AHP model. This is accomplished using a simple additive function. The products of each attribute score and its associated attribute weight are summed across each branch of the hierarchy. This sum becomes the attribute value for the node directly above and the process is repeated at the next level of the hierarchy.

Take, for example, a single objective with three sub-objectives. Using the pairwise comparison technique previously discussed, assume the weight for each of the three sub-objectives was determined to be equal to x_1, x_2, and x_3, respectively. Every alternative under consideration will have attributes that correspond to each of these three sub-objectives. Using techniques presented in the previous section, assume each attribute of each alternative has been reduced to a relative value. We will call this relative value for a general alternative y_1, y_2, and y_3, respectively. To calculate the overall sustainability score for the objective, S, the products of each attribute score and its associated attribute weight are summed, yielding the equation $S = x_1y_1 + x_2y_2 + x_3y_3$. If this objective is used as a sub-objective in the next higher level of the hierarchy, the relative value used for this attribute is S.

7.5.2 The composite sustainability index

The overall score for a given alternative means nothing when standing alone. Only when compared with the overall scores for other alternatives does this number become meaningful. At this point, alternatives can be ranked by their importance in contributing to the goal of the analysis by simply sorting alternatives based on their overall sustainability score. This overall sustainability score will be term the composite sustainability index value of material alternatives. Those alternatives with the higher score will receive a higher overall ranking. The sustainability index (SI) model of alternative *i* can based on the derived weight be calculated using the following formula adapted from the works of Ding (2005):

$$SI_i = \sum_{j=1}^{J} e_{ji} W_j \quad (i=1,\text{.............}I)\text{........................ ....}7.18$$

$$e_{ji} = f(LCC, EI, SI, RE, WE, MP)\text{.................................} \ 7.19$$

The symbol SIi denotes the sustainability index for an alternative I; W_j represents the weight of criterion j; and e_{ji} indicates value of alternative i for criterion j. The result will indicate that higher values for e_{ji} and W_j imply a better score, and that alternative i will be judged as better than alternative i' if the score of SIi is greater than the score of SIi'. The LCC is life cycle cost where EI denotes Environmental impact, RE resource efficiency, WM waste minimization, SB socio benefit and PB performance capacity.

They are obtained from the following formulae:

$$LCC = \sum_{j=1}^{I} C_{ji} W_j \text{...}7.20$$

Where: LCC= Life cycle cost
i =alternatives
j= sub-criteria
C =cost impact

$$EI = \sum_{j=1}^{I} R_{ji} W_j \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.21$$

Where: EI= environmental impact
i=alternatives
j=sub-criteria
R=impact

$$RE = \sum_{j=1}^{I} E_{ji} W_j \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.22$$

Where: RE= resource efficiency
i=alternatives
j=sub-criteria
E=Efficiency

$$WM = \sum_{j=1}^{I} M_{ji} W_j \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.23$$

Where: WM= Waste minimization
i=alternatives
j=sub-criteria
M=Minization

$$SB = \sum_{j=1}^{I} S_{ji} W_j \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.24$$

Where: SB= Socio benefit
i=alternatives
j=sub-criteria
S=benefit

$$PB = \sum_{j=1}^{I} B_{ji} W_j \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.25$$

Where: PC= performance capacity
i=alternatives
j=sub-criteria
B=benefit

The sustainability index is calculated for each alternative by first multiplying each value by its appropriate weight followed by totalling the weighted scores for all criteria. In the context of maximizing the sustainability of a material alternative, the preferred material option would be the alternative that gives the highest corresponding value of the Sustainability Index (SI). The amalgamation method yields a single index of alternative worth, which allows the options to be ranked. The higher the sustainability index, the better the chosen alternative. Fig. 7.4 shows the flowchart for the assessment and selection model.

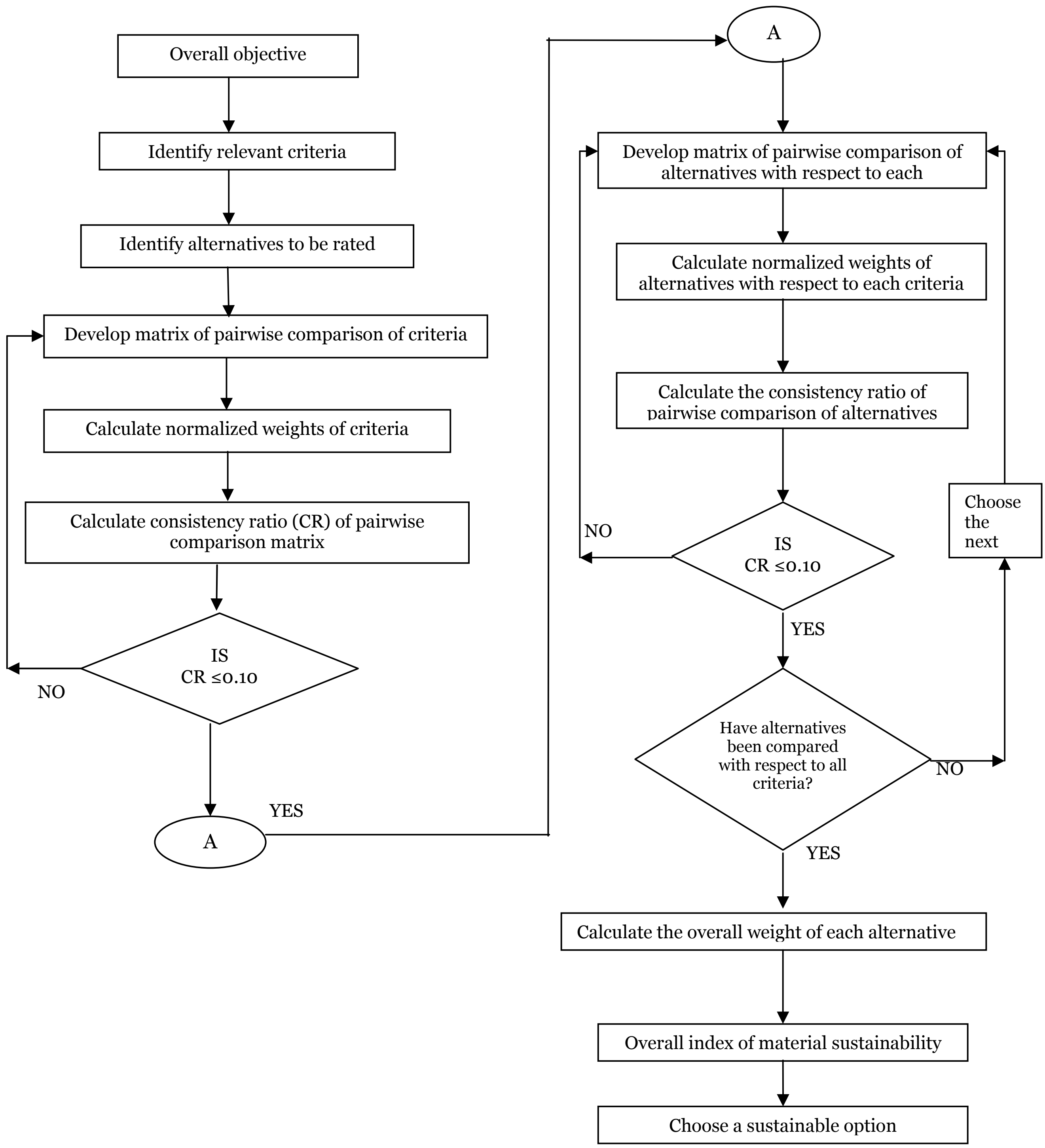


Figure 7.4 Flow chart for the selection model

7.5.3 Assumptions

Again to maintain simplicity of the model formulation, the sensitivity of various criteria and their impact to ranking of alternatives is not considered within the scope of this research. Another underlying assumption in all MCDM methods is that the decision maker can evaluate sustainability for a given material alternative. Thus, the decision maker is considered to have sufficient knowledge and expertise (including experiential knowledge) in scoring the sustainability of material alternatives.

7.6 The benefits of using sustainability index for material selection

The development of a sustainability index framework provides a tool to enable the decision-maker to integrate issues of sustainable development into the building material selection and assessment process. It uses a mixture of resources covering socio-economic, technical and environmental issues within a unified approach in a full life-cycle estimate for each material option. The broad range of topic areas covered in the model of the sustainability index still permits the use of a composite index containing all the diverse criteria, allowing the selection of sustainable material option from the alternatives.

The sustainability index is a comprehensive methodology that includes the quantification of both objective and subjective measures that give a full life-cycle analysis of materials, which will allow the impacts created by the buildings during their life cycle to be compared (Uher, 1999). Uher (1999) argues that an environmental assessment can be achieved by using absolute rather than marginal criteria for life cycle assessment of building materials. The advantage of obtaining absolute data is that the ecological footprint of materials can be calculated, and that large internal differences in impacts for comparable functional units will appear.

With regards to the environmental building assessment methods, BREEAM, BEPAC, LEED and GBC use similar frameworks with a credit-weighting scale to assess buildings. ENER-RATE is principally set up to assess multiple criteria in design. BEQUEST is predominantly used for sustainable urban planning (details refer to Chapter Four, Section 4.2). The sustainability index can assist in decision-making for material selection from as early as the feasibility stage. The survey revealed that professionals in the building industry are of the opinion that materials should already be considered at the feasibility stage in order to choose the best material option that maximises cost and minimises detrimental effects to the environment. The concept of a sustainability index is enhanced by the development of the comprehensive project evaluation (CPA) by the RICS, which indicates that building material assessment methods should move away from relative scales into absolute measures (RICS, 2001).

Soebarto and Williamson (2001), when comparing environmental building assessment methods, say that most methods exclude cost and in some schemes, only part of the total cost is included. Curwell (1996) states that since they are not a life-cycle analysis method for building materials these methods would not give a balanced assessment between a material and the environment. Cooper (1999) further states that the methods provide only a relative, not absolute, assessment of building material. Such relative assessments conceal the specific impact of a material on the environment and there is no guarantee that the material which score highly against the framework, are making a substantive contribution to increase environmental sustainability on a global scale. Rees (1999) continues, commenting that such relative assessments do not reveal the global carrying capacity appropriated by the material, and therefore cannot be used to measure progress for sustainability.

Due to the weakness of environmental building assessment methods of assessing buildings using relative terms, Cooper (1999) states that the direction for assessing building material needs to be capable of providing absolute measures. Such absolute assessment can reveal the global carrying capacity appropriated by the material and be capable of measuring progress toward sustainability.

The sustainability index is used at the outset to assessing building material in selecting a sustainable option from the alternatives. The index helps to distinguish material with reduced environmental impacts, and to induce design teams to incorporate holistic environmental performance requirements, significantly reducing the potential environmental impact of a building material at an early stage. It can facilitate the designer's iterative approach, where initial understanding of the problems and means of addressing it are allowed to evolve even before the building project arrives at the design stage. However, environmental building assessment methods are rarely used during the design stage.

Soebarto and Williamson (2001) state that environmental building assessment methods endorse the concept of a complete design rather than assisting the designer during the design process. The environmental building assessment methods are apparently providing guidelines in design development and offer some insight into the issue of the comparability of design solutions. Nevertheless, they are, in general, inadequate as assessment tools to be used in the design process. The time and effort that need to be spent on verifying the compliance of building designs with the magnitude of current energy and environmental regulations are enormous, both in the process of verification and in terms of producing necessary documentation (Crawley and Aho, 1999).

According to Cooper (1999), Cole (1999) and *Todd et al.* (2001), environmental building assessment methods are predominantly concerned with environmental protection and resource efficiency, with only limited ability to assess socio-economic sustainability. The environmental assessment of buildings using methods such as BREEAM and BEPAC are inadequate for addressing wider sustainability issues (Curwell and Cooper, 1998; Lee *et al.,* 2002). Curwell and Cooper (1998) go on to state that these methods deal with environment and futurity only. The sustainability index, in principle, embraces economic, technical and social concerns as well as environmental aspects of sustainability. It has provided a theoretical framework to consider potential contributions in furthering sustainable building material selection and practices. The evaluation of the six criteria over the life span of a material further enhances the principle of futurity and equity in material assessment.

The environmental building assessment methods based the assessment on the opinion of a trained assessor to validate the achievement of building performance. Not only may the outcome be subjective but also it is only larger projects that can afford external expertise (Crawley and Aho, 1999). In addition, the assessment results are derived from just adding up all the points to get a total score. Even if a material rates poorly on a few key factors such as energy consumption, it can still achieve a high score from meeting other, more marginal criteria (Curwell, 1996).

The inherent weakness of subjectivity and point systems in assessment methods will not be a problem in the model of sustainability index. The composite index is obtained from a methodology that involves the participation of the design teams that participate in assessing the sustainability of material options. The sustainability index ranks materials using a composite index, but it is derived from absolute measures of criteria using the most suitable methodology. Therefore the outcome, whilst providing a ranking of materials with competing alternatives, also reveals the resources consumption and the extent of environment effects in the assessment process.

7.7 Summary

Building material selection and assessment involve complex decisions and the increased significance of environmental issues has further complicated the situation. Society is not just concerned with economic growth and development, but also the long-term affects on living standards for both present and future generations. Certainly sustainable development is an important issue in design decisions. Using a conventional single-dimension evaluation technique such as LCCA to aid decision-making is no longer adequate. A much more sophisticated model needs to be developed to handle multi-dimensional arrays of data. The development of a sustainability index is a way to address multiple criteria in relation to material selection decision-making. Using a sustainability index will greatly enhance the assessment of environmental issues generated by construction activity, realise sustainable development goals and thereby make a positive contribution to the identification of sustainable material alternative.

The model of a sustainability index has been established and discussed in this chapter. The model of the sustainability index is based on a multiple dimensional concept that encompasses socio-economic, technical and environmental factors in the evaluation process. The combination of these criteria into a single decision tool using the AHP technique is fundamental to decision-making. It provides a flexible and easy-to-use evaluation instrument that represents a systematic and holistic approach to decision-making. The sustainability index will be examined by studying the six criteria over an illustrated case example showing the potential application of the index in the development to rank different Roofing element in a specific application context is presented in the next chapter (eight).

CHAPTER 8: APPLICATION AND VALIDATION OF THE SUSTAINABILITY MODEL FOR MATERIAL SELECTION

8.1 Introduction

The research objective posed in chapter one include developing a sustainable material selection and assessment model for aggregating sustainability criteria into a composite index. This was covered in detail in Chapter seven. Therefore, the aim of this chapter is to demonstrate this in practical application to material selection problem. This chapter first provides the background to the selected case study and input data collection procedures for the sustainability model described in the preceding chapter. In view of the complex nature of the research, case study was chosen as the best means to validate the model and show how the sustainability index works to rank building materials.

Case studies have previously been adopted as a relevant and adequate research methodology in planning, design and construction, economic and political science (Gillham, 2000; Yin, 2003). They allow an empirical inquiry into the real-life context of research work. They are particularly useful when the research context is too complex for surveys or experimental strategies (Gillham, 2000). Data on the six criteria and sub-criteria included in the model were collected and computed analyzed to test the model's robustness

To test the applicability of the index, three commonly used roofing covering materials in UK residential buildings were selected as a sample for the case study. Residential building was chosen for the case study because majority of respondents in the initial survey specialize in residential buildings and have adequate experience in residential roofing materials. A further benefit is that residential buildings are based on the same set of pre-designed criteria, providing an ideal platform for analysis and comparison. Given that building projects are in many ways unique, these 3 roofing materials facilitated easier data analysis and comparison and provided a good opportunity to test the sustainability model.

8.2 Implementation of the Selection Model: The AHP survey

The worked example for elucidating the application of the model in practice involves the application to a hypothetical but realistic scenario of a building material selection problem. The scenario assumed for the worked example is defined as follows:

8.2.1 The scenario: a hypothetical study case

The case study used intends to provide an indication of the use of the AHP multi-criteria decision-making model for the problem analyzed (i.e., the selection of sustainable building materials).The proposed scenario taken as study case is a hypothetical design of a single family home located in a light residential area of Wolverhampton, West midlands. An architect is working with a client to select materials (in this case roofing material) for a proposed residential building. The client tells the architect that he wants a building made from materials that are friendly to the environment. The client qualifies his specifications, however, to say that he does not want the building's functions to be compromised by the design or choice of materials. He goes on to say that, while he is willing to spend more money on materials to achieve a "sustainable building," cost is still a consideration. The architect decides to use MADA to make the material choices that will best satisfy the clients' needs.

Table 8.1 summarizes the details for the three options of roof covering materials for the proposed project. From the table, the description of the three options was based on the standard practices and construction details commonly used in the UK.

Table 8.1 Summary of roofing options for the proposed project

Description	Option A	Option B	Option C
Element type	Pitched Roof Timber Construction	Pitched Roof Timber Construction	Pitched Roof Timber Construction
Building type	Residential	Residential	Residential
Element	Timber trussed rafters and joists with insulation, roofing underlay, counterbattens, battens and UK produced concrete interlocking tiles	Structurally insulated timber panel system with OSB/3 each side, roofing underlay, counterbattens, battens and UK produced reclaimed clay tiles	Structurally insulated timber panel system with plywood (temperate EN 636-2) decking each side, roofing underlay, counterbattens, battens and UK produced Fibre cement slates
Size of tile or slate	420mm x 330mm	420mm x 330mm	420mm x 330mm
Pitch of roof	22.5^{o}	22.5^{o}	22.5^{o}

These 3 roof covering materials described above will be analyzed for the selection of sustainable option among alternatives. In other words, this section will analyze, through the use of the mathematical multi-criteria decision-making model described in the previous chapter, which one is the most sustainable roofing material for this scenario.

8.2.2 Measurement and data collection

The research instrument used was a questionnaire that captured data about the pair-wise comparison of each of the hierarchy level of the AHP model. The questionnaire (the second questionnaire as shown in Appendix C) was designed to facilitate systematic data collection. The questionnaire format was synthesised with reference to an AHP matrix proposed by Saaty (2000). Since the assignment of weights requires logical and analytical thinking, only the relevant building experts or professionals who were capable of providing penetrating insights were highly valuable to this empirical inquiry. To search for appropriate respondents, a question in the earlier general survey (chapter 6) questionnaire asked the respondents if they were experienced or specialized in the application of sustainable material for building project. An invitation note for the AHP survey was sent by e-mail to 86 participants who reported that they were well experienced in sustainable building projects. Of all the experienced building practitioners contacted, 19 professionals expressed interest and were willing to participate in providing their opinion to the second stage AHP questionnaire survey.

AHP is a subjective MCDM method (Reza *et al.,* 2010) where it is not necessary to involve a large sample, and it is useful for research focusing on a specific issue where a large sample is not mandatory (Cheng and Li, 2002; Wong and Li, 2008). Cheng and Li (2002) pointed out that AHP method may be impractical for a survey with a large sample size as ‘cold-called’ respondents may have a great tendency to provide arbitrary answers, resulting in a very high degree of inconsistency. AHP survey with a small sample size has been conducted in previous research. For example, Cheng and

Li (2002) invited 9 construction experts to undertake a survey to test comparability of critical success factors for construction partnering. Lam and Zhao (1998) also invited 8 experts for a quality-of-teaching survey. In this study, 10 returned questionnaires were received for the AHP survey.

All these studies indicate that AHP method is appropriate for research focusing on a specific area, where there are difficulties in achieving a large sample size or high response rate. Due to the small sample size involved, it is important to ensure that only valid and good quality data are acquired. Chua *et al.* (1999) provide a number of suggestions which was used in this study in the design of AHP questionnaire survey which helps to achieve these ends. These suggestions include:

- A brief presentation with regard to the objective and methodology of the AHP was made to every respondent individually. An illustrative example was provided in the questionnaire.
- The respondents were reminded of the importance of observing consistency in their answers in the questionnaire.
- The questions relating to different aspects were presented in different sections. This helps respondents to focus on one aspect at a time.

The questionnaire was used to assess the respondents judgments about each roof covering material with respect to the criteria introduced before in section 6.7. Prior to the design of the pair-wise comparison matrices for the survey, the decision hierarchies should be established. The chain of decision hierarchy is established based on the identification of sustainability criteria in chapter 6 of the general survey and the decision model presented in the preceding chapter. A Fundamental scale suggested by Saaty (1980) was utilized to enable paired comparisons in the questionnaires. The fundamental scale is a 9 point scale and is very practical to use for paired comparisons. By definition, its purpose is to assess the dominance of each element over other elements with respect to each element of the immediate higher levels of the hierarchy (Wind and Saaty 1980). On the criteria scoring matrix, all have been listed and compared, one against another. One pair of sustainability criteria is compared at a time. Letters of both criteria were indicated on each cell. If two criteria are judged to be equally important, respondents were asked to insert both letters. On the other hand, if a criteria was judged to be more important than the other, only the letter of that criteria will be inserted.

By evaluating the consistency level of the collected questionnaires, 9 questionnaires out of the 10 received have acceptable consistency and were entered into the analysis. A list of the experts and their positions in the corresponding companies is summarized in Table 8.2. The names of experts that participated in the survey were undisclosed in order to respect their anonymity.

Table 8.2. List of experts for the AHP survey

Position (organization type)	Years of exprerience	No. of sustainable building handled
1. Principal architect (Architectural/design office)	50	>30
2. Principal architect (Architectural/design office)	40	>30
3.Project architect (Architectural/design office)	8	-
4. Director (Architectural/design office)	25	<30
5. Senior architect (Architectural/design office)	40	A lot
6. Director (Architectural/design office)	38	<30
7. Senior associate (Architectural/design office)	28	>30
8. Director (Architectural/design office)	25	>30
9. Associate director (Architectural/design office)	17	<30

8.3 The application of the AHP model to the problem

To better illustrate the procedure of AHP, a complete example of applying AHP to the problem of roofing material selection is provided here. The first steps were done in the previous chapters (Chapter 6 and 7) where a series of criteria were defined and categorized into six groups. The hierarchy is constructed based on that set of factors as illustrated in Fig. 7.3 in preceding chapter

8.3.1 Decomposition of the decision problem

At first, a user defines the problem. Fig. 8.1 shows the exemplary hierarchy of the problem. To select sustainable choice among alternatives, the user should define decision criteria. In other word, the problem is which alternative could be the best choice to meet the goal considering all criterion. The goal is to choose a sustainable roof covering material among options for the project described in section 8.2. The goal is placed at the top of the hierarchy.

The hierarchy descends from the more general criteria in the second level to sub-criteria in the third level to the alternatives at the bottom or fourth level. The general criteria level involved six major criteria: environmental impact, life cycle cost, waste minimization, performance capability, Resource efficiency and socio benefit. The decision-making team considered three roofing materials for the decision alternatives, and located them on the bottom level of the hierarchy. Figure 8.1 shows the hierarchical representation of the roofing material selection model.

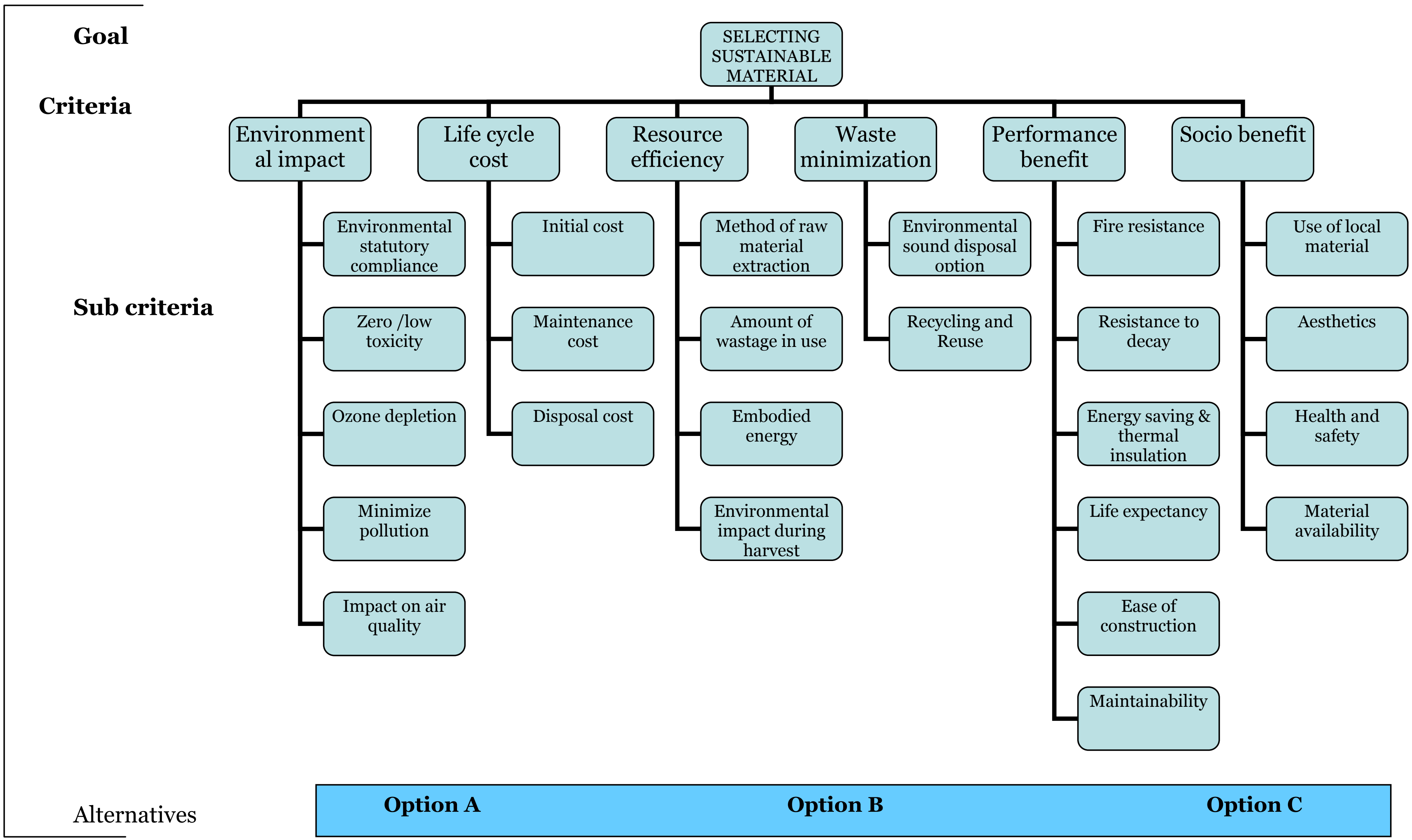


Figure 8.1 Hierarchy of the decision problem

8.3.2 Performing Pair-wise Comparisons

After constructing the hierarchy, pair-wise comparisons were performed systematically to include all the combinations of criteria and sub-criteria relationships. The criteria and sub-criteria were compared according to their relative importance with respect to the parent element in the adjacent upper level. Prior to the study, the actual implementation of this model required that a group of decision makers should get together in a brainstorming session and arrive at a consensus about each of these value judgments. It was not possible due to the differences in the schedule of the respondents. Hence, questionnaire (appendix C) including all possible pair-wise comparison combinations were distributed to the decision makers (9 respondents from different organization).

They first made all the pair-wise comparisons using semantic terms from the fundamental scale and then translated these to the corresponding numbers, separately. The questions to ask when comparing two criteria being compared, which is considered more important by the decision-maker while selecting a sustainable material, and how much more important is it with respect to selection. After performing all pairwise comparisons by the decision-makers, the individual judgments were aggregated using the geometric mean as Saaty suggested (Saaty, 2001). The judgments were based upon the gathered information through the questionnaires. The results are then combined by applying the geometric mean.

8.3.2.1 Pair-Wise Analysis of main criteria

The nine respondents filled the pair-wise comparison matrices using the verbal scale proposed by Saaty (1980), as presented in table 7.2. The responses of each respondent were analyzed using Expert Choice Pro 11.5 to calculate the consistency ratio (CR) and the weighting vectors of each main criteria and sub-criteria. As mentioned earlier, the pair-wise comparison matrices obtained from the 9 respondents were combined using the geometric mean approach at each hierarchy level to obtain the corresponding consensus pair-wise comparison matrices, as shown in figures 8.3-8.9. Each of these matrices was then translated into the corresponding largest eigenvalue problem and is solved to find the normalized and unique priority weights for each criterion.

According to Saaty (1980) the judgment of a respondent is accepted if CR ≤ 0.10. The mean values of the Eigenvector comparisons were calculated. The result of two of the respondents was not consistent and the inconsistencies in the results were communicated back to the two evaluators who agreed to go through the comparison again, but this time with the researcher. They were requested also to carefully evaluate the criteria until consistency was achieved.

Table 8.3 represents the principal matrix of comparison, which contains the comparison between main criteria in relation to the overall objective of the problem (i.e., the selection of a sustainable roof covering material). From the Table, it is possible to observe that criterion EI is 5 times more important that criterion SB. As a logical consequence, criterion SB is 5 times less important than criterion EI. It is also possible to observe that the elements in the principal diagonal are always equal to 1, because $W_{ij}=1$ when $i=j$. In other words, the weight of a criterion in relation to itself, obviously, is always 1. These values, as mentioned before, were given by the decision maker based on his/her aprioristic knowledge.

Table 8.3 Pairwise matrix and priorities for main criteria

Main criteria	EI	LCC	RE	WM	PC	SB
EI	1	½	1/3	1/6	2	3
LCC	2	1	½	1/3	4	5
RE	3	2	1	½	3	6
WM	6	3	2	1	5	6
PB	½	¼	1/3	1/5	1	2
SB	1/3	1/5	1/6	1/6	½	1

A local priority vector can be generated for the matrix of judgements in Table 8.3 by normalizing the vector in each column of the matrix (i.e. dividing each entry of the column by the column total) and then averaging over the rows of the resulting matrix (Saaty, 1980). The normalized eigenvector shown in Table 8.4a represents the relative importance of the criterion. Based on the above calculation, the relative priorities of criteria in the final selection of a sustainable roof covering material are shown on Table 8.4b. The resulting local priority vectors can be given as: (0.154, 0.321, 0.077, 0.057, 0.350, and 0.041).

Table 8.4a Computing the priority vector from the judgment in table 8.3

Main criteria	EI	LCC	RE	WM	PB	SB	Priority vector
EI	0.178	0.172	0.170	0.171	0.129	0.129	0.154
LCC	0.234	0.288	0.234	0.209	0.194	0.261	0.321
RE	0.156	0.144	0.117	0.126	0.158	0.117	0.077
WM	0.039	0.036	0.070	0.105	0.065	0.087	0.057
PB	0.469	0.432	0.468	0.418	0.323	0.261	0.350
SB	0.023	0.029	0.040	0.071	0.032	0.043	0.041

Table 8.4b Relative priority of criteria

Criterion	Relative priority
Performance capability	0.350
Life cycle cost	0.321
Environmental impact	0.154
Resource efficiency	0.077
Waste minimization	0.057
Social benefit	0.041

Thus, in order to measure the consistence of this first matrix of comparison, the consistence index (CI) is calculated. Imputing the values into the formula in 7.16, the CI for this first matrix was then calculated:

$$0.154 \left| \begin{matrix} 1 \\ 2 \\ 3 \\ 6 \\ 0.5 \\ 0.33 \end{matrix} \right| + 0321 \left| \begin{matrix} 0.5 \\ 1 \\ 2 \\ 3 \\ 0.25 \\ 0.2 \end{matrix} \right| + 0.077 \left| \begin{matrix} 0.33 \\ 0.5 \\ 1 \\ 2 \\ 0.33 \\ 0.16 \end{matrix} \right| + 0.057 \left| \begin{matrix} 0.16 \\ 0.33 \\ 0.5 \\ 1 \\ 0.06 \\ 0.16 \end{matrix} \right| +0.350 \left| \begin{matrix} 2 \\ 4 \\ 3 \\ 5 \\ 1 \\ 0.5 \end{matrix} \right|$$

$$+ 0.041 \left| \begin{matrix} 3 \\ 5 \\ 6 \\ 6 \\ 2 \\ 1 \end{matrix} \right| = \left| \begin{matrix} 0.803 \\ 1.292 \\ 1.506 \\ 0.926 \\ 0.413 \\ 0.614 \end{matrix} \right|$$

$$\frac{0.803}{0.154} = 5.21 \quad \frac{1.292}{0.321} = 4.02 \quad \frac{1.506}{0.077} = 9.60 \quad \frac{0.926}{0.057} = 6.2 \quad \frac{0.413}{0.350} = 1.18 \quad \frac{0.614}{0.041} = 10.5$$

$$\lambda_{\max} = \frac{5.21 + 4.02 + 9.60 + 6.20 + 1.18 + 10.50}{6} = 6.119$$

$$CI = \frac{(\lambda_{\max} - n)}{n - 1} = \frac{6.119 - 6}{6 - 1} = 0.023$$

Another index that is needed to be calculated is the random index (RI). According to Saaty (2008), for matrix of order 6, the RI is 1.24 (see Table 7.3). Finally with these two values in hand, the CR is the then calculated as:

$$CR = \frac{0.023}{1.24} = 0.019$$

According to the AHP model, a matrix is considered as being consistent when the CR is less than 10%. So, for this case, the matrix is considered as consistent and the same procedure is then carried out for the other comparison matrices in this case with the aid of expert choice software.

8.3.2.2 Pair-Wise Analysis of sub-criteria

The next pairwise comparison matrices are shown from table 8.5 -8.9. The same calculations done for the principal matrix are done for these matrices as well. The local priority vector and the consistency ratio for each matrix were computed and displayed on each corresponding Table.

Table 8.5 Pair-wise matrix & priorities for Environmental impact

Sub criteria	Environmental statutory compliance	Zero/low toxicity	Ozone depletion	Minimize pollution	Impact on air quality	Priority vector
Environmental statutory compliance	1	4	3	7	7	0.517
Zero/low toxicity		1	½	2	3	0.137
Ozone depletion			1	3	4	0.219
Minimize pollution				1	1	0.68
Impact on air quality					1	0.60

C.I. =0.01, R.I. =1.12, C.R. =0.009

Table 8.5 Pair-wise matrix & priorities for LCC

Sub criteria	Purchase cost	Disposal cost	Maintenance cost	Priority vector
Purchase cost	1	6	4	0.69
Disposal cost		1	1/3	0.22
Maintenance cost			1	0.09

C.I. =0.02, R.I. =0.58, C.R. =0.03

Table 8.6 Pair-wise matrix & priorities for Resource efficiency

Sub criteria	Embodied energy	Amount of wastage	Method of extraction	Impact during harvest	Priority vector
Embodied energy	1	½	4	2	0.289
Amount of wastage		1	5	3	0.475
Method of extraction			1	½	0.081
Impact during harvest				1	0.155

C.I. =0.025, R.I. =0.90, C.R. =0.028

Table 8.7 Pair-wise matrix & priorities for Waste minimisation

Sub criteria	Recycling and reuse	Environmental sound disposal	Priority vector
Recycling and reuse	1	2	0.67
Environmentally sound disposal		1	0.33

C.I. =0.00, R.I. =0.00, C.R. =0.00

Table 8.8 Pair-wise matrix & priorities for performance capability

Sub criteria	Fire resistance	Maintainability	Resistance to decay	Life expectancy	Energy saving & thermal insulation	Buildability	Priority vector
Fire resistance	1	½	4	1	1	2	0.183
Maintainability		1	5	1	1	3	0.258
Resistance to decay			1	¼	1/5	½	0.47
Life expectancy				1	1	2	0.204
Energy saving & thermal insulation					1	2	0.212
Buildability						1	0.095

C.I. =0.00821, R.I. =1.24, C.R. =0.007

Table 8.9 Pair-wise matrix & priorities for Social benefit

Sub criteria	Local material	Aesthetics	Health & Safety	Material availability	Priority vector
Local material	1	½	½	3	0.193
Aesthetics		1	1	5	0.368
Health & Safety			1	5	0.368
Material availability				1	0.070

C.I. =0.025, R.I. =0.90, C.R. =0.03

8.3.3 Final Weights of Each Criterion

To find the final (global) sustainability weight of each sub-criterion, the results of the weighting vector for standing sustainability criteria list were arranged in Table 8.10 and Figure 8.2. The main criteria weighting vectors (1) are multiplied by the corresponding sub-criteria weighting vectors (2) to obtain the (global) criteria weight (3). The five highest weighted sub-criteria for standing list were: initial cost, resistance to decay, minimizes pollution, maintainability and impact on air quality. These weights and other weights will subsequently be used to evaluate the material attributes that will be fed into the model for sustainable building material selection.

Table 8.10 Priority weights for sustainability criteria and sub criteria used in the case study

Sustainability Criterion	Local weight (1)[a]	Sustainability Sub-criterion	Local weight(2)	Global weight (3)[b]
Environmental impact	0.154	Environmental statutory compliance Zero/low toxicity Ozone depletion Minimize pollution Impact on air quality	0.517 0.137 0.219 0.68 0.60	0.07962 0.02109[c] 0.03373 0.10472 0.0924
Life cycle cost	0.321	Maintenance cost Initial cost Disposal cost	0.22 0.69 0.09	0.07062 0.22149 0.02889
Resource efficiency	0.077	Method of raw material extraction Amount of wastage Embodied energy Environmental impact during harvest	0.081 0.475 0.289 0.155	0.00624 0.03658 0.02225 0.01194
Performance capability	0.350	Fire resistance Resistance to decay Energy saving & thermal insulation Life expectancy Ease of construction Maintainability	0.183 0.47 0..212 0.204 0.095 0.258	0.06405 0.1645 0.0742 0.0714 0.03325 0.0903
Social benefit	0.041	Use of Local material Aesthetics Health and safety Material availability	0.193 0.368 0.368 0.070	0.00791 0.01508 0.01508 0.00287
Waste minimization	0.057	Environmental sound disposal option Recycling and reuse	0.33 0.67	0.01881 0.03819
∑	**1.000**		**∑**	**1.000**

a Local weight is derived from judgement with respect to a single criterion
b Global weight is derived from multiplication by the priority of the criterion
c This entry is obtained as follows: 0.154 x 0.137=0.02109. The global weight of the subcriterion is obtained by multiplying the local weight of the sub-criterion by the weight of the criterion.

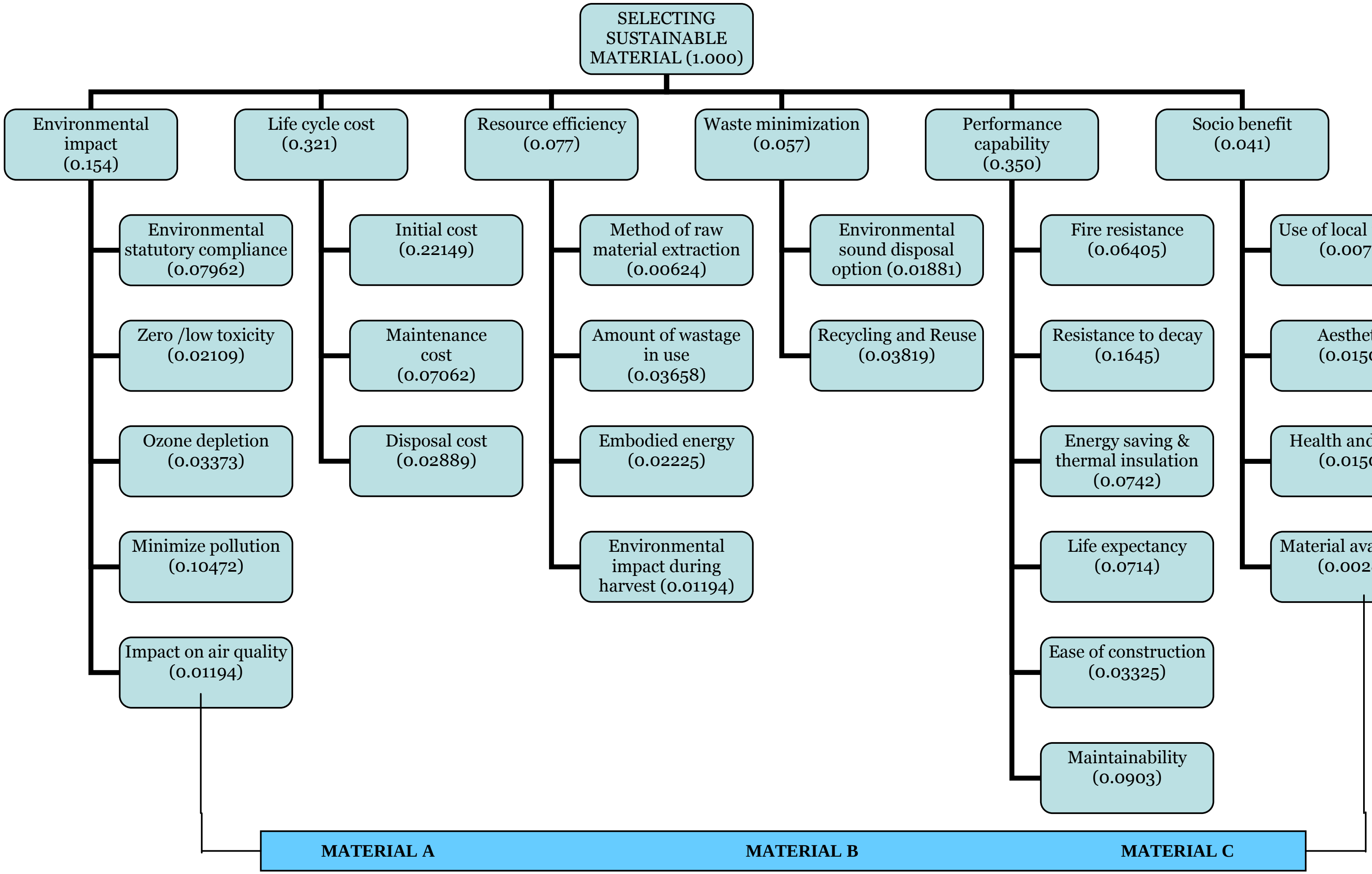


Figure 8.2 Global weights set for sustainability criteria and sub-criteria for material selection problem in the study

8.3.4 The Alternatives Pair-Wise Comparison

The final step in the pair-wise comparison involves comparing each pair of alternatives with respect to each sub-criterion. In comparing the three roof covering materials, the decision-makers were asked which material is preferred with respect to each sub-criterion in level 3. They are represented by letter A, B and C. Table 8.11 to 8.34 explain the pair-wise matrix and priorities for each sub-criterion.

Table 8.11: Env. Statutory compliance

E1	A	B	C	Priority vector
A	1	1/7	1/5	0.072
B	7	1	3	0.650
C	5	1/3	1	0.278

λ_{max}= 3.065; C.I. =0.032; CR =0.056

Table 8.12: Zero/low toxicity

E2	A	B	C	Priority vector
A	1	½	½	0.200
B	2	1	1	0.400
C	2	1	1	0.400

λ_{max} =3.000; C.I. =0.00; CR=0.00

Table 8.13 Ozone depletion

E3	A	B	C	Priority vector
A	1	8	6	0.747
B	1/8	1	1/5	0.060
C	1/8	5	1	0.193

λ_{max} = 3.197; C.I. =0.099; CR= 0.170

Table 8.14 Minimize pollution

E4	A	B	C	Priority vector
A	1	¼	1	0.674
B	4	1	2	0.101
C	1	½	1	0.226

λ_{max}=3.053; C.I=0.025; CR=0.151

Table 8.15 Impact on air quality

E5	A	B	C	Priority vector
A	1	8	8	0.796
B	1/8	1	2	0.125
C	1/8	½	1	0.079

λ_{max} =3.053; C.I. =0.027; CR= 0.051

Table 8.16 Maintenance cost

L1	A	B	C	Priority vector
A	1	4	6	0.691
B	¼	1	3	0.218
C	1/6	1/3	1	0.091

λ_{max}= 3.053; CI=0.027; CR=0.051

Table 8.17 Initial cost

L2	A	B	C	Priority vector
A	1	9	6	0.770
B	1/9	1	1/3	0.068
C	1/6	3	1	0.162

λ_{max} =3.053; C.I. =0.027; CR= 0.051

Table 8.18 Disposal cost

L3	A	B	C	Priority vector
A	1	7	5	0.731
B	1/7	1	1/3	0.081
C	1/5	3	1	0.188

λ_{max} =3.064; C.I. =0.032; CR= 0.062

Table 8.19 Method of raw material extraction

R1	A	B	C	Priority vector
A	1	2	1	0.400
B	½	1	½	0.200
C	1	2	1	0.400

λ_{max} =3.000; C.I. =0.00; CR= 0.00

Table 8.20 Amount of wastage

R2	A	B	C	Priority vector
A	1	1/3	¼	0.126
B	3	1	1	0.416
C	4	1	1	0.458

λ_{max} =3.009; C.I. =0.005; CR= 0.009

Table 8.21 Embodied energy

R3	A	B	C	Priority vector
A	1	6	4	0.691
B	1/6	1	1/3	0.091
C	¼	3	1	0.218

λ_{max} =3.136; C.I. =0.068; CR= 0.117

Table 8.22 Env. Impact during harvest

R4	A	B	C	Priority vector
A	1	6	8	0.754
B	1/6	1	4	0.181
C	1/8	¼	1	0.065

λ_{max} =3.053; C.I. =0.027; CR= 0.051

Table 8.23 Fire resistance

P1	A	B	C	Priority vector
A	1	9	8	0.804
B	1/9	1	½	0.074
C	1/8	2	1	0.122

λ_{max} =3.036; C.I. =0.018; CR= 0.035

Table 8.24 Resistance to decay

P2	A	B	C	Priority vector
A	1	6	1	0.472
B	1/6	1	5	0.084
C	1	5	1	0.444

λ_{max} =3.004; C.I. =0.002; CR= 0.004

Table 8.25 Energy saving & thermal insulation

P3	A	B	C	Priority vector
A	1	9	7	0.802
B	1/9	1	1/5	0.075
C	1/7	5	1	0.211

λ_{max} =3.035; C.I. =0.0016; CR= 0.032

Table 8.26 Life expectancy

P4	A	B	C	Priority vector
A	1	¼	1	0.184
B	4	1	2	0.584
C	1	½	1	0.232

λ_{max} =3.053; C.I. =0.027; CR= 0.051

Table 8.27 Ease of construction

P5	A	B	C	Priority vector
A	1	6	4	0.691
B	1/6	1	1/3	0.091
C	¼	3	1	0.218

λ_{max} =3.035; C.I. =0.016; CR= 0.032

Table 8.28 Maintainability

P6	A	B	C	Priority vector
A	1	5	1	0.45
B	1/5	1	1/5	0.09
C	1	5	1	0.46

λ_{max} =3.000; C.I. =0.00; CR= 0.00

Table 8.29 Use of local material

S1	A	B	C	Priority vector
A	1	1/3	1/3	0.300
B	3	1	1	0.600
C	3	1	1	0.600

λ_{max} =4.000; C.I. =0.000; CR= 0.000

Table 8.30 Aesthetics

S2	A	B	C	Priority vector
A	1	1/8	1/6	0.082
B	8	1	3	0.700
C	6	1/3	1	0.378

λ_{max} =3.064; C.I. =0.032; CR= 0.056

Table 8.31 Health & safety

S3	A	B	C	Priority vector
A	1	9	6	0.770
B	1/9	1	½	0.058
C	1/6	2	1	0.162

λ_{max} =3.053; C.I. =0.027; CR= 0.051

Table 8.32 Material availability

S4	A	B	C	Priority vector
A	1	9	7	0.770
B	1/9	1	1/5	0.050
C	1/7	5	1	0.170

λ_{max} =3.210; C.I. =0.105; CR= 0.180

Table 8.33 Env. Sound disposal option

W1	A	B	C	Priority vector
A	1	6	4	0.69
B	1/6	1	1/3	0.09
C	¼	3	1	0.22

λ_{max} =3.05; C.I. =0.025; CR= 0.04

Table 8.34 Recycling & reuse

W2	A	B	C	Priority vector
A	1	5	1	0.45
B	1/5	1	1/5	0.09
C	1	5	1	0.46

λ_{max} =3.00; C.I. =0.00; CR= 0.00

KEYS:	E1-W2	L1-S4	P1-P6
	E1: Environmental statutory compliance E2: Zero or low toxicity E3: Ozone depletion potential E4: Minimise pollution (e.g. air, land) E5 Impact of material on air quality R1 Method of raw material extraction R2 Amount of likely wastage in use of material R3 Embodied energy within material R4 Environmental Impact during material harvest W1 Availability of environmentally sound disposal options W2 Potential for recycling and reuse	L1: Maintenance cost L2: Initial cost (acquisition cost) L3: disposal cost S1: Use of local material S2: Aesthetics S3:Health and safety S4: Material availability	P1: Fire resistance P2:Resistance to decay P3: Energy saving and thermal insulation P4:Life expectancy of material (e.g. strength, durability etc) P5: Ease of construction (buildability) P6: Maintainability

8.3.5 Synthesizing the Results

After computing the normalized priority weights for each pair-wise comparison judgment matrices (PCJM) of the AHP hierarchy, the next phase was to synthesize the rating for each criteria. The normalized local priority weights of dimensions of sustainability and various SC were obtained and were combined together in order to obtain the global composite priority weights of all SC used in the third level of the

AHP model. Expert Choice 11.5 was used to determine these global priority weights. It provides two ways of synthesizing the local priorities of the alternatives using the global priorities of their parent criteria: the distributive mode and the ideal mode. In the distributive mode the weight of a criterion reflects the importance that the decision maker attaches to the dominance of each alternative relative to all other alternatives under that criterion. In this case, the distributive mode would be the way to synthesize the results. After deriving the local priorities for the criteria and the alternatives through pair-wise comparisons, the priorities of the criteria are synthesized to calculate the overall priorities for the decision alternatives. As shown in Table 8.35, the materials are ranked according to their overall priorities. Material option (A) turns out to be the most preferable material among the three materials, with an overall priority score of 0.453.

Table 8.35 Overall rating of the three assessed roofing material using AHP model

Criterion	**Local weight (1)**	**Sub-criterion**	**Local weight (2)**	**Local weight (3)** $M\ (A)$	$M(B)$	$M(C)$	**Global weight (4)** $M\ (A)$	$M\ (B)$	$M(C)$
Environmental impact	0.154	Environmental statutory compliance	0.517	0.072	0.650	0.278	0.0057	0.0504	0.0725
		Zero/low toxicity	0.137	0.200	0.400	0.400	0.0042	0.0084	0.0084
		Ozone depletion	0.219	0.747	0.060	0.193	0.0252	0.0020	0.0065
		Minimize pollution	0.68	0.674	0.101	0.226	0.0306	0.0106	0.0237
		Impact on air quality	0.60	0.796	0.125	0.079	0.0736	0.0116	0.0073
Life cycle cost	0.321	Maintenance cost	0.22	0.691	0.218	0.091	0.0088	0.0054	0.0064
		Initial cost	0.69	0.770	0.068	0.162	0.0705	0.0151	0.0359
		Disposal cost	0.09	0.731	0.081	0.188	0.0216	0.0023	0.0054
Resource efficiency	0.077	Method of raw material extraction	0.081	0.400	0.200	0.400	0.0025	0.0012	0.0025
		Amount of wastage	0.475	0.126	0.416	0.458	0.0046	0.0152	0.0168
		Embodied energy	0.289	0.691	0.091	0.218	0.0154	0.0020	0.0049
		Environmental impact during harvest	0.155	0.754	0.181	0.065	0.0090	0.0027	0.0008
Performance capability	0.350	Fire resistance	0.183	0.804	0.074	0.122	0.0515	0.0047	0.0078
		Resistance to decay	0.47	0.472	0.084	0.444	0.0376	0.0138	0.0330
		Energy saving & thermal insulation	0.212	0.802	0.075	0.211	0.0295	0.0056	0.0157
		Life expectancy	0.204	0.184	0.584	0.232	0.0131	0.0417	0.0166
		Ease of construction	0.095	0.691	0.091	0.218	0.0229	0.0030	0.0072
		Maintainability	0.258	0.45	0.90	0.46	0.0206	0.0313	0.0215
Socio benefit	0.041	Use of local material	0.193	0.300	0.600	0.600	0.0024	0.0048	0.0048
		Aesthetics	0.368	0.082	0.700	0.378	0.0012	0.0106	0.0057
		Health and safety	0.368	0.770	0.058	0.162	0.0116	0.0009	0.0024
		Material availability	0.070	0.770	0.050	0.170	0.0022	0.0001	0.0005
Waste minimization	0.057	Environmental sound disposal option	0.33	0.69	0.09	0.22	0.0130	0.0017	0.0041
		Recycling & reuse	0.67	0.45	0.09	0.46	0.0172	0.0034	0.0176
							0.453	**0.249**	**0.324**
Total	**1.000**		**Overall priority**						
			***Sustainability index**				**1**	**3**	**2**

*Sustainability index was calculated using weighted summation method as detailed in Chapter seven

8.3.6 Recap of the application of the model

As discussed in Chapter seven, the sustainability index is the function of the six criteria. It is calculated for each option by multiplying each value by the weight, followed by summing the weighted scores for all criteria using the weighted summation method. The best material option has the highest score in the sustainability index. The amalgamation method yields a single index of alternative worth, which allows the options to be ranked. The higher the sustainability index, the better the option. The sustainability index as calculated for the three material alternatives was 0.453, 0.249 and 0.324 for options A, B and C respectively. In respect to the principle of a sustainability index, the ranking for the three options for the material alternatives is A>C>B. Option A emerges as the best option amongst the rival alternatives.

This example verifies that the sustainability model is able to provide rankings in material assessment and the outcome of ranking for the proposed material appear to the best alternative. The sustainability model is an important part of this research, combining economic, technical, social and environmental criteria into a composite index system for material selection. The sustainability index was developed to fill the gap between existing material assessment techniques and the increasing demand for sustainable development in the construction industry.

This section demonstrates that the six criteria can be combined together to rank building materials and also remain constant for any type of construction. The sustainability index has demonstrated a more environmentally friendly practice, and a more responsible attitude towards the environment.

8.4. Validating the decision model

Validation is a key part of model development process which increases confidence in the model and make it more valuable (Kennedy, *et al*, 2005). Thus, the developed sustainable material selection model reported in the preceding chapter, and its application to case materials was sent to building design and construction experts in the UK for their comments, as a means of validating the model and its application. This section reports on the validation process and its findings. However, as background information, the section first outlines what is meant by validation, the various techniques available for performing it and the rationale behind the adoption of the technique used for validating this model.

8.4.1 Validation and its Techniques

There are many perspectives regarding the importance of validation in research, its definition, terms to describe it and the techniques for establishing it (Creswell, 2007). Given the many perspectives, Winter (2000) argue that "validation" is not a single, fixed or universal concept, but rather a contingent construct, inevitably grounded in the process and intentions of particular research projects and methodologies. From modelling standpoint, validation is the process of defining whether the model is a meaningful and accurate representation of the real system in a particular problem domain (Borenstein, 1998). Unlike model verification, which is concerned with developing the model right, validation is concerned with developing the right model, (Gass, 1983; Kennedy, *et al*, 2005). It thus attempts to establish how closely the model mirrors the perceived reality of the model user/developer team (Gass, 1983). Sargent (1998) argue that a model is developed for a specific purpose (or application) so its validity should be determined with respect to that purpose. The main purpose of validation is to get a better understanding of the model's capabilities, limitations and appropriateness in addressing the problem being modelled (Macal, 2005). These insights are often used to improve the model to an acceptable standard. In addition, they enable the modeller to meet certain criticisms of the model such as omissions and assumptions used; and help instil confidence in the model's output (Gass, 1983). However, it is often too costly and time-consuming to determine that a model is *absolutely* valid over the complete domain of its intended applicability (Sargent, 1998). Perhaps, this is because models are inherently unable to totally reproduce or predict the real environment (Gass, 1983). Thus, the validation process is often not aim at achieving absolute validity but rather confined to checking for *Operational Validity*. This validity concerns the process of establishing that the model's output behaviour has sufficient accuracy for the model's intended purpose over the domain of the model's intended applicability (Sargent, 1998). Other elements that concern operational validity include establishing whether the model (Gass, 1983): (i) offer a reasonable improvement in terms of net cost savings (ii) is robust enough that a user would find it difficult to make it yield an ostensibly wrong solution.

There are various techniques for validating a model, each of which can be used either subjectively or objectively, the latter referring to the use of some type of statistical or mathematical procedures (Sargent, 1998; Qureshi *et al.*, 1999). The basic idea behind any of these techniques is the accumulation evidence regarding the credibility and applicability of the model by an independent, interested party (Gass, 1983). It is common to use a combination of the techniques when validating a model. Brief descriptions of these techniques, as defined in the literature (Gass, 1983; Sargent, 1998; Kennedy *et al.*, 2005), are presented follows.

Animation*:* Watching a visual or graphical animation of the model's operational behaviour and comparing this with how the actual system behaves.

Comparison to Other Models*:* The output of the model being validated is compared to the results of other valid models of the actual system. This is applicable if such valid models are already available.

Degenerate Tests*:* The model behaviour is known to degenerate at certain situations. The model can be tested to see if it degenerates as expected by simulating such situations in the model using appropriate selection of values of the input and internal parameters.

Extreme Condition Tests: Similar to the degeneracy tests, the model can be tested by running it under extreme conditions to see if the model would behave as would be expected.

Event Validity: This technique is by comparing the "events" of occurrences of the model being validated to those of the real system to determine if they are similar.

Face Validity: This is by asking people who are knowledgeable about the system whether the model and/or its behaviour are reasonable. This technique can be used in determining if the logic in the conceptual model is correct and if a model's input output relationships are reasonable.

Fixed Values: By using fixed values (e.g., constants) for various model input and internal variables and parameters, the results of the model can be checked against easily calculated values.

Historical Data Validation: If historical data exist (or if data are collected on a system for building or testing the model), part of the data is used to build the model and the remaining data are used to determine (test) whether the model behaves as the system does.

Internal Validity: This is by running several replications of the model to determine the amount of internal variability in the model. A high amount of variability is an indication of lack of consistency and this may cause the model's results to be questionable and, if typical of the problem entity, may question the appropriateness of the policy or system being investigated.

Sensitivity Analysis: This technique consists of changing the values of the input and internal parameters of a model to determine the effect upon the model's behaviour and its output. The same relationships should occur in the model as in the real system. Those parameters that are sensitive, i.e., cause significant changes in the model's behaviour or output, should be made sufficiently accurate prior to using the model. This may require iterations in model development.

Predictive Validation: This technique consist of using the model to predict (forecast) the system behaviour, and then comparing the system's behaviour and the model's forecast to determine if they are the same. The system data may come from an operational system or from experiments performed on the system.

Traces: The behaviour of different types of specific entities in the model is traced (followed) through the model to determine if the model's logic is correct and if the necessary accuracy is obtained.

Turing Tests: People who are knowledgeable about the operations of a system are asked if they can discriminate between system and model outputs. Inability to discriminate between these outputs is an indication that the model is valid.

8.4.2 The technique adopted for validating the SBM selection model

According to Gass (1983), the appropriate technique to use for validating a model mainly depends on the real world aspect being analysed and the type of model being used. Consideration of the various techniques suggests *face validity* or expert opinion as the only appropriate techniques for validating the developed material selection model, mainly because no real-system data were available. Also, the aim of this study to validate the model for industry-wide application also makes this approach more suitable than the others. The objectives of expert opinion validation are to assess the feasibility of the model in terms of its adequacy and clarity, and to ensure that the model is reasonably robust and will be acceptable to users, much in the same spirit as member checking or validation in qualitative research (Bloor, 1997; Creswell, 2007).

Three options for carrying out the validation were considered: (i) focus group (ii) interviews and (iii) postal surveys. The use of focus group or interviews was handicapped by the time and cost constraints of the research, leaving postal survey as the most appropriate option. Problems associated with postal surveys such as the restrictive nature of the questionnaire and lack of opportunity to clarify respondents' doubts were overcome by carefully designing the questionnaire and including with it a worked example on the application of the model to clarify any misunderstandings the experts may have.

The following sections describe the detailed procedure of the validation exercise, which includes development of validation questionnaire, selection of experts, administration of the questionnaire and the findings.

8.4.3 Development of validation questionnaire

The second stage of the validation process was to develop a questionnaire indicating the areas where experts' views or comments are sought. The questionnaire was designed bearing in mind a number of criteria for validating a model including (Gass, 1983; Macal, 2005):

Accuracy and precision - can the model accurately and precisely select a sustainable material?

Completeness – does the model include all important decision variables required in the selection of sustainable material?

Comprehensibility – is the model simple and understandable to the intended users?

Cost effectiveness – does the cost involved in implementing the model outweigh its potential benefits?

The questionnaire also made provision for experts to express their comments on the model in general or on specific aspects of it. A copy of the questionnaire is set out in Appendix D.

8.4.4 Selection of the experts and response

For the model to be of acceptable standard to material specifiers, it is essential that the validation generates useful and relevant comments from relevant experts. This can only be achieved if the experts chosen to participate in the validation have the required expertise. In view of this, the experts were selected from the list of practitioners who responded to the postal questionnaire survey based on the following criteria: relevant expertise, relevant experience and academic and professional qualifications. The use of the previous survey's respondents list as a sample frame has two main advantages. Firstly, most of the practitioners in this list were individuals in senior positions from architectural and design firms with relevant expertise and experience material assessment and selection. Secondly, their prior involvement in the earlier survey makes them familiar with this research, which will ensure good response rate. Prior to sending out the questionnaire, letters were sent to the experts requesting for their kind assistance in the validation exercise. Following this, a brief description of the model incorporating the work example was send out via post to 25 selected experts. The mail also included the validation questionnaire and a cover letter, stating the purpose of the research, the validation process and what was expected of them.

8.4.5 Analysis of experts' response

Of the experts contacted, 7 responded to the survey. Table 8.36 shows the profile of these experts in terms of their organization, job designation, area of expertise, qualifications and years of experience in building design and construction. As can be seen, the experts are all actively involved in sustainability related project and material selection. They possess relevant qualifications and their total combined construction industry experience is over 98 years.

Table 8.36 Profile of the validation experts

Expert	Organization	Designation	Expertise	Qualification	Years of experience
1	Architectural & design firm	Principal	Full architectural service	BA (Hons) DipArch RIBA	13
2	Project management	Director	General practice	BA (Hons) DipArch RIBA	20
3	Architectural & design firm	Director	Material advice	MA (Cantab) DipArch RIBA	15
4	Engineering firm	Principal	Sustainable design	BArch (Hons) Dip Arch MArch RIBA	10
5	Architectural & design firm	Project architect	Sustainable design	BArch (Hons) Dip Arch MArch RIBA	12
6	Architectural & design firm	Senior associate	Full architectural service	BSc (Hons) Dip Arch FRSA RIBA	12
7	Architectural & design firm	Director	Material advice	MA DipArch RIBA	16

As mentioned earlier on, the respondents were asked in a structured, semi-closed questionnaire to comment on the model. In addition to offering ticked-box responses, some of the experts provided their own comments about the model. All the responses received were, to a large extent, positive. A summary of the responses to the various questions in the questionnaire are set out in Table 8.37.

Table 8.37 Summary of response from experts

Validation Criteria	Expert response						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Model address important problem in the area of material selection?	Yes, quite significant	Yes, quite significant	Yes, quite significant	Yes, but not significant	Yes, quite significant	Yes, quite significant	Yes, but not significant
Models Capability in assisting in material selection selection	Yes capable	Yes, highly capable	Yes, capable	No, not capable	Yes, highly capable	Yes, capable	Yes, highly capable
Comprehensibility of the model	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Resources needed to apply the model	Wouldn't be too costly to operate	Wouldn't be too costly to operate	Benefits of using it justifies any resource requirements	Wouldn't be too costly to operate	Wouldn't be too costly to operate	Wouldn't be too costly to operate	Wouldn't be too costly to operate
Completeness of the Model	Yes	Yes	No	Yes	Yes	Yes	Yes
Scale for rating material alternatives against criteria	Very suitable	Very suitable	Very suitable	not sure of suitability	Very suitable	Very suitable	not sure of suitability
Approaches/methods for evaluating the criteria in material rating	Not sure of its suitability	suitable	Not sure of its suitability	suitable	suitable	suitable	suitable
Attributes of material selection defined	Not sure of its suitability	suitable	Very suitable	suitable	suitable	Very suitable	suitable

As can be observed from the table, most of the experts agreed that the model addresses an important problem in the area of sustainable material selection. Concerning its capability in performing its intended function accurately, most of the experts were of the opinion that it is capable. This suggests that the model would be regarded by practitioners as a very useful tool for sustainable material selection.

In terms of the model's completeness, most experts felt that the model is comprehensive and detailed, touching on all relevant criteria for selecting building material. With regard to comprehensibility, most experts found the model to be clear and simple to understand and implement. One expert noted "*it has covered a very complex aspect of material assessment in a simple and logical manner, which I think would not be difficult to apply in practice*". Most experts felt that the model would not be too costly to implement at current resource level. One expert commented that "*its implementation would not consume great resources and time and consequently its benefit would outweigh the costs"*. The various approaches proposed for evaluating the selection criteria were found to suitable. The scale for rating the methods was also found to be appropriate. Issues of concern raised relates to the pairwise comparison technique adopted in the model. One expert mentioned that the "pairwise judgments in AHP are ambiguous, that the weights so determined may be meaningless*"* The author does agree with this in principle but considers the weightings to have sufficient objectivity, rigour and basis for generalisation over some period of time since they were views expressed by practitioners based on their many years of experience on projects. One expert recommended that for improve usage, the model must be computerised.

By and large the opinions of the experts were in favour of the model suggesting that the model would be regarded as valuable tool for sustainable building material selection. This represents a positive contribution to the body of knowledge and practice of sustainability within construction organisations. The model can now be recommended to practitioners, subject to future modifications that can improve its acceptability and performance.

8.5 Summary of the chapter

This chapter demonstrated the use of material selection model to rank material alternatives taking their sustainability into consideration. It also reports on the validation of the model. It involves first the application of the model to a hypothetical case study. This example application together with brief description of the model was then posted to acknowledged material specification experts within UK for their opinion on the significance of the model, its adequacy, completeness, comprehensibility and cost effectiveness. Out of 25 experts who were sent questionnaires for the validation, only 7 responded. The majority of them were in favour of the model indicating that the model is a positive contribution to sustainability implementation in building material selection.

CHAPTER 9: SUMMARY AND CONCLUSIONS

9.1 Introduction

This chapter presents a summary of the study. It embraces the findings from the literature review, the environmental awareness and sustainable practices survey of architects and designers, sustainable material selection practices and the development of a multi criteria assessment and model to aggregate sustainability attributes into a composite index for material selection. This conclusion links and integrates the research findings. The recommendations provide suggestions for future research which have emerged as a result of the findings of this study.

This thesis critically examines the environmental problems associated with construction activities, and investigates ways of implementing sustainable practices in the design and construction of buildings through the selection of building materials. It also investigates building assessment methods used in construction and their deficiencies as a tool to evaluate a building material sustainable performance.

In acknowledging the importance of considering sustainability issues in material selection, the conventional economic approach of decision-making was critically examined and discussed. This was explored by identifying and measuring the principal sustainable development criteria that embrace environmental considerations within a sustainable assessment framework for building projects.

The remainder of this chapter has been divided into several sections to discuss and summarize the research findings. It includes a review of aim and objectives for this research, a summary of the research, conclusions, policy implications arising from the study, limitations and areas for further research.

9.2 Review of aim and objectives

This thesis has satisfied the aims and objectives specified in the introduction. It has identified six sustainable development criteria and developed a model for aggregating the criteria into a composite sustainability index for material selection. This index uses a multi-criteria analysis approach to assess the complexity in building material assessment and selection for sustainability.

The sustainability index strikes a balance by considering the key variables of economic, social technical and environmental criteria to select the best option among alternatives. The research has satisfied the aims and objectives as outlined at the beginning.

9.2.1 Impacts of developments and building construction

The first research objective was to investigate the impacts of building construction on the environment. The literature review in Chapters Two and Three discovered that the environment has an inherent connection with economic growth. The growth of the economy will be jeopardized if the environment continues to deteriorate and natural resources overused. The literature shows that the global environment has degraded through various human activities and the environment will become inhabitable if environmental protection and conservation are not considered in building construction. The literature also reveals that construction plays a significant role in degrading the environment through on-site building activities and energy consumption during occupancy. In the literature, there is increasing realization of the need to design and construct for sustainability. The literature has also revealed that careful selection of sustainable building materials is the easiest way for designers to begin incorporating sustainable principles in building project. It calls for a decision support system that can aid building designers in sustainability assessment of building materials.

9.2.2 Aid to better decision-making

The second research objective was to review the literature and suggest ways to improve the conventional decision-making methodology used in construction. In Chapter Two, the conventional economic approach of life cycle cost analysis was examined and found wanting. Its deficiency, the methodological framework which monetarises environmental issues, was discussed at length. It was discovered that this deficiency has caused environmental degradation because the true prices have not been reflected in the decision-making process. The literature has revealed that life cycle cost analysis fails as an evaluation tool if environmental values are not incorporated in the decision-making model. The literature also revealed that decisions are seldom single-dimensional, as life cycle cost analysis does not capture the complex nature of the environment. Finally, emerging environmental building assessment methods were investigated and discussed in Chapter four.

The literature has revealed that environmental building assessment methods are insufficient in incorporating sustainability in the decision-making process, as most of them are single-dimensional. As derived from the literature, a multi-dimensional assessment model is required to effectively assess material sustainability. The concept and methodology of multi-criteria analysis was presented and discussed in Chapter Four, forming the foundation on which the sustainability index was developed.

9.2.3 Environmental awareness and sustainability implementing sustainability in building design and construction

The fourth objective was to investigate environmental issues awareness and sustainable material selection practices of architects and designers. The findings where covered extensively in chapter six. The concept of 'sustainable design is now the norm in many construction and design firm, as the survey shows that firms have adopted environmental policies and practices to enhance their competitiveness and image, and comply with increasingly stringent regulations. As in many other areas, the construction industry lags behind other sectors in these regards The study confirmed previous findings that architects and designers in UK claim to have a high level of awareness and knowledge of the adverse environmental impact of construction and how their design decisions contribute to this. However, the findings of the study showed a discrepancy between what architects claim to be convinced about, and knowledgeable in, and their commitment and practices; architects seem to be unable to translate their environmental awareness and knowledge into appropriate design decisions.

The last decade have seen sustainable development issues been gradually adopted in the UK construction industry, changing the traditional methods and technology. Part of the study therefore investigates the different drivers forcing architects and designers to adopt sustainable construction practices, as it concern material selection. Likewise, barriers facing designers in implementing sustainability was investigated and an important issue raised is the perception among clients and some architects that sustainable material cost more. With the cost issue in mind the chapter therefore explore various techniques for assessing sustainability of building materials while taking cost into consideration, was investigated, with the call for a decision support system for supporting architects and designers in assessing the sustainability of building materials.

9.2.4 Identify sustainable criteria and develop an assessment model for material selection decision-making

The fifth and the sixth research objective were to identify principal sustainable development criteria and develop an evaluation model for modelling decision-making for material selection. With reference to the deficiency of environmental building assessment methods and the need for a multi-dimensional approach in material assessment in the literature, a multi criteria evaluation model for aggregating the identified criteria into a composite index of material selection was developed in chapter seven.

A list of criteria was identified from the literature and responses from a questionnaire were used to rank the principal criteria to be incorporated in the sustainability index. Based on the survey results, the list of sustainable development criteria was narrowed down and grouped into the six criteria:

- Life cycle cost,
- Resource efficiency,
- Waste minimization,
- Environmental impact,
- Performance capability and

- Socio benefit

The development of a sustainability model that incorporates economic, social, technical and environmental criteria into a composite index was presented and discussed in Chapter seven in line with the sixth objective set out in the introduction.

9.2.5 Validating the decision-making model

The seventh objective of this research was to test the effectiveness and usefulness of the developed model by applying it to a decision making problem of selecting a sustainable roofing material among options for a case study building project. The data collection for the sustainability criteria was presented in Chapter eight. Data for the six criteria were collected and measured using a multi criteria decision analysis (analytic hierarchy process). The results indicate that the model is effective in aggregating sustainability attribute into a composite sustainability index and is able to rank the material options and obtain a best solution for the case project.

9.2.6 Concluding remarks

This thesis, therefore, has:

- Successfully explored the relationship between building construction and environmental degradation,
- Investigated environmental issues awareness and attitude of UK architects and designers and how it impact on their design decisions,
- Investigated sustainable construction practices and barriers faced in implementing sustainability in material selection decision making process,

- Developed a holistic sustainable assessment criteria (SAC) for the selection of sustainable building materials for building project,
- Developed a model to evaluate and incorporate sustainability criteria into an index for material assessment and selection.
- Validated the model through an application to building roof covering materials and the finding suggest the model is valuable and suitable for use in practice.

Sustainability issues are of growing concern and should be incorporated into the decision-making process of selecting the best material option among alternatives. This thesis provides a platform for this procedure to be carried out in the most effective way.

9.3 Summary of research

The purpose of this research was to ascertaining current practice in sustainability implementation in building design and construction, especially in the selection of building materials; highlights drivers and obstacles of sustainable design implementation and identifies those factors that are critical for developing an assessment model for assessing material sustainability. This model incorporated sustainability attributes into the decision-making process in order to promote sustainable practices in construction. The deterioration of natural and physical environment due to construction activities has become an important consideration in every building project. Environmental issues are externalities and intangibles that cannot be sufficiently handled by the current economic approach, but need to be included for a total assessment.

Therefore, the ultimate target, of this research, was to develop a sustainability index to assess the environmental performance of building material. The sustainability index that takes into consideration externalities and intangibles as well as material environmental impact. The study involved identifying the principal sustainable development criteria, investigating methods of quantification and, finally, developing a model to combine the criteria into a single decision-making tool.

The sustainability index is a decision-making tool that uses a composite index to rank material options of a building project. The process enables the principle of trade-off to take place in the decision-making process and to enable environmental attributes to be part of the consideration in selecting a material option. This makes it possible to optimize cost, maximize resource consumption and minimize detrimental effects to the natural and man-made world. The research was divided into three parts: a literature review, a survey of sustainability implementation practices of architects and designers in the UK construction industry, and the development of a sustainability index. The literature discussed the impacts of construction activities on the environment. It also investigated the use of environmental building assessment methods in assessing the sustainability of buildings and materials.

The study also critically examined the use of a multi-dimensional evaluation approach, as opposed to the conventional single dimensional methods, in assessing the sustainable performance of building material. From the discussions in the literature review, the sustainable development criteria were identified and an industry survey was formulated and carried out to examine the environmental awareness and sustainability practices among architects and designers. Simultaneously, these professionals ranked the identified sustainable development criteria in order to determine the principal variables to be included in the sustainability index.

The literature review and the industry survey provided the foundation for the development of multi criteria model of material selection that formed the major part of this research. The model utilizes an analytic hierarchical process which is a multi criteria analysis method for developing the index of material sustainability. The survey indicated that Life cycle cost, Resource efficiency, Waste minimization, Environmental impact, Performance capability and Socio benefit were the principal determinants for assessing material sustainability. The ultimate goal of this research was to develop a model to aggregate the sustainsbility criteria into a sustainability index to assess sustainability performance of building materials.

The sustainability index was finally validated by demonstrating it to the selection of roofing material for a proposed building project. The six criteria included in the sustainability index were assessed and quantified. Members of the building design team comprising architects and designers carried out the assessment procedure. The data on the six criteria were used to calculate the sustainability index of each option and the decision was made in accordance with the ranking. The result indicated that the sustainability index was able to rank material options. The sustainability index being developed in this research is a multi-criteria approach for material selection, which extended the conventional economic methodology to encompass environmental attributes and other intangibles into the assessment framework.

9.4 Conclusions

The primary aim of this research, to develop a sustainability index for material selection, has been achieved. The mathematical model for developing the sustainability index was presented, discussed and tested in the thesis using proposed roofing material alternatives. The result indicated that the sustainability index ranked the options, aiding the decision-making process. The sustainability index is a composite index that combines economic, social, technical and environmental criteria into an indexing algorithm to rank building material on their contribution to sustainability. There is a worldwide trend in environmental assessment away from purely the qualitative descriptions of environmental practices towards a more comprehensive, quantitative interpretation of environmental performance by using multi criteria decision analysis The sustainability index, as a tool for material assessment and evaluation, has used the AHP model as a basis for developing an index that provides an operational framework and guidance for making decisions. The demand for a standardization of a framework of accounts for economic development and environmental concerns is growing and the sustainability index was developed to satisfy this demand.

The sustainability index reflects the possibility of using a composite index to incorporate sustainability issues that cannot really be measured by other evaluation methods. Other evaluation methods such as BREEAM and BEPAC (see Chapter Four) assess environmental issues on a 'feature-specific' basis where points are awarded for the presence or absence of desirable features. However, environmental issues were successfully measured and incorporated using the methodology established in this research into the sustainability index. Another achievement of the research was using a multi-dimensional approach for decision-making. The sustainability index is a multi- dimensional assessment method that assesses building material for performance capability, economic values as well as environmental, and the trade-off principle in the approach concerns equity for generations today and in the future. The sustainability index also provides an opportunity for stakeholder's participation in the decision-making process. This is another area in which most evaluation methods are deficient.

The development of a sustainability index can be used as the basis for benchmarking building material allowing decisions to be made to improve the quality of the built environment. The benchmarks of the six criteria developed in this research can be set as a common target for comparison. The development of the sustainability index helps to make better decisions as environmental issues are successfully measured and incorporated into the decision- making methodology. There is, therefore, no doubt that a better decision can be arrived at that will improve the overall quality of the built environment.

9. 4.1 Policy implications

Sustainable development is of growing importance to the world because the current exploitation and uncaring use of resources, together with the pollution generated, cannot continue at present rates. The development of the sustainability index demonstrates a significant contribution to enhance and implement sustainable development and exhibits a way to bridge the gap between the current methodology of assessing building materials and sustainable requirements in construction. The sustainability index will have an important part to play in the future to ensure that sustainability is achieved in material selection for building project.

If sustainable construction is to be achieved, it has to adopt more long-term sustainable strategies at the feasibility stage of a building project to promote environmental protection and conservation. These strategies must focus on continual improvement through the consideration of sustainable development in the decision process. Therefore, construction has to place a higher priority on sustainability considerations in building projects and ensure that the concept of sustainability is valued and rewarded as well as practised at all levels throughout the project's entire life span.

At the same time, cost cannot be the key consideration in material selection as in the conventional assessment approach, but also has to consider the impacts a material may have on the environment. If the construction industry and its stakeholders want to facilitate a change in the customary and traditional way of thinking and doing things, focusing on cost, it may have to allow for the consideration of environmental sustainability in the decision-making process.

As discussed, the benefits of using benchmark systems in other industries are so evident that potential benefits may also be gained in construction. It is, therefore, also important for the construction industry to establish a benchmarking system to assess buildings' sustainability performance. The development of benchmarks in construction relies heavily on the participation and co-operation of the practitioners in the construction industry. Hence, the construction industry can become more aware of the benefits of research and development and establish a more co-operative approach to encourage and promote more sustainable practices in a building design and construction process.

The assessment of environmental performance of a building material is largely voluntary. In order to have better protection and conservation of the environment it is important for the regulatory authorities to assist by increasing the statutory requirements for sustainable performance in the consideration and use of materials for building project.

This thesis demonstrates that incorporating sustainability in material selection is important in achieving sustainable performance of building project. These should be considered in the future decision-making processes by ensuring that the six criteria are assessed in every material decision making process. In a deteriorating environment, this proactive strategy is essential for ensuring a superior environment for generations to come.

9.4.2 Limitations of this research

The research carried out in this thesis is significant and the findings from the study are useful for the construction stakeholders, helping them to incorporate sustainability into material assessment and selection. However, there are limitations associated with this study. These principally relate to identifying key sustainability criteria using a questionnaire of architects and designers in the UK. Therefore, the research results may only be valid for the characteristics and culture of architects and designers in the UK construction industry.

The case study was undertaken on 3 roof covering materials used in residential buildings. Even though the methodology will remain appropriate for any type of building element the result may be confined to this type of building. However, the validation exercise indicated that the model was conceptually sound. What may thus be worth doing, in future, is elaborate the model to enable diverse design/construction decisions to be made by using it. In addition, sustainability criteria as identified in this research may be confined to the time of the research, as people's perception of sustainability awareness and conditions may change. The model will thus require regular updates, which is not unexpected.

Finally, it is appreciated that there are deficiencies with a survey procedure. In this instance, the survey of the study was based on data collected from a sample obtained from a composite sampling method and, prior to the survey, a pilot study was undertaken. The participants for the survey were derived from random sampling of architects and designers to form a composite sample. This sampling method does not include other stakeholders, who in a way influence material selection like the client. The sample size may need to be extended to include more stakeholders involved in material selection in order to minimise sampling error.

However, it is also acknowledged that there was time, administrative and financial constraints. However, the importance of the study remains, for the limitations do not detract from them, but merely provide scope for further research.

9.5 Recommendations for further research

As indicated in previous sections, this research has investigated sustainability practices in building design in particular in the consideration of materials for building projects. The investigation has also identified six principal sustainability criteria that can promote sustainable performance of building material. During the study, some observations indicated the need for further study outside the scope and the aims of this research. However, the scope of this research has meant that the in- depth investigation that many of the research issues warranted was not possible. Accordingly, it is recommended that further research is necessary to extend and to modify the findings in this research.

Building professionals' perception in relation to the importance of the environment in a development was an area of concern. From the literature, the perception that building professionals have on the environment is that the consideration of environmental issues means higher costs, making sustainable material uptake undesirable given the main concern is to minimize building cost. Even though most of architect and designers surveyed recognised the importance of environmental issues in the industry survey (see Chapter six), they retain this perception that looking after the environment will inevitably cost more. When it comes to practically incorporating environmental consideration in material selection, environmental issues was not rank highly. Minimizing cost remains a deep-rooted requirement in building construction. Therefore, research needs to be undertaken to investigate this perception and to recommend a range of actions to foster a serious attitude change among architects and designers and other construction stakeholders.

This thesis has focused on developing a sustainability index to assess building material sustainability. One of the difficulties of applying the sustainability index to assess building material is the unique nature of material in construction. The relative importance of the six criteria may vary according to the types of construction. Further research can be developed to explore the changes of the six criteria in the context of their impact on different types of building material. It is, therefore, significant for the sustainability index to be tested on different types of construction in order to establish the relative importance for each criterion in calculating the sustainability index. The development of the sustainability index is important in every type of building and to promote sustainable practices among building stakeholders.

This area of research can, of course, be expanded to investigate other countries besides UK, with the opportunity to draw some interesting international comparisons. The development of the sustainability index has international applications and international co-operation in testing the model using projects and materials from different countries will enable more interesting comparisons to be made and to consolidate the robustness of the methodology. This area of research can further be acknowledged if the concept and principle of sustainability index is taken to the international arena.

Based on the literature review, sustainable development criteria were identified for material selection. This research ranked and summarised sustainable development criteria into six criteria group using a questionnaire of UK architects and designers. The opinions and rankings received from the survey may be confined to these particular practitioners and the opinions in ranking these criteria from other stakeholders deserve further investigation. Other survey methods such as personal interview and telephone surveys may also be used to increase the coverage and to strengthen the survey results.

This research was based on residential building. Further research can be carried out by applying the sustainability index to other building types as well as large-scale infrastructure projects such as roads, dams and bridges. The nature, construction methods, specifications and impacts on the environment will be different from residential building and further research on studying the sustainability index may provide new insights. This is particularly important for infrastructure projects which are usually large scale and more likely to cause environmental degradation.

The research in the development of a sustainability index was the prime objective and the model has been successfully applied in ranking building materials to provide the best solution for a building project. The research, whilst completed at this stage, has opened up opportunities for further research in many other areas including an international application. The findings in this research can be further extended and modified to accomplish the ultimate goal of promoting and improving sustainable practices in construction.

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Appendix A
Cover letter for postal questionnaire survey
Copy of postal survey questionnaire

School of Engineering and the Built Environment (SEBE)
University of Wolverhampton

To Whom It May Concern:

Dear Sir or Madam,

RESEARCH INTO SUSTAINABILITY PRACTICES IN THE UK CONSTRUCTION INDUSTRY

The School of Engineering and Built Environment (SEBE) of the University of Wolverhampton is sponsoring a research aimed at investigating sustainable construction practices of UK architects and designers, with focus on sustainable building material selection. This questionnaire is designed in a way that you can make suggestions as part of your invaluable contributions to this work. We would very much appreciate if you could please spare some few minutes to complete the questionnaire. There are no correct or incorrect responses, only your much-needed opinion. All answers will be treated in absolute confidence and used for academic purposes only. Extra space is provided to enable you expand your answers to the questions where necessary.

We do appreciate that the questionnaire will take some of your valuable time but without your kind and expert input the research objectives aimed at improving sustainability implementation cannot be realised. To this end, we would like to thank you very much for your valued and kind consideration. Please return the completed questionnaire in the self-addressed stamped envelope provided to the address below.

Akadiri Peter
Doctoral Research Student
School of Engineering and the Built Environment (SEBE)
University of Wolverhampton
Wulfruna Street, Wolverhampton
WV1 1SB
Tel:01902518537
E-mail: *p.o.akadiri@wlv.ac.uk*

SECTION A. BACKGROUND OF RESPONDENT (Optional)

Name of company: ....
Position in company: ....
Work Experience in the construction industry…. ………….(Years)…………(Months)
Address: ....
Telephone: .... E-mail: ....

SECTION B. GENERAL INFORMATION (Please tick √ options where applicable)

1. What type of organisation do you work for? (Please tick √ box as appropriate).

a. Architecture & design office	□	b. Engineering	□	c. Quantity surveying	□	d. Project management	□
e. Education	□	f. Real Estate	□	g. Government agency	□	h. Contractor	□

Others (Please specify)..

2. What is the size of the company /organisation you represent? (Please tick √ one box).

a. <10 staff	□	b. 11 - 50 staff	□	c. 51 - 249 staff	□
e. 250 – 500 staff	□	f. > 500 staff	□		

3. What type of building project do you specialise in? (Please tick √ box as appropriate).

a. Commercial	□	b. Residential	□	c. Institutional	□	d. Industrial	□	e. Leisure	□

Others (Please specify)..

4. Age of organisation? (Please tick √ one box).

a. < 5 yrs	□	b. 6-10yrs	□	c. 11- 20yrs	□	21-30yrs	□	d. 31-40yrs	□	e. >40 yrs	□

5. Please give an indication of the size of your organisation in terms of annual turnover. (Please tick √ one box).

a. < £5m	□	b. £5m – £25	□	c. £26m -£100m	□	d. > £100m	□

6. Your regular client type? (Please tick √ box as appropriate)

a. Public sector	□	b. Private sector	□	c. uasi-Public	□

SECTION C. ENVIRONMENTAL AWARENESS AND RELATED ACTION
(Please tick √ options where applicable)

7. Please indicate your level of awareness of environmental issues in building construction (Please tick √ box as appropriate)

a. extremely aware	□	b Moderately aware	□	c. somewhat aware	□	d. slightly aware	□	e. not at all aware	□	

8. Please indicate the extent of your agreement or disagreement with the following statements about environmental issues in building design and construction (Please tick √ box as appropriate).

Statements	Strongly disagree				Strongl y agree
	1	2	3	4	5
a. environmental assessment is an important issue in building project	□	□	□	□	□

b. construction activities contributes to nega ive environmental impact	□	□	□	□	□
c. it is important to include environmental issues at the conceptual stage of building project	□	□	□	□	□
d. it is important to understand the environmental impacts of design decision	□	□	□	□	□
e. i is important to be conscious that some of the materials have impacts on the environment	□	□	□	□	□
f. environmental consideration need to be incorporated into material selec ion decision making					
g. i is important to consider the full range of environmental impacts of construction materials by assessing their entire life cycle	□	□	□	□	□

9. Please rate on a scale of 1-5 the following project objectives when embarking on a building project (Please tick √ box as appropriate).

	Lowest				Highest
	1	2	3	4	5
a. Minimize cost	□	□	□	□	□
b. Meet project deadline	□	□	□	□	□
c. Meet building regulations	□	□	□	□	□
d. Satisfy client specification	□	□	□	□	□
e. Minimize project impact on the environment	□	□	□	□	□
Others (Please specify)	□	□	□	□	□

SECTION D. APPLICATION OF SUSTAINABILITY PRINCIPLES IN BUILLDING DESIGN AND MATERIAL SELECTION PROCESS (Please tick √ options where applicable)

10. How will you rate your knowledge in sustainable material selection? (Please tick √ box as appropriate).

a. Excellent	□	b. goo	□	c. Sufficient	□	c. Insufficient	□	e. Don't know	□

11. Do you consider sustainability assessment of building material an important issue for building development? (Please tick √ box as appropriate).

a. Yes	□	b. No	□

If No, Please give reason(s)...
....

12. Which of the following categories of stakeholders will be more attuned to sustainability in a building project? (Please tick √ box as appropriate).

a. Public	□	b. Private	□	c. No difference	□	e. Cant tell	□

13. Overall percentage (%) of projects you've handled involving sustainability consideration? (Please tick √ box as appropriate).

a. Less than 10%	□	b. 10 – 20%	□	. 21- 30%	□	e. > 30%, pls state_______	□

14. Which of the following sustainable construction practices have you implemented to show your commitment to sustainable construction and to what extent? (Rate on a scale of 1 – 5 . The lowest = 1 and the highest = 5).

Description of the practice	Lowest				Highest
	1	2	3	4	5
a.Having obtained the ISO 14001 certification	□	□	□	□	□
b. Having obtained the code for sustainable homes standard	□	□	□	□	□
c. Investing on Research & development for implementing sustainable construction	□	□	□	□	□
d. Investing resources for improving sustainable equipment and technology	□	□	□	□	□
e. Implementing comprehensive energy saving plan	□	□	□	□	□
f. Implementing comprehensive material saving plan	□	□	□	□	□
g. Imple enting comprehensive water saving plan	□	□	□	□	□
h. Implementing comprehensive land saving plan	□	□	□	□	□
i.Implementing comprehensive noise controlling	□	□	□	□	□
j. Implementing comprehensive waste abatement plan	□	□	□	□	□

k. Implementing comprehensi e air pollution controling plan	□	□	□		□
Others (Please specify)	□	□	□	□	□

15. Rate on a scale of 1- 5 how the following factors facilitate adoption of sustainable construction practices listed in question 9 above.

Factors	Lowest				Highest
	1		3	4	5
a. ENVIRONMENTAL REGULATION	□	□	□	□	□
1. Regulation for sustainable construction are stringent	□	□	□	□	□
2. The need to meet regulation is increasing client demand for sustainable home	□	□	□	□	□
3. Regulations for sustainable construction have a considerable impact on design practice	□	□	□	□	□
4. Regulations for sustainable construction can effectively deal with issues regarding the sustainability of construction process	□	□	□	□	□
5. The sustainable construction laws are appropriate for UK co struction industry environment	□	□	□	□	□
b. STAKEHOLDERS PRESSURE		□	□	□	□
6. Designers faced with pressure from client	□	□	□	□	□
7. Designers faced with pressure from community	□			□	
8. Designers faced with pressure from environmental NGO	□	□	□	□	□
9. Designers faced with pressure from colleague	□	□	□	□	□
c. DESIGNER ENVIRONMENTAL CONCERN		□	□	□	
10. Sustainable construction is an important component of the firm design practice	□	□	□	□	□
11. Designers conceive sustainable construction as an effe tive strategy	□	□	□	□	□
12. Sustainable construction is necessary for improving environmental performance	□	□	□	□	□
13. Designers pay considerable attention to sustainability issues in the construction process	□	□	□	□	□

16. Below is a list of sources of information on new building products. Kindly indicate on a scale of 1-5 how often you consult the sources (Please tick √ box as appropriate).

	Never	Sometimes	Average	Often	Very often
	1	2	3	4	5
a. Trade journals & Magazines	□	□	□	□	□
b. Catalogu brochures	□	□	□	□	□
c. Trade representatives	□	□	□	□	□
d. Colleagues	□	□	□	□	□
e. Exhibitions & fairs	□	□	□	□	□
f. Web based information (e.g. interne)					
Others (Please specify)	□	□	□	□	□

17. Please rate the following (on a scale of 1- 5) as they affect your material selection practises (The lowest = 1 and the highest = 5).

	Lowest				Highest
	1	2	3	4	5
a. Budget constraints	□	□	□	□	□
b. Lots of manpower and time in analyzing & selecting proper material	□	□	□	□	□
c. Problem in determining priorities	□	□	□	□	□
d. Lack of access to current and relevant information	□	□	□	□	□
e. Inadequate current construction techniques	□	□	□	□	□
f. Inadequate instructions about materials	□	□	□	□	□
g. Building regulation(codes & ordinances)	□	□	□	□	□
h. Consideration of sustainable materials	□	□	□	□	□
Others (Please specify)	□	□	□	□	□

18. For each of the following professionals, indicate how much influence each has in material selection on a scale of 1 – 5 (The lowest = 1 and the highest = 5).

	Lowest				Highest
	1	2	3	4	5
a. The client / client representative	□	□	□	□	□
b. Architects & designers	□	□	□	□	□
c. Quantity surveyors	□	□	□	□	□
d. Project Managers	□	□	□	□	□
e. Site Managers	□	□	□	□	□
f. Contractors	□	□	□	□	□
g. Technical consultants	□	□	□	□	□
h. Suppliers of products	□	□	□	□	□
i. Product manuf cturers	□	□	□	□	□
Others (Please specify)	□	□	□	□	□

19. On a scale of 1- 5, rate the following statements that best represents your perception of sustainability in building projects. (1 = strongly disagree & 5= strongly agree)

	Strongly disagr e				Strongly agree
	1	2	3	4	5
a. Material specification should include sustainability considerations	□	□	□	□	□
b. Guides for selecting sustainable materials can be easily found in the UK	□	□	□	□	□
c. Sustainability considerations are mainly for satis ying mandatory requirements	□	□	□	□	□
d. Adopting sustainable material should be voluntary	□	□	□	□	□
e. Use of environmentally friendly materials and sustainable construction methods will help to preserve natural resources.	□	□	□	□	□
f. I am aware that sustainability is getting more recognition among my colleagues and co-workers.	□	□	□	□	□
g. I believe that using environmentally friendly materials and will increase construction cost and time.	□	□	□	□	□
h. On the contrary, the use of environmentally friendly materials would reduce construction cost and time.	□	□	□	□	□
i. Even if there is an increase in the construction cost and time, I have noticed that my colleagues and co-workers intended to incorporate sustainability in material selection	□	□	□	□	□
j. Even if there is an increase in the construction cost and time, I have noticed that my clients intended to apply sustainable construction methods in pro ects	□	□	□	□	□
k. Important for architects to be conscious that some of the materials they specify have an impact on the environment	□	□	□	□	□
l. Important for architects to consider the full range of environmental impacts of construction materials by assessing their entire life cycle	□	□	□	□	□

20. What obstacles currently prevent you from specifying sustainable products and materials in your design? Please rate on a scale of 1 -5 (1= least important & 5 = extremely important):

	Least important				Extremely important
	1	2	3	4	5
b. Lack of information on sustainable construction materials	□	□	□	□	□
c. Problem in Evaluating information	□	□	□	□	□
d. Uncertainty in the liability for the final works	□	□	□	□	□
e. Maintenance concern	□	□	□	□	□
e. building code restriction	□	□	□	□	□
f. Lack of tools and data to compare material alternatives	□	□	□	□	□
g. Perception of extra cost being incurred	□	□	□	□	□
h. Perception of extra time being incurred	□	□	□	□	□
k. Difficulties in balancing environmental, economic & social issues	□	□	□	□	□
l. perception that sustainable materials are low in quality	□	□	□	□	□
m. aesthetically less pleasing	□	□	□	□	□
o. Possible delay due to sustainability requirement	□	□	□	□	□
p. Limited availability & reliability of suppliers	□	□	□	□	□
q. Low flexibility for alternatives or substitutes					
. Unwillingness to change the conventional way of specifying	□	□	□		□

Others (Please specify)	◻	◻	◻	◻	◻

21. As a practising professional in the construction industry, how often do you use the following techniques/tools for material and building assessment? (Please tick √ box as appropriate).

	Very low				Very high
	1	2	3	4	5
a. Multi-Criteria Analysis (a decision-making tool)	◻	◻	◻	◻	◻
b. Building for Environmental and Economic Sustainability (BEES)	◻	◻	◻	◻	◻
c. BRE Environmental Assessment Method (*BREEAM*)	◻	◻	◻	◻	◻
d. ATHENA™ impact estimator for buildings	◻	◻	◻	◻	◻
e. Environmental Preference Method (EPM) – developed in Netherland	◻	◻	◻	◻	◻
f. Building Environment Assessment Tool (BEAT 2001)	◻	◻	◻	◻	◻
g. Leadership in Energy and Environm ntal Design (LEED)	◻	◻	◻	◻	◻
h. Building Environmental Performance Assessment Criteria (BEPAC)	◻	◻	◻	◻	◻
Others (Please specify)	◻	◻	◻	◻	◻

22. Most practitioners/commentators have sought to explain the relatively low use of the tools by pointing out perceived obstacles to their successful usage. Please indicate how frequently each of the following factors has been an obstacle to the use of the tools in practice (Please tick √ box as appropriate).

	Not frequent				Most frequent
	1	2	3	4	5
a. Lack of familiarity with the technique	◻	◻	◻	◻	◻
b. High cost involved in its use	◻	◻	◻	◻	◻
c. High time consumption in using technique	◻	◻	◻	◻	◻
d. Lack of skills in using technique	◻	◻	◻	◻	◻
e. Lack of suitable programming software	◻	◻	◻	◻	◻
f. Poorly updated programmes	◻	◻	◻	◻	◻
g. La k of adequate project information	◻	◻	◻	◻	◻
Others (Please specify)	◻	◻	◻	◻	◻

<u>SECTION E. DEVELOPMENT OF MATERIAL SELECTION DECISION CRITERIA</u> (Please tick √ options where applicable)

23. Rate on a scale of 1 to 5 the following criteria in term of their importance in the selection of building material and in relation to the sustainability categories under which they are listed. (1= least important & 5 = extremely important):

Criteria's	Least important				Extremely important
	1	2	3	4	5
Environmental criteria					
1. Potential for recycling and reuse	◻	◻	◻	◻	◻
2. Availability of environmentally sound disposal options	◻	◻	◻	◻	◻
3. Impact of material on air quality	◻	◻	◻	◻	◻
4. Ozone depletion potential	◻	◻	◻	◻	◻
5. Environmental Impact during material harvest	◻	◻	◻	◻	◻
6. Zero or low toxicity	◻	◻	◻	◻	◻
7. Environmental statutory compliance	◻	◻	◻	◻	◻
8. Minimise pollution (air, land, water etc)	◻	◻	◻	◻	◻
Technological criteria					
1. Maintainability	◻	◻	◻	◻	◻
2. Sound insulation	◻	◻	◻	◻	◻
3. Resistance to decay	◻	◻	◻	◻	◻
4. Fire resistance	◻	◻	◻	◻	◻
5. Life expectancy of material (e.g. strength, durability etc)	◻	◻	◻	◻	◻
6. Energy saving and thermal insulation	◻	◻	◻	◻	◻
Resource consumption criteria					
1. Embodied energy within material	◻	◻	◻	◻	◻

2. Material availability	□	□	□	□	□
3. Amount of likely wastage in use of material	□	□	□	□	□
4. Methods of extraction of raw materials	□	□	□	□	□
5. Amount of transportation required	□	□	□	□	□
Socio-economic criteria					
1. Life cycle cost (initial cost, maintainace cost, repair cost etc)	□	□	□	□	□
2. Health and safety	□	□	□	□	□
3. Ease of construction / buildability	□	□	□	□	□
4. Aesthetics	□	□	□	□	□
5. Use of local material	□	□	□	□	□

24. Please rate the following on a scale of 1-5 as they affected your rating of the criteria listed above. (Please tick √ box as appropriate).

	Lowest				Highest
	1	2	3	4	5
a. Nature of the project	□	□	□	□	□
c. Building type Codes and regulation	□	□	□	□	□
c. Context and climate	□	□	□	□	□
d. Building technology	□	□	□	□	□
e. Sustainability	□	□	□	□	□
f. Project schedule	□	□	□	□	□
g. Client preference	□	□	□	□	□
h. Contractual agreement	□	□	□	□	□
Others (Please specify)	□	□	□	□	□

This is the end of the interview. Thank you very much for your time.

FEEDBACK FORM

1. How long did it take you to complete the interview?

Less than 30 minutes [ ]
More than 30 minutes [ ]

2. Did you find any questions ambiguous or difficult to answer?

Yes [ ]
No [ ]

3. If you answered 'Yes' above, can you please list those questions below or tick/highlight them on the interview form?

4. Are there any specific questions that you consider irrelevant and should be omitted from the interview?

5. Are there any other issues that you think could be considered in the interview? (Please give details below.

NB: Confidentiality and anonymity are guaranteed. All information collected will conform to the University's Human Research Ethical procedures.

Appendix B

Result of factor analysis for sustainability criteria

Correlation Matrix[a]

		life cycle cost	health and safety	ease of construction /buildability	aesthetics	use of local materials	material availability	amount of transportation required
Correlation	life cycle cost	1.000	.252	.184	.217	-.092	.226	.118
	health and safety	.252	1.000	.384	.147	.150	.344	.298
	ease of construction/buildability	.184	.384	1.000	.392	.063	.291	.063
	aesthetics	.217	.147	.392	1.000	-.016	.064	-.177
	use of local materials	-.092	.150	.063	-.016	1.000	.286	.475
	material availability	.226	.344	.291	.064	.286	1.000	.271
	amount of transportation required	.118	.298	.063	-.177	.475	.271	1.000

a. Determinant = .313

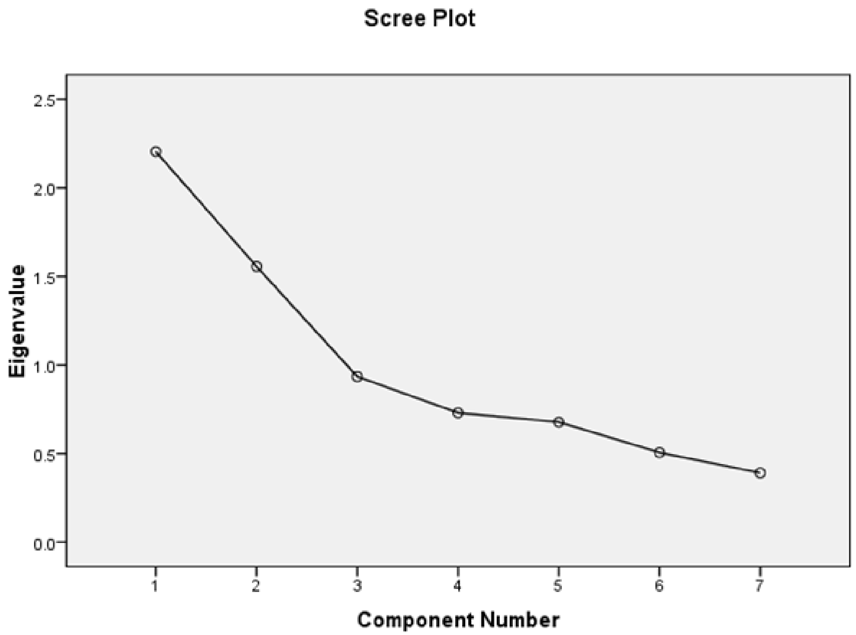
KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.606
Bartlett's Test of Sphericity	Approx. Chi-Square	96.100
	df	21.000
	Sig.	.000

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.205	31.502	31.502	2.205	31.502	31.502	1.908	27.250	27.250
2	1.556	22.234	53.736	1.556	22.234	53.736	1.854	26.486	53.736
3	.934	13.350	67.086						
4	.730	10.428	77.514						
5	.678	9.680	87.194						
6	.506	7.225	94.419						
7	.391	5.581	100.000						

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component	
	1	2
life cycle cost		
health and safety	.722	
ease of construction/buildability	.623	
aesthetics		.673
use of local materials		-.607
material availability	.690	
amount of transportation required	.545	-.627

Extraction Method: Principal Component Analysis.

a. 2 components extracted.

Reproduced Correlations

		disposal cost	health and safety	maintenance cost	first cost	use of local materials	labour availability	aesthetics
Reproduced Correlation	disposal cost	.333[a]	.352	.440	.388	-.009	.269	.021
	health and safety	.352	.526[a]	.481	.281	.290	.490	.349
	maintenance cost	.440	.481	.582[a]	.497	.021	.377	.064
	first cost	.388	.281	.497	.557[a]	-.259	.142	-.246
	use of local materials	-.009	.290	.021	-.259	.582[a]	.392	.632
	labour availability	.269	.490	.377	.142	.392	.491[a]	.452
	Aesthetics	.021	.349	.064	-.246	.632	.452	.690[a]
Residual[b]	disposal cost		-.099	-.256	-.170	-.083	-.043	.097
	health and safety	-.099		-.097	-.134	-.140	-.146	-.051
	maintenance cost	-.256	-.097		-.105	.042	-.086	-.001
	first cost	-.170	-.134	-.105		.243	-.078	.069
	use of local materials	-.083	-.140	.042	.243		-.106	-.157
	labour availability	-.043	-.146	-.086	-.078	-.106		-.180
	aesthetics	.097	-.051	-.001	.069	-.157	-.180	

Extraction Method: Principal Component Analysis.

a. Reproduced communalities

b. Residuals are computed between observed and reproduced correlations. There are 18 (85.0%) nonredundant residuals with absolute values greater than 0.05.

Rotated Component Matrix[a]

	Component	
	1	2
life cycle cost	.576	
health and safety	.579	
ease of construction/buildability	.757	
aesthetics	.693	
use of local materials		.759
material availability		.556
amount of transportation required		.830

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 3 iterations.

Component Transformation Matrix

Component	1	2
1	.736	.677
2	.677	-.736

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Correlation Matrix[a]

		recycling and reuse	environmentally sound disposal options	impact on air quality	ozone depletion potential	impact during harvest	zero/low toxicity	environmental statutory compliance	Minimise pollution	amount of likely wastage in use	method of raw material extraction	embodied energy
Correlation	recycling and reuse	1.000	.786	.477	.460	.435	.392	.310	.304	.392	.256	.351
	environmentally sound disposal options	.786	1.000	.593	.413	.514	.465	.231	.315	.391	.322	.300
	impact on air quality	.477	.593	1.000	.682	.657	.641	.473	.515	.528	.444	.444
	ozone depletion potential	.460	.413	.682	1.000	.598	.703	.616	.458	.528	.392	.453
	impact during harvest	.435	.514	.657	.598	1.000	.411	.341	.447	.395	.558	.383
	zero/low toxicity	.392	.465	.641	.703	.411	1.000	.676	.408	.315	.251	.461
	environmental statutory compliance	.310	.231	.473	.616	.341	.676	1.000	.496	.333	.197	.347
	minimise pollution	.304	.315	.515	.458	.447	.408	.496	1.000	.395	.300	.356
	amount of likely wastage in use	.392	.391	.528	.528	.395	.315	.333	.395	1.000	.625	.487
	method of raw material extraction	.256	.322	.444	.392	.558	.251	.197	.300	.625	1.000	.451
	embodied energy	.351	.300	.444	.453	.383	.461	.347	.356	.487	.451	1.000

a. Determinant = .001

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.801
Bartlett's Test of Sphericity	Approx. Chi-Square	540.416
	df	55.000
	Sig.	.000

Communalities

	Initial	Extraction
recycling and reuse	1.000	.824
environmentally sound disposal options	1.000	.901
impact on air quality	1.000	.719
ozone depletion potential	1.000	.743
impact during harvest	1.000	.597
zero/low toxicity	1.000	.781
environmental statutory compliance	1.000	.789
minimise pollution	1.000	.476
amount of likely wastage in use	1.000	.689
method of raw material extraction	1.000	.816
embodied energy	1.000	.503

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.505	50.048	50.048	5.505	50.048	50.048	3.002	27.294	27.294
2	1.216	11.057	61.105	1.216	11.057	61.105	2.570	23.362	50.656
3	1.116	10.149	71.254	1.116	10.149	71.254	2.266	20.598	71.254
4	.708	6.438	77.692						
5	.626	5.693	83.384						
6	.534	4.853	88.237						
7	.395	3.587	91.825						
8	.351	3.188	95.013						
9	.247	2.247	97.260						
10	.181	1.646	98.906						
11	.120	1.094	100.000						

Extraction Method: Principal Component Analysis.

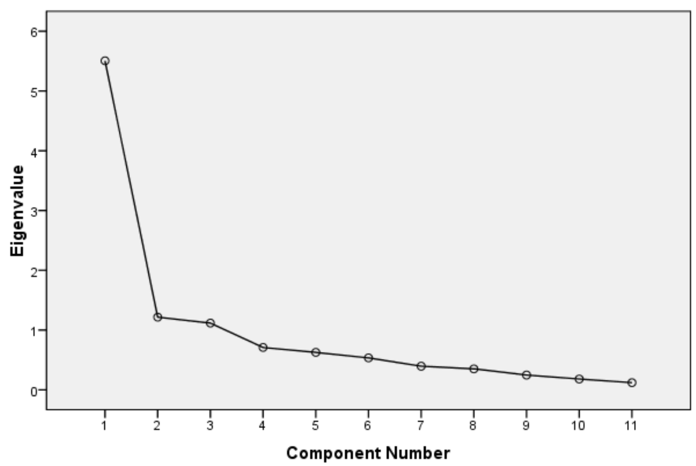
Component Matrix[a]

	Component		
	1	2	3
recycling and reuse	.663		-.567
environmentally sound disposal options	.689		-.571
impact on air quality	.845		
ozone depletion potential	.826		
impact during harvest	.746		
zero/low toxicity	.749		
environmental statutory compliance	.648	-.604	
minimise pollution	.638		
amount of likely wastage in use	.688		
method of raw material extraction	.607		
embodied energy	.639		

Extraction Method: Principal Component Analysis.

a. 3 components extracted.

Scree Plot



Reproduced Correlations

		Recycling and reuse	environmentally sound disposal options	impact on air quality	ozone depletion potential	Impact during harvest	zero/low toxicity	environmental statutory compliance	Minimise pollution	amount of likely wastage in use	method of raw material extraction	Embodied energy
Reproduced Correlation	recycling and reuse	.824[a]	.860	.588	.460	.533	.446	.239	.283	.342	.259	.272
	environmentally sound disposal options	.860	.901[a]	.609	.466	.565	.436	.216	.285	.378	.304	.291
	impact on air quality	.588	.609	.719[a]	.700	.625	.649	.556	.535	.556	.477	.522
	ozone depletion potential	.460	.466	.700	.743[a]	.569	.723	.684	.586	.509	.407	.526
	impact during harvest	.533	.565	.625	.569	.597[a]	.464	.364	.436	.584	.559	.497
	zero/low toxicity	.446	.436	.649	.723	.464	.781[a]	.753	.559	.333	.182	.413
	environmental statutory compliance	.239	.216	.556	.684	.364	.753	.789[a]	.555	.280	.135	.394
	minimise pollution	.283	.285	.535	.586	.436	.559	.555	.476[a]	.422	.353	.438
	amount of likely wastage in use	.342	.378	.556	.509	.584	.333	.280	.422	.689[a]	.727	.564
	method of raw material extraction	.259	.304	.477	.407	.559	.182	.135	.353	.727	.816[a]	.560
	embodied energy	.272	.291	.522	.526	.497	.413	.394	.438	.564	.560	.503[a]
Residual[b]	recycling and reuse		-.074	-.111	-1.724E-5	-.098	-.054	.071	.021	.050	-.004	.079
	environmentally sound disposal options	-.074		-.016	-.052	-.051	.029	.015	.030	.013	.018	.008
	impact on air quality	-.111	-.016		-.018	.031	-.007	-.083	-.020	-.028	-.032	-.078
	ozone depletion potential	-1.724E-5	-.052	-.018		.030	-.020	-.069	-.129	.019	-.015	-.073
	impact during harvest	-.098	-.051	.031	.030		-.053	-.022	.011	-.189	-.001	-.114
	zero/low toxicity	-.054	.029	-.007	-.020	-.053		-.077	-.151	-.018	.069	.048
	environmental statutory compliance	.071	.015	-.083	-.069	-.022	-.077		-.059	.053	.062	-.047
	minimise pollution	.021	.030	-.020	-.129	.011	-.151	-.059		-.028	-.052	-.081
	amount of likely wastage in use	.050	.013	-.028	.019	-.189	-.018	.053	-.028		-.102	-.076

	method of raw material extraction	-.004	.018	-.032	-.015	-.001	.069	.062	-.052	-.102		-.109
	embodied energy	.079	.008	-.078	-.073	-.114	.048	-.047	-.081	-.076	-.109	

Extraction Method: Principal Component Analysis.

a. Reproduced communalities

b. Residuals are computed between observed and reproduced correlations. There are 28 (50.0%) nonredundant residuals with absolute values greater than 0.05.

Rotated Component Matrix[a]

	Component		
	1	2	3
recycling and reuse			.871
environmentally sound disposal options			.912
impact on air quality	.557		
ozone depletion potential	.719		
impact during harvest		.546	
zero/low toxicity	.824		
environmental statutory compliance	.882		
minimise pollution	.586		
amount of likely wastage in use		.773	
method of raw material extraction		.893	
embodied energy		.588	

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 4 iterations.

Component Transformation Matrix

Component	1	2	3
1	.645	.570	.509
2	-.762	.530	.372
3	.058	.628	-.776

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Correlation Matrix[a]

		maintainability	Sound insulation	Resistance to decay	fire resistance	life expectancy of material	energy saving/thermal insulation
Correlation	maintainability	1.000	.312	.373	.329	.271	.387
	sound insulation	.312	1.000	.494	.478	.265	.279
	resistance to decay	.373	.494	1.000	.457	.436	.369
	fire resistance	.329	.478	.457	1.000	.530	.528
	life expectancy of material	.271	.265	.436	.530	1.000	.486
	energy saving/thermal insulation	.387	.279	.369	.528	.486	1.000

a. Determinant = .181

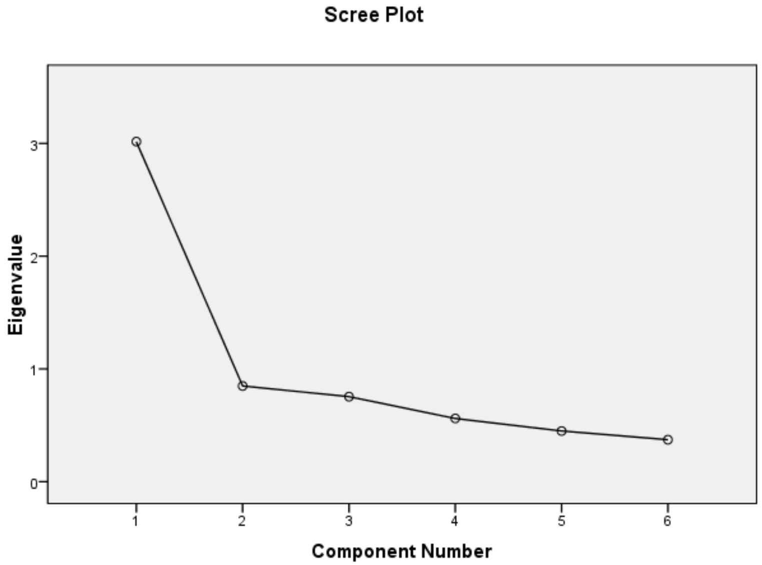
KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.804
Bartlett's Test of Sphericity	Approx. Chi-Square	149.128
	df	15.000
	Sig.	.000

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.016	50.264	50.264	3.016	50.264	50.264
2	.849	14.143	64.408			
3	.754	12.564	76.972			
4	.560	9.338	86.310			
5	.449	7.489	93.799			
6	.372	6.201	100.000			

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component
	1
maintainability	.604
sound insulation	.658
resistance to decay	.740
fire resistance	.799
life expectancy of material	.712
energy saving/thermal insulation	.724

Extraction Method: Principal Component Analysis.

a. 1 components extracted.

Reproduced Correlations

		maintainability	Sound insulation	resistance to decay	fire resistance	life expectancy of material	energy saving/thermal insulation
Reproduced Correlation	maintainability	.365[a]	.397	.447	.483	.430	.437
	sound insulation	.397	.433[a]	.487	.526	.469	.476
	resistance to decay	.447	.487	.548[a]	.592	.527	.536
	fire resistance	.483	.526	.592	.639[a]	.569	.578
	life expectancy of material	.430	.469	.527	.569	.507[a]	.515
	energy saving/thermal insulation	.437	.476	.536	.578	.515	.524[a]
Residual[b]	maintainability		-.085	-.074	-.154	-.159	-.050
	sound insulation	-.085		.007	-.048	-.204	-.197
	resistance to decay	-.074	.007		-.135	-.092	-.167
	fire resistance	-.154	-.048	-.135		-.039	-.050
	life expectancy of material	-.159	-.204	-.092	-.039		-.029
	energy saving/thermal insulation	-.050	-.197	-.167	-.050	-.029	

Extraction Method: Principal Component Analysis.

a. Reproduced communalities

Reproduced Correlations

		maintainability	Sound insulation	resistance to decay	fire resistance	life expectancy of material	energy saving/thermal insulation
Reproduced Correlation	maintainability	.365[a]	.397	.447	.483	.430	.437
	sound insulation	.397	.433[a]	.487	.526	.469	.476
	resistance to decay	.447	.487	.548[a]	.592	.527	.536
	fire resistance	.483	.526	.592	.639[a]	.569	.578
	life expectancy of material	.430	.469	.527	.569	.507[a]	.515
	energy saving/thermal insulation	.437	.476	.536	.578	.515	.524[a]
Residual[b]	maintainability		-.085	-.074	-.154	-.159	-.050
	sound insulation	-.085		.007	-.048	-.204	-.197
	resistance to decay	-.074	.007		-.135	-.092	-.167
	fire resistance	-.154	-.048	-.135		-.039	-.050
	life expectancy of material	-.159	-.204	-.092	-.039		-.029
	energy saving/thermal insulation	-.050	-.197	-.167	-.050	-.029	

Extraction Method: Principal Component Analysis.

b. Residuals are computed between observed and reproduced correlations. There are 10 (66.0%) nonredundant residuals with absolute values greater than 0.05.

Appendix C

Pairwise Comparison Questionnaire

UNIVERSITY OF WOLVERHAMPTON

School of Engineering and the Built Environment (SEBE)
University of Wolverhampton

To Whom It May Concern:

Dear Sir or Madam,

RESEARCH INTO SUSTAINABILITY PRACTICES IN THE UK CONSTRUCTION INDUSTRY

As you have effectively participated in the first questionnaire which identified sustainable material selection criteria, you are herby again asked to evaluate the criteria by assigning weights to them through pairwiase comparison. This is required in order to validate the decision support model developed for building designers in incorporating sustainability into building projects especially when selecting building materials. Three roof covering material alternatives is used as a study case on a hypothetical design of a single family home. Detail description of the case project and roof covering materials assessed are described below.

The research will help toward improved sustainable material evaluation and selection process, which would be of benefit to the construction industry. All of data collected from you will be used only for academic purpose.

If you would like any further information about the research, please let me know.

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The scenario: a hypothetical study case

The proposed scenario taken as study case is a hypothetical design of a single family home located in a light residential area of Wolverhampton, West midlands. An architect is working with a client to select materials (in this case roofing material) for a proposed residential building. The client tells the architect that he wants a building made from materials that are friendly to the environment. The client qualifies his specifications, however, to say that he does not want the building's functions to be compromised by the design or choice of materials. He goes on to say that, while he is willing to spend more money on materials to achieve a "sustainable building," cost is still a consideration. The architect decides to use MADA to make the material choices that will best satisfy the clients' needs. Table 8.1 summarizes the details for the three options of roof covering materials for the proposed project. From the table, the description of the three options was based on the standard practices and construction details commonly used in the UK.

Summary of roof covering options for the proposed project

Description	Option A	Option B	Option C
Element type	Pitched Roof Timber Construction	Pitched Roof Timber Construction	Pitched Roof Timber Construction
Building type	Residential	Residential	Residential
Element	Timber trussed rafters and joists with insulation, roofing underlay, counterbattens, battens and UK produced concrete interlocking tiles	Structurally insulated timber panel system with OSB/3 each side, roofing underlay, counterbattens, battens and UK produced reclaimed clay tiles	Structurally insulated timber panel system with plywood (temperate EN 636-2) decking each side, roofing underlay, counterbattens, battens and UK produced Fibre cement slates
Size of tile or slate	420mm x 330mm	420mm x 330mm	420mm x 330mm
Pitch of roof	22.5°	22.5°	22.5°

Guide lines for filling and establishing relative importance

Each criterion will be rated according to its degree of relative importance to another criterion within the group in the bases of pair wise comparison. The consistency of replies will be tested. The results will be sent to the respondent to think about his replies where no consistency achieved. Participants who did not achieve acceptable level of consistency will be requested to refill the questionnaire until they reach an acceptable level of consistency. The scale used to find pair wise relative importance is nine point scales as follows:

SCALE

Importance	Definition	Explanation
1	Equal importance of both elements	Two elements contribute equally
3	Moderate importance of one element over another	Experience and judgement favour one element over another
5	Strong importance of one element over another	An element is strongly favoured
7	Very strong importance of one element over another	An element is very strongly dominant
9	Extreme importance of one element over another	An element is favoured by at least an order of magnitude
2,4,6,8	Intermediate values	Used to compromise between two judgements

Any criteria can take a scale from 1 to 9 if they are equally or more important. However, if the criteria are less important it can take the inverse of the scale. In the above table you find that when the criteria have an equal importance it takes score (1). This usually happened when you compare the criteria with itself. When one criterion is from equally to moderately important it takes the score (2) and so on you can continue to evaluate to how much each criterion is preferred than the other. In the table, environmental impact is moderately important than waste minimization while the resource efficiency is very strongly important than waste minimization. This means that when waste minimization is compared with resource efficiency then waste minimization is preferred by 1/7 of resource efficiency.

Pair wise comparison example

Main criteria	Environmental impact	Resource efficiency	Waste minimization
Environmental impact	1	½	3
Resource efficiency	2	1	7
Waste minimization	1/3	1/7	1

Part I: Relative importance/preference of criteria for roof covering selection

1.1 Select the degree of relative importance/preference of each main criterion compared to each other in the seelction of above roof covering material option using the scale stated above.

Pairwise matrix and priorities for main criteria

Main criteria	Environmental Impact	Life Cycle Cost	Resource Efficiency	Waste minimization	Performance Capability	Social benefit
EnvironmentalImpact	1					
Life Cycle Cost		1				
Resource Efficiency			1			
Waste minimization				1		
Performance Capability					1	
Social benefit						1

1.2 Select the degree of relative importance/preference of each sub criterion for Environmental impact compared to each other

Pair-wise matrix & priorities for Environmental impact

Sub criteria	Environmental statutory compliance	Zero/low toxicity	Ozone depletion	Minimize pollution	Impact on air quality
Environmental statutory compliance	1				
Zero/low toxicity		1			
Ozone depletion			1		
Minimize pollution				1	
Impact on air quality					1

1.3 Select the degree of relative importance/preference of each sub criterion for Life cycle cost compared to each other

Pair-wise matrix & priorities for Life Cycle Cost

Sub criteria	Purchase cost	Disposal cost	Maintenance cost
Purchase cost	1		
Disposal cost		1	
Maintenance cost			1

1. 4. Select the degree of relative importance/preference of each sub criterion for Resource efficiency compared to each other

Pair-wise matrix & priorities for Resource efficiency

Sub criteria	Embodied energy	Amount of wastage	Method of extraction	Impact during harvest
Embodied energy	1			
Amount of wastage		1		
Method of extraction			1	
Impact during harvest				1

1. 5. Select the degree of relative importance/preference of each sub criterion for waste minimization compared to each other

Pair-wise matrix & priorities for Waste minimisation

Sub criteria	Recycling and reuse	Environmental sound disposal
Recycling and reuse	1	
Environmentally sound disposal		1

1. 6. Select the degree of relative importance/preference of each sub criterion for performance capability compared to each other

Pair-wise matrix & priorities for performance capability

Sub criteria	Fire resistance	Maintainability	Resistance to decay	Life expectancy	Energy saving & thermal insulation	Ease of construction
Fire resistance	1					
Maintainability		1				
Resistance to decay			1			
Life expectancy				1	1	
Energy saving & thermal insulation					1	
Ease of construction						1

1. 7. Select the degree of relative importance/preference of each sub criterion for social benefit compared to each other

Pair-wise matrix & priorities for Social benefit

Sub criteria	Local material	Aesthetics	Health & Safety	Material availability
Local material	1			
Aesthetics		1		
Health & Safety			1	
Material availability				1

Part II: Relative preference of roof covering alternatives for selection

1.9 Select the degree of relative preference of each alternative with respect to each sub-criterion

ENVIRONMENTAL STATUTORY COMPLIANCE

	A	B	C
A	1		
B		1	
C			1

ZERO/ LOW TOXICITY

	A	B	C
A	1		
B		1	
B			1

OZONE DEPLETION

	A	B	C
A	1		
B		1	
C			1

MINIMIZE POLLUTION

	A	B	C
A	1		
B		1	
C			1

IMPACT ON AIR QUALITY

	A	B	C
A	1		
B		1	
C			1

MAINTENANCE COST

	A	B	C
A	1		
B		1	
C			1

INITIAL COST (PURCHASE COST)

	A	B	C
A	1		
B		1	
C			1

DISPOSAL COST

	A	B	C
A	1		
B		1	
C			1

METHOD OF RAW MATERIAL EXTRACTION

	A	B	C
A	1		
B		1	
C			1

AMOUNT OF WASTAGE IN USE OF MATERIAL

	A	B	C
A	1		
B		1	
C			1

EMBODIED ENERGY

	A	B	C
A	1		
B		1	
C			1

ENVIRONMENTAL IMPACT DURING HARVEST

	A	B	C
A	1		
B		1	
C			1

FIRE RESISTANCE			
	A	B	C
A	1		
B		1	
C			1

RESISTANCE TO DECAY			
	A	B	C
A	1		
B		1	
C			1

ENERGY SAVING & THERMAL INSULATION			
	A	B	C
A	1		
B		1	
C			1

LIFE EXPECTANCY			
	A	B	C
A	1		
B		1	
C			1

EASE OF CONSTRUCTION			
	A	B	C
A	1		
B		1	
C			1

MAINTAINABILITY			
	A	B	C
A	1		
B		1	
C			1

USE OF LOCAL MATERIAL			
	A	B	C
A	1		
B		1	
C			1

AESTHETICS			
	A	B	C
A	1		
B		1	
C			1

HEALTH & SAFETY			
	A	B	C
A	1		
B		1	
C			1

MATERIAL AVAILABILITY			
	A	B	C
A	1		
B		1	
C			1

ENVIRONMENTALLY SOUND DISPOSAL OPTION			
	A	B	C
A	1		
B		1	
C			1

RECYCLING & REUSE			
	A	B	C
A	1		
B		1	
C			1

This is the end of the questionaire. Thank you very much for your time.

NB: Confidentiality and anonymity are guaranteed. All information collected will conform to the University's Human Research Ethical procedures.

Appendix D

Validation questionnaire survey

School of Engineering and the Built Environment (SEBE)
University of Wolverhampton

Dear Sir or Madam,

A QUESTIONAIRE FOR VALIDATING A MODEL FOR THE SELECTION OF SUSTAINABLE BUILDING MATERIAL

The aim of this questionnaire is to gather and assess experts' opinions on the attached model, which is intended for assisting architects and designers in evaluating and selecting sustainable materials for building projects. This is meant for validating the proposed model as to its significance to the industry, workability in practice and adequacy in addressing the decision problem confronting designers on SBM selection.

The questionnaire is in three (3) parts. Section A seeks to collect information on your background; Sections B and C ask for your opinions or comments on general and specific aspects of the model, respectively. There are no correct or incorrect responses, only your much-needed opinion. Please return the completed questionnaire in the self-addressed stamped envelope provided to the address below .We would like to thank you in advance for your valued and kind consideration.

If you would like any further information about the research, please let me know.

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Section A: Background of Respondent

Name of Respondents (optional):..
Profession: ....
Qualification:..
Current job designation:..
Years of experience in the construction industry: ....

Section B: General Impression on the model (Please tick√ as appropriate)

1. Does the model address an important problem in sustainable material evaluation and selection
yes, quite significant
yes, but not significant
no, would make no difference
not sure of its significance
Comments (if any)
2. Would you say the model is capable of assisting architects and designers in the selection of sustainable materials for building projects
yes, highly capable
yes, capable
no, not capable
not sure of its capability
Comments (if any)
3. Would you say the model is simple, clear and easy to understand and use with little or no practical difficulties?
Yes
No
4. If No to Q3, please comment on the specific aspects of the model that, in your view, is likely to cause major difficulties to its use.
5. What is your opinion on the resources needed to apply the model in real life selection exercise?
would be too costly to operate at current resource levels
would not be too costly to operate at current resource levels
the benefits of using the model justifies any resource requirements
Comment (if any)
6. What is your opinion on the description of the model and its lay out?
comprehensive
adequate
poor
Comment (if any)
7. In your opinion, are there any further matters of importance which ought to be included in the model or considered?
Yes
No
8. If Yes to Q7, please specify:

Section C: Impression on the model's techniques

9. What is your opinion on the scale of "1-9" adopted for pairwise comparison of the sustainability criteria and rating the roof covering materials?
very suitable
suitable
not suitable
not sure of its suitability
Comments (if any)
10. What is your opinion on the approaches/methods used for evaluating the selection criteria in rating the roof covering materials?
very suitable
suitable
not suitable
not sure of its suitability
Comments (if any)
11. Are there any further approaches/methods, which in your opinion are important to consider in rating the roof covering materials against the criteria?
Yes
No
12. If Yes to Q11, please specify:
13. What is your opinion on the set of criteria used in evaluating and rating the roof covering materials
very suitable
suitable
not suitable
not sure of its suitability
Comments (if any)
14. In your opinion, are there any other important criteria that were not considered?
Yes
No
15. If you have answered Yes to Q14, please list these criteria that ought to have been considered.
16. Please provide any other general comments that you have on the model or suggestions for improvement (continue on a separate sheet if necessary)

Thank you very much for your time

NB: *Confidentiality and anonymity are guaranteed. All information collected will conform to the University's Human Research Ethical procedure*