Sustainable Building Services Systems Management

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By

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Declaration

Programme: Management of Projects (PhD)

Supervisor: Dr. Taha Elhag

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Abstract

The rapid expansion in the construction industry worldwide has placed more pressure on the available natural resources, as the various construction activities and the services they require, increasingly draw on supplies of water and energy. The provision of these utilities and their continual maintenance activites within a building, promote human daily sustenance, and economic development generally, but the exploitation of these resources, their environmental impact, socio-economic implications, and sustainability, all necessitate proper management. Indeed, sustainability has now become the cornerstone for effective building services infrastructure and building construction management. It is against this backdrop that this study, which focuses on building services infrastructure and construction activities management, is set.

The study aims to integrate the sustainability agenda in this context as a basis for achieving sustainable development goals. Increasingly, building services infrastructure processes and the interdisciplinary engineering fields cannot operate optimally without the incorporation of the sustainability agenda as a core management consideration. In pursuit of its aims, the study has employed various theoretical propositions, suitable methods, and frameworks, all aimed at addressing the sustainability issues as a way forward. The current technologies and management techniques related to building management do already offer sustainable and good quality service delivery, but the findings from this study have yielded value added contributions capable of promoting greater success in the drive for sustainability, by employing the sustainable engineering infrastructure (SEI) model, sustainability index matrix (SIM), and partial differential equation techniques. The SEI model was used in evaluating building services infrastructure characteristics within the UK and Nigeria in the study phases I– IV, and the outcomes are presented.

Life cycle assessment (LCA) and life cycle costs (LCC) methods were also applied to examine building services infrastructure systems and their performance in the study phase V. The LCA phase in this study considered ten environmental impacts during the construction, operation (use), maintenance, and the end-of-life phases of six buildings.

The LCC technique appraised the use of construction materials, water, energy, and utilities to avoid duplication that leads to unnecessary costs in the aforementioned phases of buildings. The results of the different analyses are presented. Energy and utilities usage, together with carbon footprint management evaluation in both the healthcare and education sectors in the UK are also shown in the study phase VI. In appraising these scenarios, the partial differential equation method was adopted, generating results for the healthcare and education sectors of 0.74 and 0.62 respectively, which expresses a good degree of reliability of performance within these two particular contexts. In phase VII of the study, interviews with experts from academia and industry have corroborated the evidence secured from other phases of the research.

There is also a novel discovery in this study, in its use of the SIM function which is able to provide a corresponding sustainability index result for buildings/facilities performance in respect of critical and strategic management decisions. The SIM has defined the sustainability index from probability theory within the limits of $0 \leq S_{uv} \leq 1$ for any given system function. The SIM and SEI models have been applied within some phases in this study based on the acquired data and the results are indicated. Additionally, there is a proposed algorithmic project life cycle framework with an allowance for either on/offsite recycling processes in managing building infrastructure challenges.

In its scope, the study focuses on buildings (facilities) only, since the non-integration of sustainability ethics represents the major challenge undermining the building services infrastructure success. With this focus in mind, this study has delivered improved knowledge and understanding of the proper applications and management of building services infrastructure systems. This has been underpinned by the three themes of sustainable development for the present and future generations.

Keywords: Building (facility) services systems, carbon footprint, energy and utilities management, engineering sustainability, environmental impact assessment, LCA, LCC, sustainable building, sustainable development, sustainability index

Table of Contents

List of Tables

List of Figures

List of Acronyms/Abbreviations

ABCDE	Annual Bank Conference on Development Economics
ADP	Abiotic Depletion Potential
ALSCON	Aluminium Smelter Company of Nigeria
AP	Acidification Potential
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
BC	Building Construction
BCC	Building Construction Company
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BRI	Building Research Institute
BSI	British Standards Institution
CBO	Community Based Organisation
CBPP	Construction Industry Best Practice Programme
CCA	Climate Change Acts
CcalC	Carbon Calculator
CCCC	Copenhagen Climate Change Conference
CCT	Crown Carbon Trust
CHP	Combined Heat and Power
CII	Construction Industry Institute
CIOB	Chartered Institute of Building
CIRC	Construction Industry Review Committee
CIRIA	Construction Industry Research Information Association
COV	Coefficient of Variance
CR	Category Ranking
CRC	Carbon Reduction Commitment

DEA	Department of Environmental Affairs
DEFRA	Department for Food and Rural Affairs
DP	Discount Payback
EA	Environmental Assessment
EAC	Equivalent Annual Cost
EIA	Environmental Impact Assessment
ELC	Environmental Literacy Council
ELCC	Economic Life Cycle Cost
EMS	Environmental Management Systems
EoL	End-of-Life
EP	Eutrophication Potential
ESCAP	Economic and Social Commission for Asia and the Pacific
ETBP	Environmental Technology Best Practice
FAETP	Freshwater Aquatic Ecotoxicity Potential
FU	Functional Unit
GBC	Green Building Council
GHG	Green House Gas
GPG	Green Practice Guide
GWP	Global Warming Potential
HTP	Human Toxicity Potential
HVAC	Heating, Ventilation and Air-Conditioning
ICME	International Conference of Mechanical Engineers
IEM	Integrated Environmental Management
IEMS	Integrated Environmental Management Systems
IRR	Internal Rate Return
ISM	Infrastructure Systems Management
IS	Infrastructure Systems

ISO	International Organisation for Standardisation
LC	Life Cycle
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCPT	Low Carbon Plan Transition
MAEP	Marine Aquatic Ecotoxicity Potential
MDG	Millennium Development Goal
MPN	Mobil Producing Nigeria (Multi National Oil and Gas Company)
NAO	National Audit Office
NGO	Non–governmental Organisation
NHBC	National House-Building Council
NHS	National Health Service
NPV	Net Present Value
OCED	Organisation for Economic Co-operation and Development
ODP	Ozone Depletion Potential
OHSAS	Occupational Health and Safety Assessment Series
OPS	Operations
OR	Overall Ranking
POCP	Photochem Ozone Creation Potential
PPP	Public-Private Partnership
R&D	Research and Development
RICS	Royal Institute of Chartered Surveyors
RNCM	Royal Northern College of Music
RON	Return on Investment
SC	Sustainable Construction
SD	Sustainable Development
SEI	Sustainable Engineering Infrastructure

SI	Sustainability Index
SID	Sustainable Infrastructure Development
SIM	Sustainablility Index Matrix
SIMM	Sustainable Infrastructure Management Model
SIR	Saving to Investment Ratio
SP	Simple Payback
SRM	Sustainable Resources Management
SWG	Sustainable Working Group
TBL	Triple Bottom Line
TCF	Total Carbon Footprint
TETP	Terrestic Ecotoxicity Potential
TG	Task Group
UK	United Kingdom
UKGSD	United Kingdom Government Sustainable Strategy Development
UKSC	United Kingdom Sustainable Construction
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environmental Programme on Industry Environment
UNFCCC	United Nations Framework Convention on Climate Change
USDD	United States Department of Defence
VE	Value Engineering
WBCSD	World Bank Commission on Sustainable Development
WB	World Bank
WCE	World Congress on Engineering
WCED	World Commission on Environment and Development
WHO	World Health Organisation
WWF	Working With the Future

Nomenclature

A^C	Complement
⊆	Collection of elements
E	Element of set
Є	Real element of numbers
(£/FU)	Cost in pounds per functional unit
(£/ton)	Cost in pounds per ton of materials
fi	Frequency of response
wi	Weight of each rating
i	Rating
$\overline{X}$	Weight of sample mean
∉	Not element
3R	Reduce, reuse and recycle materials
f	Function
U	Universal
P	Probability
∑	Summation
∩	Intersection
∪	Union
Ø	Null set
σ^2	Variance in data population
≤	Less than equal to
MJ	Mega joule

kgm^{-3}	Kilogram per cubic metre
PO^{4-}	Phosphate emission
GWP_{100}	Global warming potential
eq	Equivalent
S_{uv}	Sustainability value
CO_2	Carbon dioxide
n	Numbers
kWh	Kilo Watt hour
m^2	Square metres
m^3	Cubic metres
l	Litres
$\int$	Integral function

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Definition of key terms

The key terms as applied in this thesis are clearly defined. They include:

Building services infrastructure performance: Explains the services delivery and the measure of the related activities to include resources use within a building (facility).

Coefficient of Variation: Expesses the percentage difference in one variable relating to another variable in data analysis (Field, 2006).

Factor: Another name for an independent variable and is typically used when describing experimental designs in analysis (Field, 2006).

Frequency: Defines the number of repetitions of sample distribution in a data test.

Matrix: Expresses a collection of numbers arranged in columns and rows. The values within a matrix are typically referred to as components or elements in a numerical test.

Normalisation: Arranging sustainablity values limit to unity or sorting of variables for the ease of computation (Heidi *et al.,* 2005).

Reliability: Describes the ability of a measure to produce consistent results when the same entities are considered under the same conditions (Field, 2006).

Sustainability index: Explains the ratio of the global bio-capacity of the earth to the ecological footprint in building infrastructure (Cleveland, 2013; Knoepfel, 2001).

Sustainability: The practice of sustainability in this context explains the creation of new techniques in the exploitation of available resources to promote equitable, bearable and viable values with a healthy future for every individual and the planet.

Severity Index: Explains the level of impact or influence.

Weighting: Describes the number by which variables are multiplied in data analysis. The weight assigned to a variable determines the influence that the variable has within a mathematical equation (Field, 2006).

Publications

This study has resulted in the following publications.

Refereed Journals:

Okon, B. B., Ekpo, S., and Elhag, T. S. M., (2010), A Sustainable Engineering Infrastructure (SEI) Model for the 21st Century. Journal: Lecture Notes in Engineering and Computer Science, **2184**, 1 pp. 1101–1105.

Okon, B. B., and Elhag, T. S. M., (2011), Sustainability Index: An Application into Sustainable Engineering Infrastructure Management and Assessment. Journal of Mechanics Engineering and Automation, **1**, 1 pp. 18 – 31.

Okon, B. B., and Elhag, T. M. S., (2011), Infrastructure Assessment: A Case Study of Aluminium Smelting Plant, Nigeria. Journal: Lecture Notes in Engineering and Computer Science, **2192**, pp. 2052–2056.

Refereed Conferences:

Okon, B. B., and Elhag, T. M. S., (2011), Sustainable Engineering and Innovative Technology in Managing Infrastructure Systems, 10th International Research Conference on Quality, Innovation & Knowledge Management, Malaysia.

Okon, B. B., and Elhag, T. M. S., (2011), The Role of Education for Sustainable Engineering and Technology in Construction Infrastructure. Proceedings of the Engineering Sustainability (ES) Conference, University of Pittsburgh, USA.

Okon, B. B., and Elhag, T. M. S., (2012), The Sustainable Infrastructure Management Model (SIMM): International Conference on Systems Engineering and Engineering Management. World Congress on Engineering and Computer Science (WCECS), San Francisco, USA.

Chapter One

1.0 Introduction to building services infrastructure systems management

This study overviews the management practices regarding building (facility) services infrastructure and building construction activities in the UK. In addition, there are also some comparative elements in this study between the UK and Nigerian scenarios. The aim of this study is to investigate the key management practices concerning the highlighted background activities and to address such problems with a view to achieving a more sustainable and good quality services delivery in buildings. The Chapter begins with an introduction to the general context of the research. This is followed with a synopsis of the situation regarding sustainability in building services infrastructure and building construction management practices. In this Chapter also, the associated management practices are assessed from the ‘cradle to grave’ processes in terms of their integration of the sustainability agenda as a means to realise sustainable development. Additionally, this chapter presents a statement of the research problem with is concerned with exploring how to deliver the appropriate management practices. Furthermore, the Chapter contains the research questions, aim and objectives, and indicates the scope of study. The significance and benefits of the research are also considered briefly, and the way in which the thesis is structured is shown.

1.1 Sustainability in building services infrastructure

The building services infrastructure utility resources and their application within the built environment is of great concern. Energy and water resources are the basic utilities commonly used in every home and all facilities around the world (Killip, 2005; NSF, 2005; Kintner-Meryer, 1999). The sustainability of these resources is now becoming a topical issue in the global economy (UNFCCC, 2012; Eco Homes, 2003; Doka, 2007). Contemporary researchers have established that one of the greatest challenges of the present era is anchored on the issue of resources exploitation and sustainable development. But, there are huge implications of the exploitation of resources for human activities (WCED, 1987; Ellis, 2007; GSGF, 2010). In this respect, BREEAM (2008) notes that the rapid industrialisation, as witnessed through building services infrastructure growth in various emerging economies worldwide, has a negative impact on the available resources and the environment (Bardos, *et al.*, 2009; CIOB, 2011). Fundamentally:

> *Building services infrastructure in this context spreads across water, wastewater, energy and utilities, heat, air-conditioning and ventilation (HVAC), fume extraction, fire protection and alarm systems. Additionally, elevators (lifts), waste management systems and information technology (IT) systems are needed for the proper functioning of buildings (facilities). Other building services responsibilities are the in-house predictive, corrective and ancillary maintenance practices undertaken on the listed equipment within the buildings (facilities) for effective services delivery (Grigg, 1988; Armstrong, 1987; Okon et al., 2010; ASHRAE, 2004).*

The overall aim in this case is to provide sustainable, economic and reliable management practices to support the buildings (facilities) use. However, these building services infrastructure practices and their development have placed the issue of resource availability and the environmental implications of current spread strategies at the centre stage in economic expansion activities (BSI, 2006; GSGF, 2010). Indeed, recent studies from (Cuellar and Adisa, 2011; Darby *et al.*, 2011) have also revealed the impact of building services infrastructure activities. More often than not, these impacts are seen through the application of cooking gas, coal, fossil fuel, and oil, within the construction and operational (use) phases of the building. In this situation, it is noted (see ASHRAE, 2004; Armstrong, 1987) that the release of these burnt products into the atmosphere means that toxins are caught up in the air, thus giving rise to the global warming threat (BREEAM, 2008; Smith, 2009). Consequently, some researchers have proposed the regulation of building services activities through the integration of the sustainability agenda within corporate business strategies as a means of achieving sustainable development goals (Welford, 2003; KPMG, 2008).

The incorporation of the sustainability agenda into building services activities is tailored towards achieving best practices in the field of resource consumption (CIOB, 2010; CIOB, 2011; CCT, 2008), and management of the buildings with a view to realising sustainable development. It is in this direction that regulatory changes (KPMG, 2008; Loosemore and Phua, 2011) concerning the social, economic and environmental reputation of building services infrastructure management activities could be attained (Epstein, 2006; Lelyveld and Woods, 2010).

1.2 Sustainability in building construction

In the 21st century, much emphasis has been placed on the concept of sustainability within building construction activities. The construction industry has been identified as one of the major drivers of economic development within the built environment (Oritz, *et al.*, 2009; OCED, 2003) but the activities undertaken within that industry need to be appraised for their sustainability (Cheshire, 2007; BREEAM, 2008). In fact, Boyle, (2005) noted that the overall concept of sustainability relating to buildings is still poorly defined. However, to a large extent, the focus of sustainability is on the utilisation of energy in buildings. In the UK, approximately 66% of the total energy consumption is accounted for by buildings and building construction activities (Boyle, 2005). That said, Winther and Hestnes (1999), and Eaton and Amato (1998) have argued that the energy consumed in the operational phase of a building overshadows that of the construction phase. Typically, 90% of the energy is consumed in the operational phase over the lifespan of the building. As a result, much research has focused on sustainability and the reduction of energy use in respect of house and water heating (ASTM, 2002; Ashworth, 1999; ASHRAE, 2004).

In respect of the integration of sustainability within construction activities, Boyle's (2005) study revealed that this has become imperative due to the growing concern that human activities are affecting global and local ecosystems (Bellandi, 2004; Sabol, 2008). These human activities within the construction industry have severe environmental impacts and potentially cause permanent changes to some ecosystems and to natural resources generally (Lorenz, 2008; Killip, 2005). For instance, Lippiatt (1999) indicates that buildings consume 40% of the gravel, stone and sand, 25% of the timber, 40% of the energy and 16% of the water used globally per year. In the UK alone, it has been estimated that about 6 tons of building materials per every member of the population are used annually (Cooper *et al.*, 1997). Clearly, such statistics show the need for a sustainability check (Bardos, *et al.*, 2009; Ding, 2008; CIOB, 2010).

It is true that the principles and benefits of sustainability and other frameworks as applied to the construction industry have been discussed (Cheshire and Maunsell, 2007; BREEAM, 2008; BSI, 2008; CCT, 2008; Hill and Bowen, 1997; ISO, 1997; Dutil *et al.*, 2011). And it has been argued that within the context of the construction industry, sustainability could be promoted through corporate social responsibility (KPMG, 2008; Mior, 2001; Welford, 2003). In fact, this is a crucial requirement as sustainable practices promote value added for building construction activities in terms of their long-term viability (Pedersen, 2006). It is noted by KPMG (2008), that the integration of sustainability as a corporate business strategy within the construction industry, provides the necessary framework for the success of building developments (Aaronson, 2009; Loosemore and Phua, 2011). Generally, the efforts expended in response to that strategy encourage building construction activities that are in harmony with the idea of sustainable socio-economic and environmental success (ESCAP, 2006; Clift, 2003).

1.3 Problem statement

Building services infrastructure management and evaluation in contemporary society is very challenging. Increasingly, building services infrastructure users are finding it difficult to adjust to the rates of water and energy use, among other resources, at the same time as attempting to introduce sustainability measures (Kintner-Meyer, 1999; Eco Homes, 2003; ASHRAE, 2004). This study recognises the pressure associated with building services infrastructure and the need for sustainability, and consequently aims to explore the challenges, mitigating situations, and the current best practice implemented in the hope of a 0practical solution. There are already many studies that have considered the current design of building services infrastructure systems and models to incorporate various innovative models to promote quality of services whilst also achieving the economical management of utilities resources (RICS, 2010; PMPCB, 2010; DEFRA, 2011).

And in this study, the building construction activities are similarly appraised from the ‘cradle to grave’ as found in the work of various authors (see for example, Clift and

Bourke, 1999; Lorenz, 2008; Clift, 2003). However, it is acknowledged, that regardless of the breakthroughs that have been made by the various modelling activities conducted by previous researchers, there remains a need for more emphasis on the expansion of tools that can be implemented, and on the need to create more awareness concerning the use of building services, and building construction activities. These challenges provide the rationale for examining the entire range of building management practices in order to arrive at possible solutions to the research problem.

1.4 Aim and objectives of the research

This study aims to examine the barriers to the implementation of best practices in managing sustainable building services systems. It focuses on the building services infrastructure and building construction activities within the UK and Nigeria.

The main objectives of the study are as follows:

- To identify the problems influencing sustainable infrastructure management practices within the building services and building construction activities.
- To investigate the obstacles to the achievement of the best practices within the context of this study.
- To appraise the current standard of performance within the building services infrastructure systems and management practices in both the public and private sectors.
- To develop suitable models and frameworks for addressing problems associated with building services management and building construction activities.
- To compare the developed models and frameworks with the existing ones and to verify the results using different phases of study.

1.5 Research questions

This study is concerned with the delivery of building services infrastructure systems that aim to produce sustainability within UK and Nigerian buildings (facilities). As a result, the following questions are formulated:

- Are building services infrastructure systems and building construction projects properly managed according to the sustainability criteria?
- Is the concept of sustainability integrated into building services infrastructure systems and construction projects?
- Is the sustainability agenda appropriately incorporated in both the public and sectors in this context?
- Is it possible for clients to manage, verify and validate sustainability processes together with other important activities relating to building services infrastructure systems and building construction projects?
- What are the private and public sectors' attitudes towards integrating the concept of sustainability within building services infrastructure and building construction projects in the 21st century?
- Does the awareness regarding the concept of sustainability in this context have any positive impact upon practical applications?

1.6 Scope of the research

This research reviews an extensive body of literature concerned with building services infrastructure, including that relating to energy, water, and wastewater among others, and the management practices associated with these services. The building construction aspect is also reviewed. This approach is necessary as the major areas of interest in this study centre on the current management practices and standards of performance associated with success in terms of sustainability. Building services infrastructure characteristics are considered within the UK and Nigerian scenarios. Additionally, the LCA and LCC among other techniques, are employed to measure the performance of services delivery in this study.

Energy and utilities management and their carbon footprint within hospitals and schools in UK are also studied and a comparative analysis is made between the two sectors. An SEI model, the sustainable index matrix, and the partial differential equation method are also developed to verify the sustainability indices of the building services infrastructure studied. The existing knowledge, identification of problem areas and applications are addressed in this study. Generally, the management practices within building services and construction projects in the UK and Nigeria are considered.

1.7 Relationship among the entire phases of study, I – VII

The study in phase I, relates to the building services infrastructure characteristics associated with the operation and maintenance management of commercial buildings (Shopping Malls) within the UK. In study phase II, construction activities are examined within five building construction companies in the UK. The study in phase III focuses on the building services infrastructure characteristics in respect of the operation and maintenance management within the Aluminium Smelter Company of Nigeria (ALSCON) facilities. In phase IV, the study addresses the building services infrastrcture characteristics associated with the operation and maintenance management within the Mobil Producing Nigeria (MPN) facilities in Nigeria.

All the phases of this study are related in terms of their architecture, components and engineering design for optimum services delivery. Classically, the building services infrastructure characteristics in the study phases I – IV are designed with holistically provide services in buildings (facilities) settings from the cradle to grave. That is, from the design, construction, operation (use) and maintenance stages of buildings and facilities (RICS, 2008; Grigg, 1988; NSF, 2005). As such, this pattern houses all the building services infrastructure components in the study phase V which LCA and LCC examined. Therefore, the environmental impact arising from the equipment and operation, energy and utilities use, together with their related costs can be evaluated to ascertain the quality of performance in buildings and facilities.

In the case of the energy and utilities appraisal in study phase VI, the activities involved are within buildings and facilities as elements of the infrastructure systems. The energy and utilities use gradually constitutes environmental impact. Hence, the impact arising from energy and utilities consumption contributes towards the climate change threat (PMPCB, 2010; RICS, 2008; Ellis, 2007; CCT, 2008). With the integration of sustainability programmes into building services infrastructure and building construction activities as core management strategies, this problem could be appropriately addressed. However, such integration can only be effectively achieved through suitable innovative design and construction, the installation of quality equipment, and the implementation of standard maintenance culture practices in study phases I – V, as revealed in data from various surveys (Horner *et al.,* 1997; Bayer *et al.,* 2010). The study in phase VII is also related to the other phases of the research activities. In phase VII of this study, structured interviews are held to evaluate the perception of sustainability in the current management practices and implementation processes in building projects. The interview findings are used to corroborate the survey information contained in Chapter Seven of this thesis.

1.8 Gaps in the literature

Sustainability ethics and their incorporation within activities concerned with building services infrastructure, and building construction projects represent a challenge for building services engineers, and therefore, the entire topic requires more study. The sustainability agenda is defined as meeting the needs of the present generation without compromising the ability of the future generation to satisfy its own needs (WCED, 1978; UM, 2002) and this agenda has had a very significant impact across the whole range of different economic activities. It has been progressively noted (see for example, KMPG, 2008; Wood, 2006; OCED, 2003) that the sustainability agenda and its implementation within this context represent a paradigm shift in respect of social, environmental and economic activities (Yudelson, 2008; UKSC, 2006; Turner, 2006). The notion of the sustainability programme as requiring innovative building management strategies has brought much transformation into the construction sector over the years (Ding, 2008; Shah, 2007), and recent studies (see for example, Wood, 2006; GSGF, 2010; Girouard, 2011; Dutil *et al.,* 2011) can be identified in this area. However, so far, the studies produced have considered sustainability from a qualitative approach.

There is little or no information from researchers who have addressed impacts upon sustainability using quantitative methods. Furthermore, studies exploring the sustainability impact from quantitative approaches, are not common within this context. Hence, there is a lack of rigorous information concerned with the measurement of the sustainability impact caused by building activities in the UK and Nigerian contexts.

This study will concentrate on providing literature in this respect, thereby producing information concerning sustainability impact within building services infrastructure activities, which is obtained using both qualitative and quantitative methods. Recent studies (Okon *et al.*, 2010; Okon and Elhag, 2012) have established the SEI model and sustainable infrastructure management model as implementable tools for appraising quantitative sustainability impact in respect of building activities goals. This study will also explore the sustainability drivers, policies, challenges, and the factors affecting the appropriate implementation of the sustainability agenda within building management. Moreover, various building management strategies will be considered to add valuable contributions to the debate about sustainable development success.

1.9 Significance and benefits of the research

The research outcomes are significant for a wide range of practitioners (experts) concerned with sustainability programmes in the general area of building services infrastructure and building construction activities. In particular, the benefits will be through the identification of management problems, characteristics, gaps, the major policy drivers, and the provision of implementation tools for sustainability goals. The indicators in respect of sustainability goals are identified through the SEI model and a partial differential equation method. A sustainability index matrix (SIM) is also established through this study as a management technique for appraising building services infrastructure performance. Also, a project life cycle frameworkis developed and applied in measuring the sustainability indices of the building projects examined in the study. These models are innovative management strategies aimed at supporting sustainable development success in this context. In the same vein, other new approaches towards the mitigation of building services infrastructure systems problems are established in this thesis. Moreover, all the phases of study address the building management problems in both the public and private sectors of the economy.

Findings from this study will provide appropriate platforms for building experts (building services, facility managers, building contractors, architects) and financiers amongst others. These findings will raise awareness among both public and private sector clients' of how they can employ the SEI model for sustainable building management. The incorporation of the sustainable infrastructure management model and sustainability index matrix model will also offer a better approach in evaluating building project delivery. Also, the project life cycle framework will create a competitive advantage in appraising the cradle to grave activities in building management processes. It is worthwhile to mention that this study will also deliver improved knowledge and understanding in respect of the integration of the sustainability agenda into building management activities.

1.10 Structure of the thesis

The structure of the thesis is illustrated in Figure 1.1.

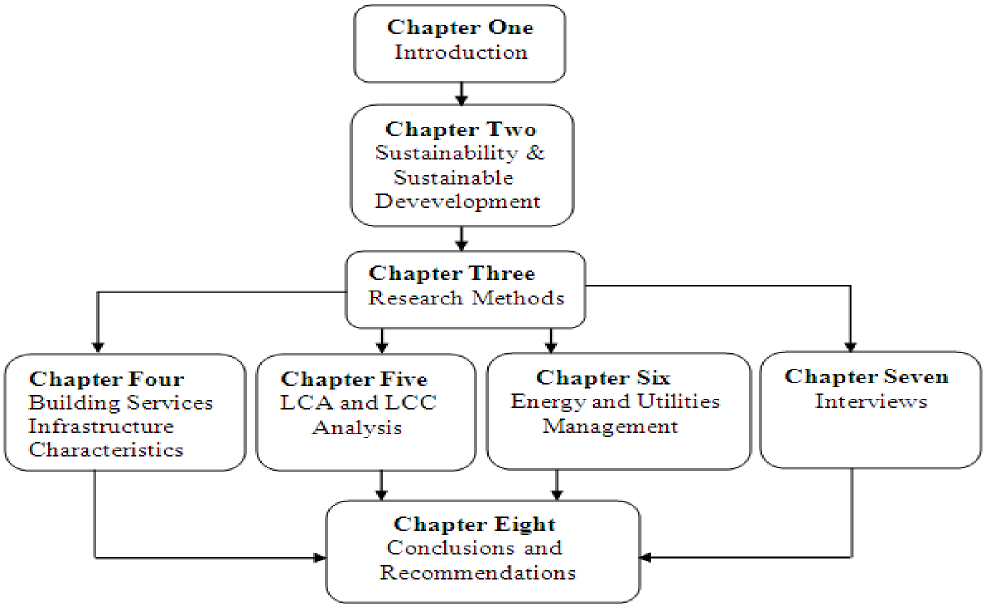


Figure 1.1: The structure of the thesis

This study is structured into eight Chapters and the appendices. Chapter One presents the introduction to building services infrastructure and building construction activities and management. It further includes sustainability integration within the context of this study, the statement of the research problem, and the questions that have been formulated to address this. The aim and objectives of the study, scope, significance and benefits, together with the structure of the thesis, and an overall summary of the chapter, are also presented.

Chapter Two provides a review of the related literature and gives an introduction to sustainability and sustainable development in respect of building services infrastructure systems management. The triple bottom line (TBL) of sustainable development is also discussed. Again, the overall context of the study and the ecological modernisation regarding building services infrastructure management are examined. Corporate sustainability and knowledge transfer in respect of building services infrastructure systems management are also considered, as are the associated challenges. Sustainable building services infrastructure in the context of economic growth in contemporary society is also analysed and discussed in this Chapter. The various frameworks for building services infrastructure and building construction development are explored, and proactive measures for addressing sustainable building services infrastructure management and engineering are indicated as best practice.

Chapter Three presents the research methods concerned with sustainable infrastructure systems management. Additionally, the design for this study is introduced, presented in an algorithmic flow chart which shows the sequence of the processes undertaken. Information regarding the surveys conducted in the different phases of study is also provided, and details of the pilot study, administration, feedback, and techniques of analysis are also given. Additionally, the Chapter includes details of the SEI model development and the methods used for the interviews and analysis.

Chapter Four explores the results and discussions relating to study phases I – IV. The study phases are commercial buildings (operation and maintenance), building construction companies, UK and ALSCON with MPN facilities in Nigeria. This basically addresses the findings from the examination of the characteristics of the building services infrastructure associated with these companies and facilities. The building services infrastructure in the UK contains shopping malls among other commercial buildings, and the building construction industry. In the Nigerian situation, ALSCON and MPN buildings (facilities) are examined. This Chapter also accounts for the sustainability index matrix used in the determination of the building services infrastructure performance. Results from the comparative analysis of the UK and Nigerian scenarios, and the sustainability indices for both cases in respect of the building services infrastructure characteristics, and the management techniques that are used to ascertain the performance of individual organisations, are also presented.

Chapter Five considers the results and offers a discussion concerning the LCA appraisal of ten environmental impacts of the infrastructure of six buildings within the UK, study phase V. Furthermore, the LCC evaluation of these six buildings' infrastructure, and the findings from the statistical examination of the findings in this respect, are also reported.

Chapter Six presents the results and a discussion of the energy and utilities management, together with a carbon footprint study, of the healthcare and education sectors within the UK. This investigation is conducted in phase VI of the study. The Chapter also incorporates information about the study process and data acquisition. The results and a discussion concerning the operation (use), maintenance and waste management activities within the investigated sectors are also presented. This Chapter includes carbon footprint management, probability analysis, sustainability index results and a comparative analysis through the application of a partial differential equation method in ascertaining building services performance.

Chapter Seven presents the concept of sustainability and its integration within building services infrastructure management as perceived by industry-specific experts with whom structured interviews are held. This section of the study represents phase VII. Also contained in this Chapter is a discussion of the relationship and the benefits derived from all the phases of the study.

Chapter Eight highlights the conclusions of the study and the recommendations made. It also discusses the contributions to knowledge made by the study, the limitations it encountered, and makes recommendations in respect of further research.

Several appendices are attached to the thesis for reference purposes.

1.11 Summary

This Chapter of the thesis has provided a detailed insight into the background to the study, and has given an introduction to the overall context of the research. The need for the integration of sustainability objectives within building services infrastructure and building construction projects activities has been presented, and from this, a statement of the problem, the aim and objectives of the study, and the research questions associated with it, have been formulated. The gaps in the current literature have been identified, and the significance and benefits of this study are noted. In addition the way in which the research study is structured has been shown. It has been noted that the benefits of this study are specifically through its application of the SEI model and other strategic management methods. Furthermore, however, the other contributions made by the study are also noted. Having produced this background information, the necessary theoretical foundations of the research have been identified.

Chapter Two

2.0 Sustainability and sustainable development in building services infrastructure systems management

2.1 Introduction

Issues relating to sustainability in the 21st century are increasingly gaining prominence in interdisciplinary engineering applications within building services infrastructure systems, sub-systems and technologies, as the aim of achieving sustainable development goals gathers momentum. Indeed, all economic development frameworks rest on sustainability for future advancement (WCED, 1987; UM, 2002). It therefore becomes imperative for the sustainability agenda to be incorporated within building services management as a core business strategy and best practice (KPMG, 2008). This study requires the exploration of different themes as shown in Figure 2.1.

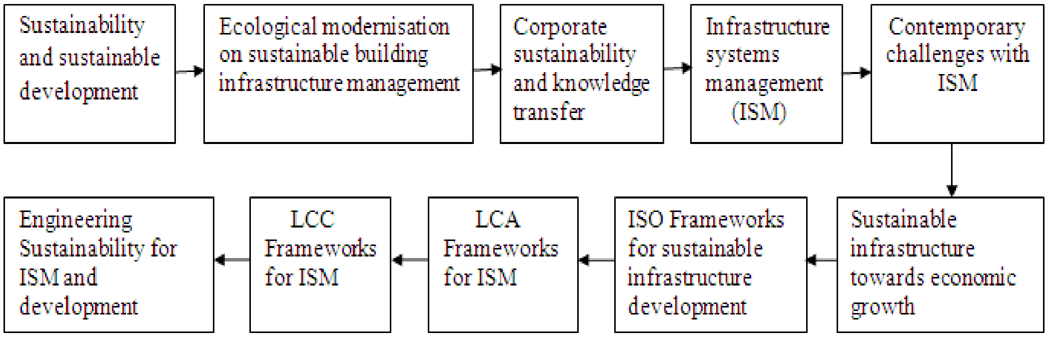


Figure 2.1: The study process

2.2 Sustainability and sustainable development

Sustainability and its wider application is quite an innovative advancement, which, in part, seeks to address the poor management of existing natural resources. The recent application of sustainability pervades every facet of economic, material and human endeavours regarding the sustainable development goals (Bardos *et al.*, 2009). More interestingly, Drexhage and Murphy (2010) argued that the concept of sustainability is perhaps best described as a measure of how well a particular endeavour is able to meet these goals of sustainable development. It can also be defined as meeting the needs of the present without compromising the ability of future generations to satisfy their own needs (WCED, 1987; Elkington, 1997). Certainly, it has grown in significance across many business organisations. Indeed, increasingly, organisations including the construction industry are becoming more concerned with the impact of their business activities on economic, social and environmental sustainability (Elmualim *et al.*, 2012).

The impact of sustainability issues on building construction activities is topical and challenging, and consequently debates on the way forward are needed (UNFCCC, 2009; CIOB, 2011; Cheshire and Maunsell, 2007). The overall debate has culminated in the discovery of the issues and drivers that can offer guidance in relation to sustainability appraisal and the improvement of building construction activities to ensure sustainable development (Cheshire, 2007; Elmualim *et al.*, 2012; Eco Homes, 2003). However, Dutil *et al.* (2011) argue that guidance in itself is not enough and that sustainability imperatives must be integrated with building management policy, and recognised as key ingredients (OECD, 2003). Such an approach will curtail a significant amount of the social, economic and environmental impact arising from building activities. Moreover, the compulsory integration of sustainability criteria will demand regulatory compliance with the recurrent issues concerning resources use and climate change (RICS, 2008; GSGF, 2010; GBPC, 2010; UNFCCC, 2012; Lazarus, 2005).

In a related development, the UNFCCC (2012) argued that issues concerning the recurrent use of resources, and climate change (ozone depletion, pollution, ecosystem destruction and global warming) amongst others, can be managed through sustainability programmes (Rio Summit, 1992). Environmental concern about the economic and social outcomes of resources over-utilisation is a must if sustainable development is to be achieved. Nonetheless, such concern in itself is not sufficient, since as several studies in this context have shown, sustainable development cannot function without actual sustainability goals (WCED, 1987; Sattertherwaite, 2001; Pope *et al.*, 2004; WB, 2010).

2.2.1 Review of the triple bottom line of sustainable development

The triple bottom line (TBL) principles of sustainable development emphasise the need for an inseparable framework to support sustainability goals (Elkington, 1997;

KPMG, 2008). Increasingly, the TBL framework in this context incorporates a highly inter-related and equally important relationship among the three values regarding the use of natural resources in building management. Furthermore, due to the significance of the TBL model in achieving sustainability, Hacking and Guthrie (2008) have noted that the framework is gradually gaining acceptability in the global building industry as a vehicle for realising sustainability objectives. Indeed, recently, business communities worldwide have adopted the TBL paradigm as a framework for corporate reporting practices to comply with regulatory changes, and to improve their social, economic and environmental reputation in respect of sustainable development goals (WCED, 1987; Elkington, 1997; KPMG, 2008). Figure 2.2 depicts the TBL model of sustainable development.

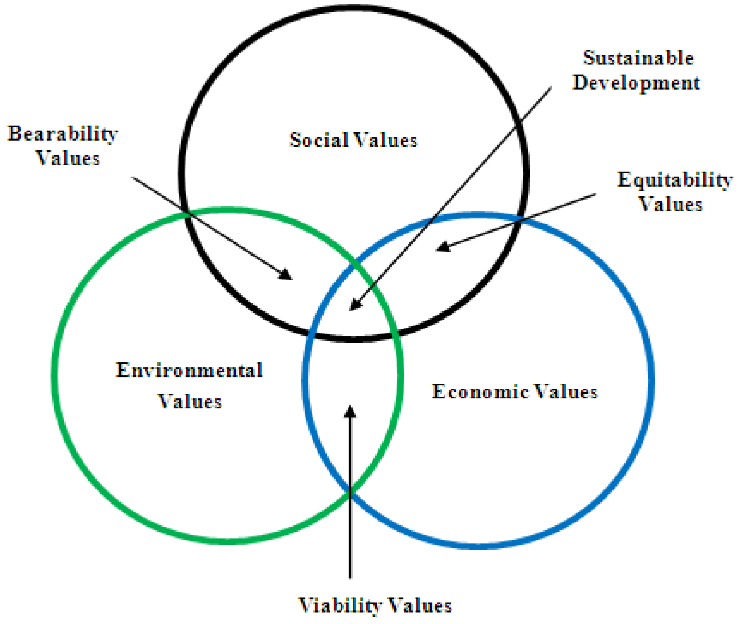


Figure 2.2: The TBL model of sustainable development (UM, 2002: Okon *et al.*, 2010).

In practical terms, the TBL framework expresses a set of environmental values that include natural resources utilisation, environmental management, and pollution prevention and controls (air, land waste, and water resources) (Annecke and Swilling, 2005). Elkington (1997) includes the notion that the social set focuses on the standards of living, equal opportunity, community, governance, institutions, inclusion, consultations, and empowerment of citizenry. The economic set outlines cost savings, profits, research and development, economic growth, efficiency, and stability. Within the sustainability model, the spheres of sustainability intersect (socio-environmental) values yielding a new set of sustainable engineering infrastructure (SEI) model values (WCED, 1987: UM, 2002; Okon *et al.*, 2010).

On the other hand it is maintained (Young, 1997; Elkington, 1997; UM, 2002) that the socio-environmental values are: environmental justice, natural resources, and stewardship. Moreover, where sustainability intersections occur between economic and social values, they can be seen to promote the equitability standards of business ethics, fair trades, and workers right. The intersection between environmental and economics values supports the viability values of energy efficiency, subsidies, and incentives through the use of natural resources, as shown in Figure 2.2 (UM, 2002; Okon *et al.*, 2010).

However, due to the rapid industrialisation witnessed throughout the building industry in various emerging economies in the world, it is necessary for all available resources to be suitably managed. This is vital, particularly because of the human-induced threat of global warming, and the fact that with more controls, the natural environment could be better protected. The TBL model is capable of integrating sustainability into corporate building industry strategies to achieve for sustainable development goals (Bardos *et al.*, 2009; Keller, 2009). In this respect, it is valuable for testing sustainability practices, thus adding value to building services activities and their evaluation, as reported in this thesis.

2.2.2 The context of the research

In this study, the main area of interest is the establishment of best practices through integrating sustainability principles into building services infrastructure management as core business strategy for sustainable development. The literature reviewed in this chapter identifies the key sustainability issues, policy drivers and frameworks, and incorporates the concept of sustainability into building services activities within a wider framework of sustainable development. The challenges associated with the environmental, economic, and social values are also investigated in the light of the ever-increasing building development and urban sprawl witnessed in the built environment. Basically, this study provides an overview of:

The services delivery within the building services (infrastructure) utilities management, and building construction projects activities generally. The infrastructure services include energy, water, heating, waste management, materials consumption, and their carbon footprint. Also, the life cycle analysis and life cycle costs evaluation associated with building services performance are studied (ASHRAE, 2004; Armstrong, 1997; GSGF, 2010; Bayer et al., 2010).

The built environment's potential as a major contributor to the achievement of sustainability initiatives cannot be over-emphasised. These potential contributions in terms of sustainability principles can be seen in the promotion of sustainable building industry activities (BREEAM, 2008; ASHRAE, 1999; ASHRAE, 2004). The principles themselves rest on gradual adoption by eco-efficient building services management of integrated and multi-disciplinary innovative approaches that will ultimately produce effective building performance. Current innovative and sustainability management protocols regarding building practices are well documented (PMPCB, 2010; Eco Homes, 2003; CCT, 2008). Figure 2.3 illustrates how sustainability principles are incorporated into the various processes involved in building construction.

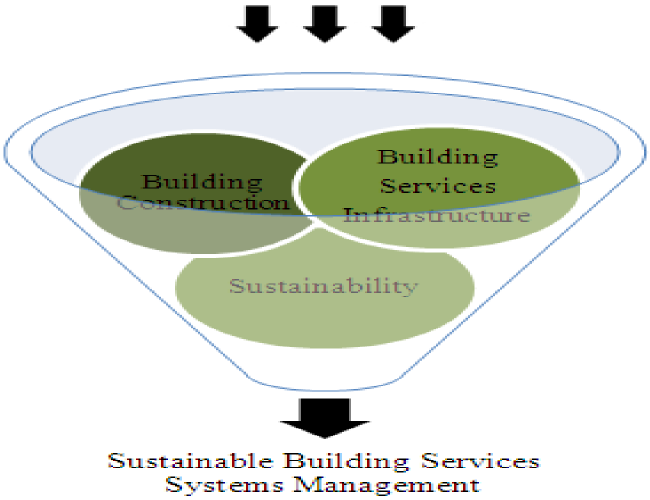


Figure 2.3: The research contextual model.

There is a need to incorporate sustainability principles within building construction processes because these principles evolve through active participation of building services experts, who through this involvement, directly influence building management (NIBS, 2006; Shah, 2007; BSI, 2008).

2.3 Ecological modernisation in building services practice

Ecological modernisation accounts for the generic polices hitherto formulated to address sustainability issues and practices in building services management, and the construction industry (Nebel, 2006; BREEAM, 2008). In this connection, a study by Pope *et al.*, (2004) has revealed that the concept of ecological modernisation within the building sector is primarily focused on the integration of sustainability goals within building practices. This is most likely because the building services and building professionals have the best opportunity to promote ecological modernisation ethics through implementing sustainability practices in the early stages of building projects (CIOB, 2008; Eco Homes, 2003; CIOB, 2011). Also, the theory and practices concerning ecological modernisation in the building services context, have overlapping significance in the social, economic and environmental (triple) values, and these overlaps strengthen sustainable development goals (Lazarus, 2005; ASHRAE, 2004; WCED, 1987).

Turner (2006) has argued that the theory underpinning ecological modernisation and its promotion of sustainable building services practice, is tailored to incorporate the technological and innovative models that will improve the triple line of sustainable development (Norris, 2006; UKSC, 2006). And other scholars (see for example, Pope *et al.*, 2004; Horner *et al.*, 1997; Wood, 2006) have noted that the non-compliance of building services experts with the theory and practices of ecological modernisation will weaken the entire success of sustainability processes. In fact, the ecological modernisation practices required to achieve sustainability objectives are well documented (IPMVP, 2002; PMPCB, 2010; UKGSD, 2005), and include information regarding protocols for assessing energy utilities, water use, wastewater, and the building services practices for sustainability attainment (Wood, 2006; ASHRAE, 2004). The ecological modernisation practices in this case, will engender a balance in the utilisation of the available resources and promote eco-friendly building services infrastructure management (GSGF, 2010).

2.4 Corporate sustainability and knowledge transfer in building services management

Breakthroughs in existing technological advancements have integrated corporate sustainability and knowledge transfer within building services management, and interdisciplinary engineering practices (Landman, 1999; ASTM, 2002). With increasing energy, water and maintenance costs currently experienced in various homes, offices and the construction industry, the integration of corporate sustainability policies becomes crucial (Moir, 2011; CIOB, 2011; CCT, 2008). In a study conducted by Kintner-Meyer (1999) on building services infrastructure, it was found that energy, water and other utilities all have a significant influence over how buildings are used, thereby necessitating corporate sustainability policies and implementation (KPMG, 2008; BREEAM, 2008).

Corporate sustainability and knowledge transfer related to building industry activities explain the paradigm shift in theory associated with the dynamic policy changes directed towards best practices within the building services domain (CIOB, 2010; OECD, 2009a; NSF, 2005). In recent times, the building industry, through the corporate sustainability agenda, has established carbon reduction targets, waste recycling, and water and energy conservation techniques amongst other policies (CCT, 2008; Pederson, 2006; Thompson, 2008). Figure 2.4 depicts the corporate sustainability agenda as reviewed in this study. Corporate sustainability policies in the construction context are aimed at establishing codes of conduct, auditing and monitoring strategies, and social principles with eco labels that will add value to sustainable growth (Moir, 2001; Welford, 2003; Aaronson, 2009).

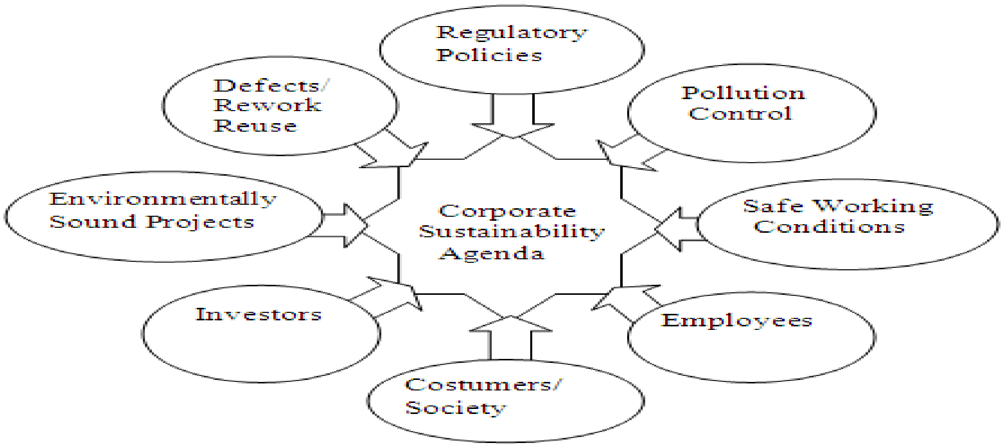


Figure 2.4: Corporate sustainability agenda for the construction industry (Robinson *et al.*, 2006).

The corporate sustainability agenda, according to a study by Robinson *et al.*, (2006) has established that current sustainability policies are influencing building industry activities. At the same time, Knoepfel (2001), and the RICS (2008) have argued that building services activities form an integral part of the building industry processes, and therefore, with the growing number of sustainability policies, issues relating to resources management and environmental impact are being addressed (Bellandi, 2004; Robinson *et al.*, 2006).

A corporate sustainability programme generally cultivates proactive levels of commitment in building services management through knowledge transfer mechanisms capable of sustaining rapid technological advancement. Hence, the involvement of the building services experts in the implementation of the corporate sustainability agenda will gradually mitigate environmental impacts and promote sustainable development success (Loosemore and Phua, 2011, Aaronson, 2009; GSGF, 2010).

2.5 Building services infrastructure systems management

Numerous research efforts have focused on the sustainable management practices related to building services infrastructure systems, as identified by their use of available resources use and the environmental consequences (ABS, 2012; Sabol, 2008). In this respect, it is understood that improved efforts seeking to address social and economic needs while minimising the potential negative environmental impacts, could promote and further sustainable development (WCED, 1987; Hill and Bowen, 1997). However, the concept of sustainability incorporation within building services management is open to a wide range of interpretations based on its vast applications. Hence, it is appropriate to summarise this concept within the context of the environmental movement. This necessitates practical frameworks for the attainment of sustainability (Ding, 2008; UNFCCC, 2009; Hill and Bowen, 1997).

Accordingly, Grigg (1988) describes building services infrastructure management activities as those activities pervading the construction sector, building industry, and facilities operations (Armstrong, 1987; ASHRAE, 1999). Building services infrastructure management also involves the processes and practices of creating, planning, and maintaining building infrastructure systems for optimum services delivery (Elmualim *et al.*, 2012; Cooke and Williams, 2004). Therefore, a sustainable building services infrastructure system must integrate sustainability models from the cradle of building design through to the completion stages in order to ensure efficient performance as best practice (CIOB, 2011; LCI, 2007). Basically:

> *Building services infrastructure systems account for the water supply, wastewater treatment, and energy use. They also include among the services: sewage management, transport (elevators), digital (IT) services, and ancillary maintenance practices within (buildings) facilities. Increasingly, the greatest building services challenges are the managerial expertise associated with the multidisciplinary applications of these systems after the design, construction, and operation activities in buildings for sustainability goals (Grigg, 1988; ASTM, 2002; Grigg, 1999; Horner et al., 1997; OECD, 2003: Broers, 2005).*

The potential contribution of building services infrastructure management and the constraints to the achievement of sustainability in the building construction sector are generally are well documented (BREEAM, 2008; Kehily and Hore, 2012; ASHRAE, 2004). In a study of sustainable management practices in building services infrastructure systems, the OCED (2003), and Sabol (2008), observed that building services experts are responsible for the integration, implementation and management of sustainability as a core building services management policy (Smith, 2009; WB, 2004). This development during the building construction processes will certainly offer the best opportunity to add value to building services infrastructure management through the resourceful use of sustainability practices. However, this cannot be achieved without a proper paradigm shift in building services management processes, which sometimes requires thoughtful integration of sound engineering judgment and economics analysis (CIOB, 2010, Grigg, 1999; Armstrong, 1987).

2.6 Contemporary challenges in building services practice

The environmental impact often arising from the style of building services management, and especially during the construction stage, is significant, thereby necessitating proper evaluation (Clift, 2003; Landman, 1999). Such environmental impacts increasingly cause problems ranging from resource depletion, pollution, and other environmental hazards, all of which do not support sustainability goals (NIBS, 2006; CIOB, 2011). Apart from the highlighted indicators driving the environmental impact in building services infrastructure activities, the use of fossil fuels by heavy duty equipment during the implementation stages also counts (DEIS, 2010; Killip, 2005).

Building services infrastructure activities frequently result in large amounts of fossil fuels consumption at different phases of building implementation (Clift, 2003). This obviously causes some environmental impact and increasingly places more pressure on resource use, in turn being responsible for climate change challenges (UN, 2003; UNFCCC, 2009). In practical terms, when cooking gas, coal, and oil, are put to use in building services operations, these products release gases, including carbon dioxide, which trap heat in the atmosphere, thereby causing climate change. This situation creates great management challenges to building services professionals in respect of their desire to achieve success in their sustainability initiatives (BREEAM, 2008; Bellandi, 2004).

Lazarus (2005) has revealed the most significant environmental impact to come from building services infrastructure networks. Buildings (facilities) such as schools, shopping malls, hospitals, factories, airports, railway stations, homes, and the building services activities associated with these all constitute sources of environmental impact

(Grigg, 1998; Halfawy, 2008). Indeed, it is noted that the building and construction sectors have produced about 19% of the UK's embodied environmental impact within the built environment (OECD, 2003; Killip, 2005). In this context, the RICS (2000) has maintained that the entire notion of sustainability should address the whole building services infrastructure life cycle processes. These processes involve all the stages in the building process, these being: pre-design and design, procurement, construction, use and maintenance, and the final commissioning and decommissioning stages (Lazarus, 2005; RICS, 2000, RICS, 2008).

The concept of sustainability integration within building services delivery has placed more challenges before both the public and private sectors due to the poor attitude of building users and the overall administrative practices (Armstrong, 1987; Horner *et al.*, 1997; Cooke and Williams, 2004). In this respect, it is crucial to create a partnership to ensure innovative, cost-effective solutions with integrated models in the building services infrastructure management systems, since only by following such a practice will sustainability goals be achieved. This collaborative development will address the overall building services infrastructure performance life cycle for the present and future generations (BREEAM, 2008; Cheshire and Maunsell, 2007; Nebel, 2006).

2.7 Sustainable building services in the interests of economic growth

Sustainability and the ways to achieve this, have been a major focus in the building construction industry and in infrastructure management within the built environment. As a result, numerous research efforts have been inclined towards sustainability, concentrating on the rate of resources consumption in the environment. Efforts which seek to address the social needs, while minimising potentially negative environmental impact contribute towards the aim of delivery sustainable building services (Hill *et al.*, 1994). Landman (1999) argued that the contributions of sustainable buildings towards achieving sustainability goals cannot be over-emphasised. Indeed, sustainable buildings and the entire services systems have been the main anchor supporting the socio-economic transformation, thus promoting economic growth (BREEAM, 2008; GSGF, 2010).

Progressively, the economic advancements which cut across building services systems, and the construction sector with the three themes of sustainable development are inextricably linked together in terms of services delivery. But these building services systems cannot function without basic energy and utilities during the construction, operation, and maintenance stages of a building (Sattertherwaite, 2001). It is also these services systems that constitute part of the living environment which affects the living conditions, social well-being, and health conditions generally (WB, 2004). Therefore, it is important to explore the social, environmental, economic, and sound design development techniques to ensure building services infrastructure systems are sustainable, affordable and healthy for habitation (Hill and Bowen, 1997). A typical model expressing the contributions regarding sustainable infrastructure services that contribute towards economic advancement is shown in Figure 2.5.

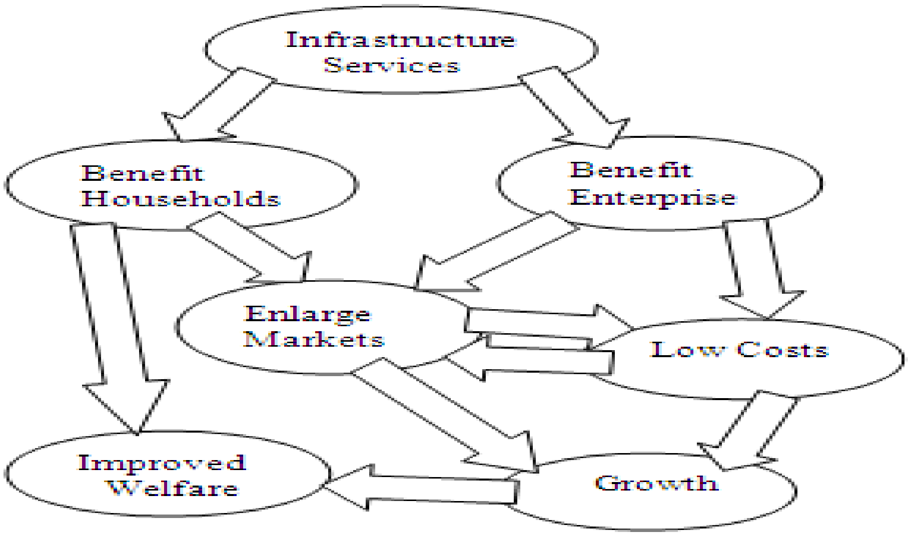


Figure 2.5: The contribution of sustainable infrastructure to economic growth (Prudhomme, 2004; WB, 2004).

Prudhomme's (2004) study clearly explains the significance of sustainable infrastructure services to the economic development of the nation in general. In Figure 2.5, the most interesting aspect is the benefit of infrastructure services to the development of households (buildings). The causality between infrastructure services, households, and other social services like the millennium development goals (MDG), operates through multiple channels. In this case, the delivery of building services, such as energy, water, wastewater, sanitation, telecommunication, and transportation (elevators), directly benefits households (buildings) and facilities. Sustainable buildings and the services delivery associated with them also play a major role in achieving the sustainable development goals, (Bohne, 2006; ESCAP, 2006a).

In order to attain the set goals of sustainability in building services management, all the various stakeholders within the building industry are expected to simulate environmental sustainability in their activities (Prudhomme, 2004; WB, 2004).

2.8 Policy frameworks and drivers for sustainable building services development

In this study, the various policy frameworks and drivers associated with sustainable building services infrastructure management are reviewed. Sustainability policy frameworks in building services management encourage the use of best practices by building managers (Smith, 2009; Eco Homes, 2003). These frameworks enable the building industry to communicate its commitment to the sustainability programme and simultaneously offer a road map for the implementation of sustainability gains. However, the adoption of such frameworks requires that they are accepted by senior management as workable models, and are supported both internally and externally (Elmualim, 2010; Lorenz, 2008). It should also be noted that sustainability policy frameworks necessitate an understanding of their overall dimensions. This means being aware of the visions, aspirations, goals, and the areas of emphasis in building organisations, but in actuality, commitment is often lacking and expectations are low (Elmualim, 2010; ESCAP, 2006a).

According to Sioshansi (2011), the sustainability policies in building services are data issues regarding water and energy consumption, waste disposal, and recycling together with employee well-being. It is argued that proper knowledge regarding the contents of sustainability policies is of greater importance as a determinant of sustainable development activities (Pitt, 2005). The main motivation for using a sustainability policy framework in promoting sustainable building expansion is to maintain best practice as shown in Figure 2.6.

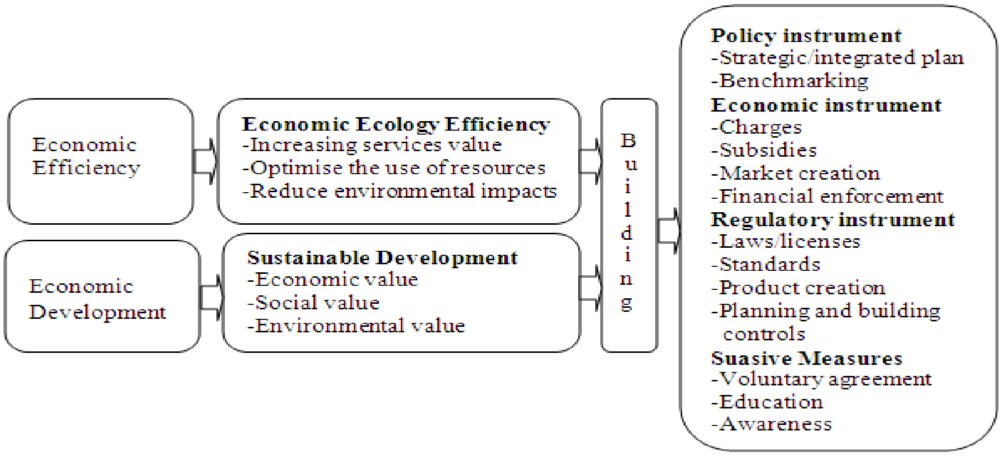


Figure 2.6: Optional policy tools in promoting sustainable buildings (ESCAP, 2006a).

In this thesis, the optional policy tool process is tailored towards improving the eco-efficiency of building growth by creating more value with fewer resources and less impact as revealed in Figure 2.6. The environmental impacts created from buildings and other infrastructure systems within the built environment demand policy frameworks and a debate on the proper issues and drivers capable of guiding the industry towards sustainability evaluation and enhancement in this context.

The CIB (2004) has pointed out that the building industry has a significant impact on the sustainability plan in that the natural resources used, and waste and greenhouse gases are responsible for about 40% of all emissions (Killip, 2005). Additionally, the existing buildings consume approximately 45% of the generated energy to produce heat and power. Increasingly, the building services infrastructure utilities and maintenance costs, along with the legislative and regulatory conditions on energy use and carbon reduction, necessitate the formulation of sustainability policies. In recent times, many building organisations have become committed to the sustainability agenda, thereby developing sustainability policies as an integral part of their corporate social requirement (Wood, 2006; Robinson *et al.*, 2006; Walker *et al.*, 2007; Loosemore and Phua, 2011).

Sustainability policies and drivers directly influence building services and facilities managers' activities in the UK. However, current research on sustainability policies and drivers influencing the activities of building services and facilities managers are limited (Elmualim *et al.*, 2010). Identifying the key issues and drivers will help to estimate how building managers are engaging with the sustainability agenda. Building managers require appropriate knowledge and familiarity with the key sustainability issues and drivers and they need to know how to implement the theory and practice of sustainability in the context of their building services activities (Elmualim *et al.,* 2010). In this respect, the key sustainability issues to be addressed are the carbon footprint, and waste management. In addition, the biodiversity and the triple themes responsibility and community engagement must be approached as sustainability issues. Progress in this respect will promote the ethics of sustainability programmes and help in the construction of more sustainable buildings (Shah, 2007; Wood, 2006).

In a recent study, Elmualim *et al.* (2012) have identified legislative pressure as the major driver of sustainability in building services and facilities management. This study further reveals that energy efficiencies and consumption in buildings are regulated through legal obligations. As such, legal obligations often play an influential role in policy-making and implementation. In other words, to accomplish the established goals of sustainability in building services and facilities management, government and international bodies employ a wide range of legislation to influence how energy is used and to promote efficiency in this case. Hence, building services activities, and the waste management (recycling) and subsequent reduction of carbon emissions, are all controlled through legislative actions (Pitt, 2005; Shah, 2007).

2.8.1 Project life cycle framework - building services management

A project life cycle framework illustrated in Figure 2.7 was developed and subsequently applied to appraise the performance of sustainable building services. The framework contains four major building activity verification phases considered necessary to ensure the growth of a sustainable building services infrastructure. Moreover, a step-by-step algorithmic approach concerning building management is stated. Within the project life cycle framework, the following abbreviations are used for clarity regarding building construction activities: acceptability standard is denoted by STDS, and specification by SPECS. The materials handling requirement is marked by REQ. These terms are used to qualify the attainment in the 'cradle to grave' principles and condition in each stage of the building project activities as presented in Figure 2.7.

The application of a project life cycle model became necessary in this context due to the enormous challenges associated with resources consumption and management (Fernandez, 2010; Okon *et al.*, 2010). These resources utilisation challenges in buildings and facilities management require the simulation and optimisation of the entire system for effective services delivery (GSGF, 2010). This obviously could be achieved through the suitable incorporation of cutting edge technological breakthroughs into building services activities management for better results (ASTM, 2002; Elmualim *et al.*, 2012). Sustainable building services management underscores eco-efficiency through the application of sound project life cycle frameworks (Eco Homes, 2003; Cheshire and Maunsell, 2007).

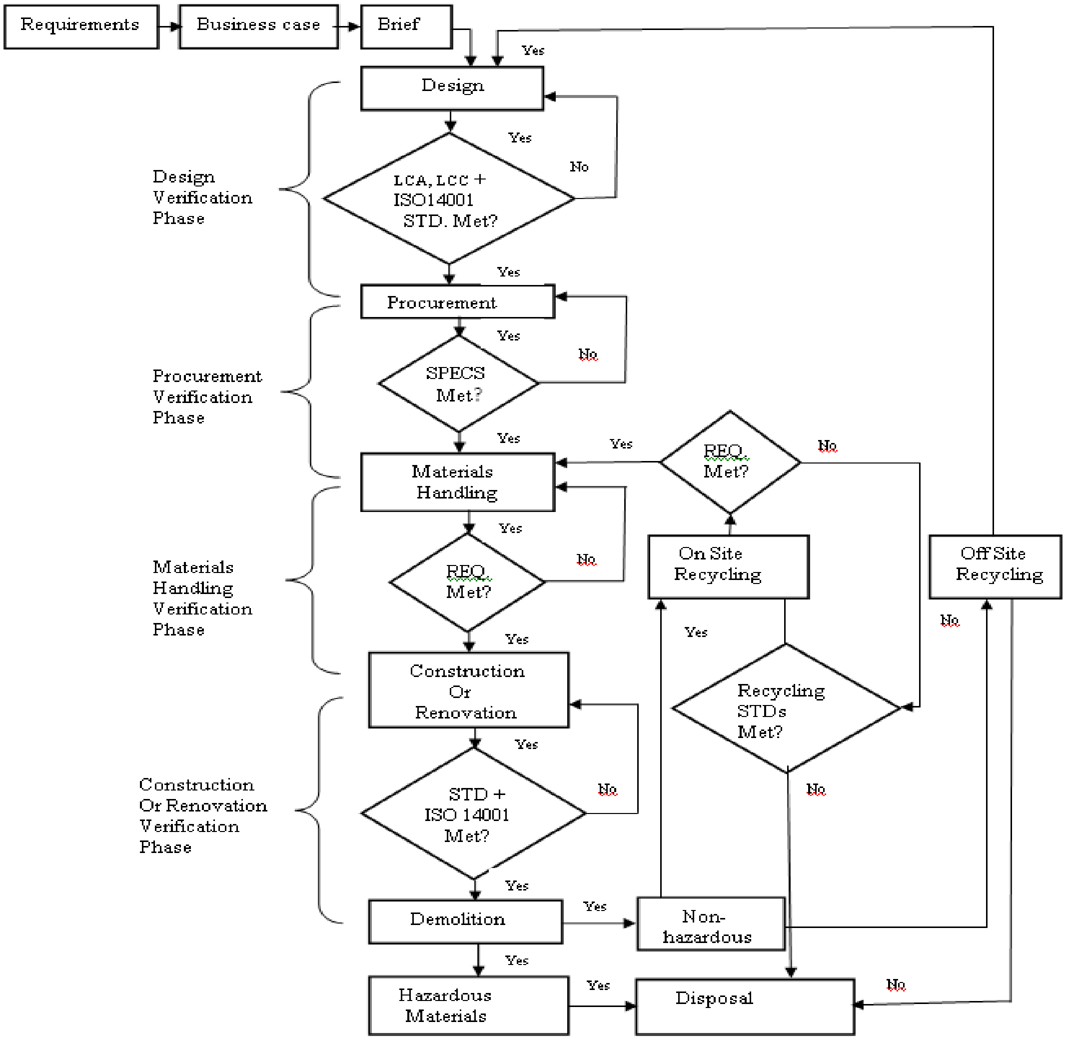


Figure 2.7: Project life cycle framework (Okon *et al.*, 2010).

In Figure 2.7, the economic benefits from the building project life cycle framework can be seen as the integrated environmental management systems (IEMS), ISO 14001, and the life cycle assessment (LCA). Also, the life cycle costs (LCC) evaluation could equally be verified from this model. It should be noted that this framework is able to address the 'cradle to grave' situation regarding sustainable buildings (facilities) management. This involves cutting across the environmental impact, costs analysis, recycling, and other related issues in building projects management for sustainability success (Okon *et al.,* 2010).

'Cradle to site' and 'cradle to grave' assessments in buildings (facilities) management are also made in a study by Darby *et al.* (2011). These authors have highlighted some factors giving rise to greenhouse gas (GHG) emissions in buildings. The factors include operational emissions, produced by buildings (facilities) during use, and embodied emissions, produced during manufacture of materials and components. In addition, the construction and demolition phases of buildings activities are indicated. Darby *et al.* (2011) further argued that at the moment, there is lack of a consistent and acceptable framework for the calculation of embodied emissions, the relationship and interaction between the embodied and operational elements in buildings. However, attempts have been made by the BSI (2006), to develop project life cycle analysis frameworks for building management. This protocol among other things is capable of handling statistics regarding the emission factors and other building management processes (BSI, 2008).

Okon *et al.* (2010) maintain that there are significant paybacks in terms of prudent resources use in sustainable buildings when suitable project life cycle frameworks are integrated, since these allow for the 'cradle to grave' activities to be evaluated, thereby adding value to the overall buildings (facilities) services activities management processes in terms of the likely success in securing sustainability (Lorenz, 2008).

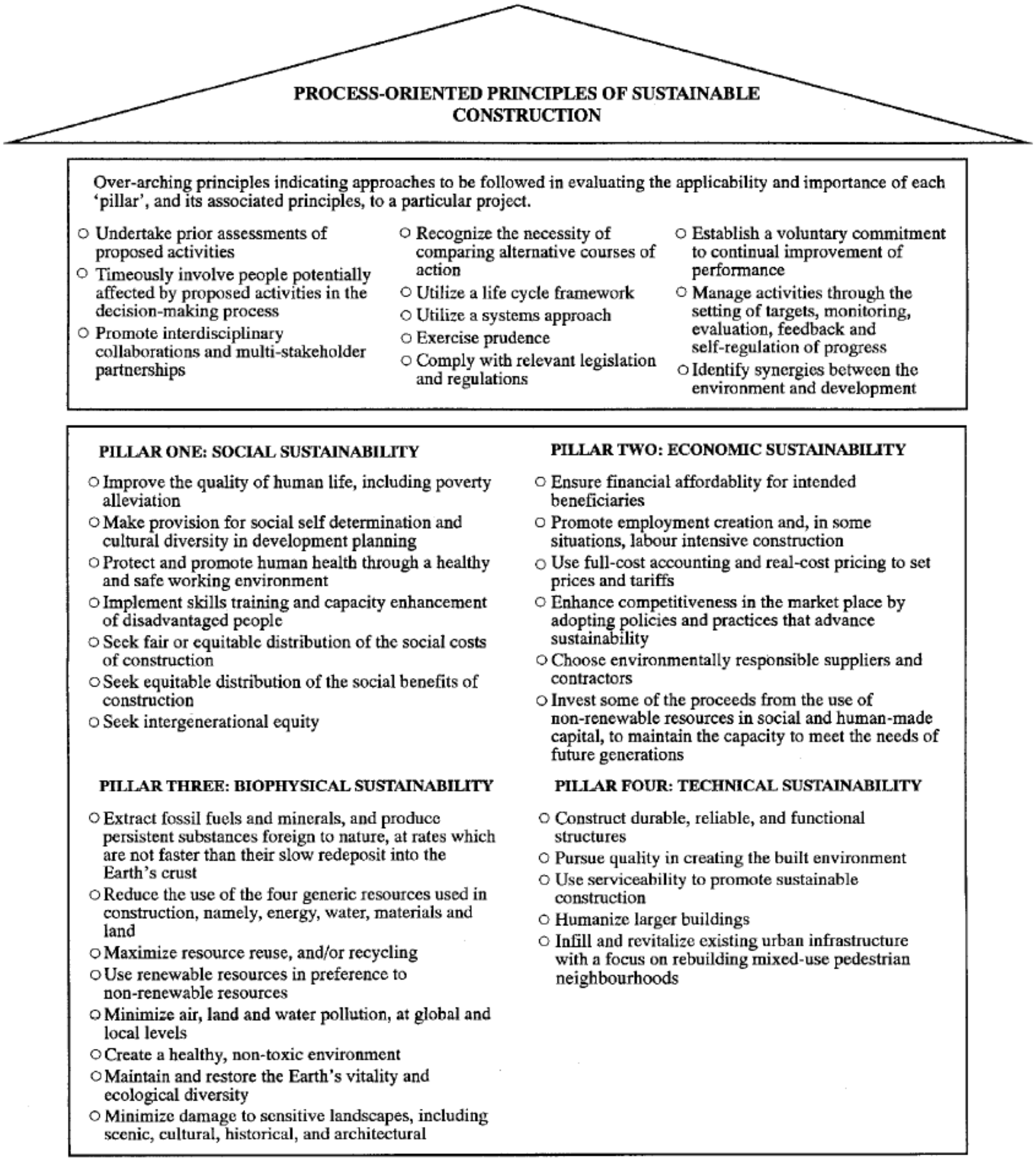
2.8.2 Principles of sustainable building construction framework

A study from Hill and Bowen (1997) has also established a significant framework for the building industry and infrastructure systems management practice. This framework addresses the best practice and principles for the building industry, thus integrating the concept of sustainability. In this framework also, a process-oriented principle regarding sustainable building is contained and divided into four broad pillars. These include economic, social, bio-physical and technical phases as illustrated in Figure 2.8. On this basis, sustainable building construction practices account for the following stages of activities:

- Application of environmental impact assessment (EIA) during the planning and design stages of building projects - provided the traditional EIA is expanded to cover the assessment of all the four 'pillars' of sustainable building construction and is undertaken in accordance with the process-oriented principles.
- Implementation of integrated environmental management systems (IEMS) as described in the specification provides international standards for the building industry. The international organisation for standardisation (ISO) is one of such frameworks as applied in the building industry. The ISO overviews building activities from the construction, and use perspectives. All these activities are included within the four 'pillars' of sustainable building framework as shown in Figure 2.8.

Hill and Bowen (1997) argued that IEMSs can only be implemented as a framework for attaining sustainable buildings if they are adopted by the construction industry. However, the package as contained in the IEMSs provides for the construction activities associated with new building projects, and existing ones as presented in Figure 2.8.

ISO, 1997 noted that usually all building construction activities are performed by the client. However, the responsibility for a building upon completion and commissioning is usually transferred to the facility management services. Therefore, another IEMS could be developed to handle the operation (use) of the building/facility, and the final decommissioning (EoL) stages. The application of IEMSs into building processes from the construction, operation and EoL phases, constitutes an essential part of this framework. It should be noted that the definition of a sustainable building includes facility operation, maintenance, and the EoL (decomissioning) activities (BSI, 2008, CIOB, 2003; Doke, 2007).



PROCESS-ORIENTED PRINCIPLES OF SUSTAINABLE CONSTRUCTION

Over-arching principles indicating approaches to be followed in evaluating the applicability and importance of each 'pillar', and its associated principles, to a particular project.

- ○ Undertake prior assessments of proposed activities
- ○ Timeously involve people potentially affected by proposed activities in the decision-making process
- ○ Promote interdisciplinary collaborations and multi-stakeholder partnerships
- ○ Recognize the necessity of comparing alternative courses of action
- ○ Utilize a life cycle framework
- ○ Utilize a systems approach
- ○ Exercise prudence
- ○ Comply with relevant legislation and regulations
- ○ Establish a voluntary commitment to continual improvement of performance
- ○ Manage activities through the setting of targets, monitoring, evaluation, feedback and self-regulation of progress
- ○ Identify synergies between the environment and development

PILLAR ONE: SOCIAL SUSTAINABILITY

- ○ Improve the quality of human life, including poverty alleviation
- ○ Make provision for social self determination and cultural diversity in development planning
- ○ Protect and promote human health through a healthy and safe working environment
- ○ Implement skills training and capacity enhancement of disadvantaged people
- ○ Seek fair or equitable distribution of the social costs of construction
- ○ Seek equitable distribution of the social benefits of construction
- ○ Seek intergenerational equity

PILLAR TWO: ECONOMIC SUSTAINABILITY

- ○ Ensure financial affordablity for intended beneficiaries
- ○ Promote employment creation and, in some situations, labour intensive construction
- ○ Use full-cost accounting and real-cost pricing to set prices and tariffs
- ○ Enhance competitiveness in the market place by adopting policies and practices that advance sustainability
- ○ Choose environmentally responsible suppliers and contractors
- ○ Invest some of the proceeds from the use of non-renewable resources in social and human-made capital, to maintain the capacity to meet the needs of future generations

PILLAR THREE: BIOPHYSICAL SUSTAINABILITY

- ○ Extract fossil fuels and minerals, and produce persistent substances foreign to nature, at rates which are not faster than their slow redeposit into the Earth's crust
- ○ Reduce the use of the four generic resources used in construction, namely, energy, water, materials and land
- ○ Maximize resource reuse, and/or recycling
- ○ Use renewable resources in preference to non-renewable resources
- ○ Minimize air, land and water pollution, at global and local levels
- ○ Create a healthy, non-toxic environment
- ○ Maintain and restore the Earth's vitality and ecological diversity
- ○ Minimize damage to sensitive landscapes, including scenic, cultural, historical, and architectural

PILLAR FOUR: TECHNICAL SUSTAINABILITY

- ○ Construct durable, reliable, and functional structures
- ○ Pursue quality in creating the built environment
- ○ Use serviceability to promote sustainable construction
- ○ Humanize larger buildings
- ○ Infill and revitalize existing urban infrastructure with a focus on rebuilding mixed-use pedestrian neighbourhoods

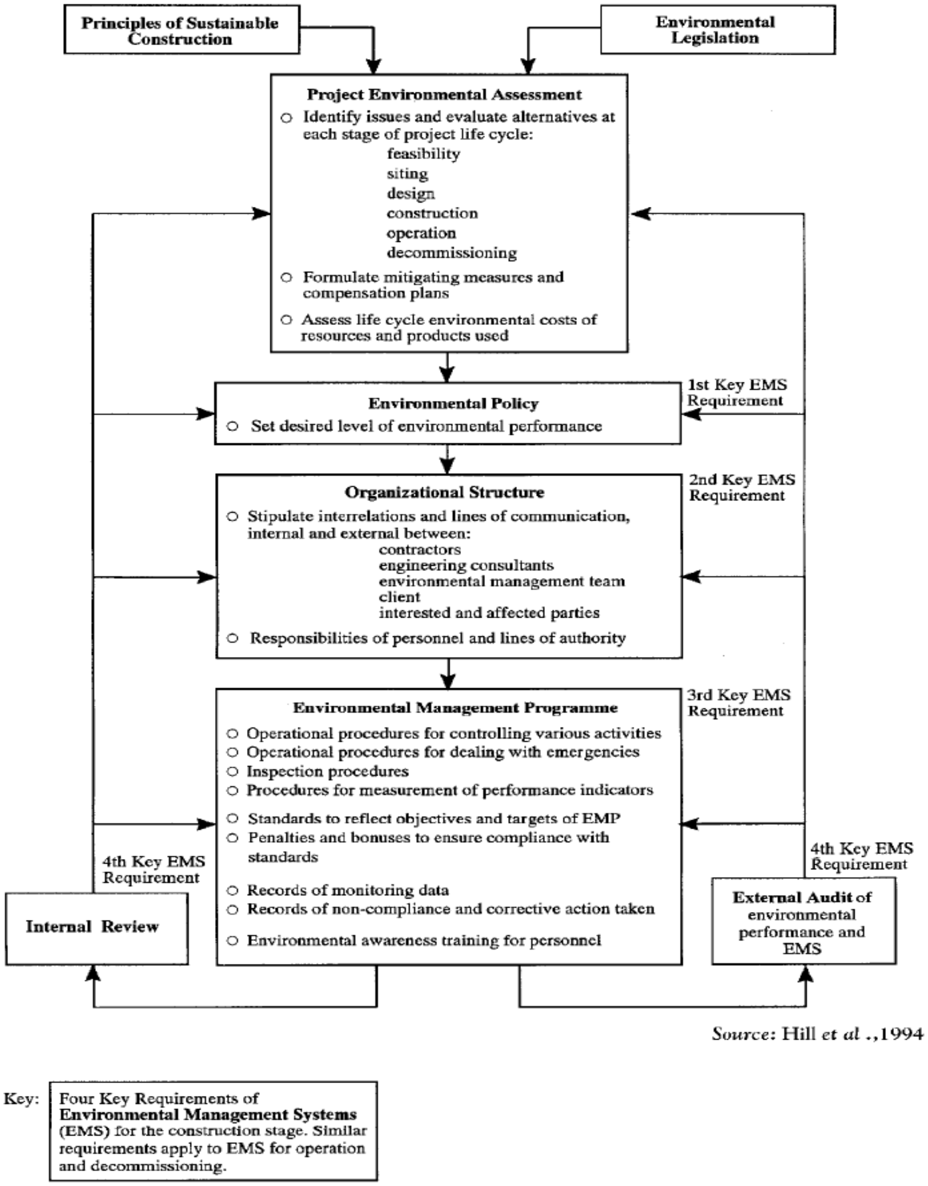
Figure 2.8: Principles of sustainable construction (Hill and Bowen, 1997).

Interestingly also, a study from Lorenz (2008) indicates that adopting the principles highlighted in Figure 2.8 will sustain innovative and cost-effective solutions in this context. These standards will facilitate a stable future in the fields of security, fire protection, water, and wastewater. In addition, power (energy) distribution and comfort in the buildings services delivery will be achieved, both promoting sustainability (CIRIA, 2005; ISO, 2002). It could be argued that the theory behind sustainable construction frameworks has provided the basic conditions for the mainstream sustainable development. This is found in the building construction industry particularly within European countries. At the same time, the major social and economic values of these frameworks can significantly hasten the implementation of the sustainability principles in the construction sectors and beyond. Generally, the outlined principles regarding sustainable building will encourage socially responsible policy-makers with a view to achieving the best practice for the present and future generations (OCED, 2003; WCED, 1987; CIRIA, 2005).

2.8.3 Framework for sustainable building and management

As a means of appraising the framework for sustainable building and management, Hill *et al.* (1994) developed a model which examines building projects, environmental ethics, organisational structure, and environmental management programmes. The scope of their model extends to cover the internal review, external audits, and the environmental legislation associated with building construction, as presented in Figure 2.9. Later, a study conducted by Hill and Bowen (1997) corroborated the findings of the earlier study by Hill *et al.* (1994), both studies seeking to achieve a standard and quality of performance in the delivery of sustainable buildings. Within the model devised by Hill *et al.* (1994), some environmental issues and management principles are emphasised, these being the ISO 14001 environmental management systems (EMS), and the easy access (EA). These principles are aimed at evaluating the entire phases of operation within sustainable buildings as shown in Figure 2.9.

CIRIA (2005) notes the ISO 14001 EMS framework offers immeasurable assistance regarding building construction practices and various environmental assessment tasks. Undoubtedly, however, it requires collaboration by the building industry to ensure a sustainable future (ISO, 2002), and in fact, the ISO 14001 EMS framework is a voluntary rather than a compulsory standard. Nonetheless, its application enables the building industry to have control over the impact of its activities in the environmental area of operation (Bellandi, 2004). Contemporary researchers have found that sustainable buildings cannot be achieved unless the building industry incorporates an EMS outline alongside the ISO 14001 framework in Figure 2.9.



Source: Hill *et al* .,1994

Figure 2.9: A Framework for sustainable construction (Hill *et al.,* 1994).

One sophisticated techniques adopted by the building construction sector is the integration of the environment within building plans. This process empowers the building industry in managing the entire building construction processes for sustainability (Koskela, 2009; Lundan, 2004; Petrovic-Lazarevic, 2006).

In a related development, Price and Newsome (2003) stressed that the application of the ISO 14001 standard stems from achieving sustainable buildings in the construction industry. In recent times ‘sustainable building’ has become a catch-phrase within the construction sectors and the built environment at large. However, the greatest challenge in this respect is not to ensure the industry is familiar with and understands the phrase, but to develop a practicable implementation framework (Lundan, 2004). In this respect, the ISO 14001 model in Figure 2.9 is being adopted by many building companies that are currently using the principle together with EMSs for their environmental auditing and labelling.

Information from Figure 2.9 also demonstrates that the framework is capable of addressing the building life cycle and evaluating environmental performance. The ISO (2002) has argued that the environmental auditing undertaken through an EMS for building construction projects could be conducted internally by the environmental managers or externally by consultants. Typically, an external auditing activity would be preferred for large building construction projects of extended duration with the potential to cause significant environmental impact (RICS, 2008). In fact, such environmental impact activities could be mitigated through a suitable ISO 14001 EMS framework, which enables the construction companies to track their day-to-day operations. Not only will the model deliver effective and efficient building performance but, it will also promote prudent management by its integration of the ISO 14001 standard (Lundan, 2004; ELC, 2006).

Figure 2.9 also demonstrates a good quality framework for sustainable buildings. Another significant benefit from the employment of the ISO 14001 EMS agenda is the ‘green and lean’ (GL) initiative (NIBS, 2006). This scheme enhances building construction support as it provides for the protection of non-renewable natural resources (Koskela, 2009). However, the ISO 14001 EMS framework in this study aims at fostering the development of a reverse distribution system driven by the building construction economics. This challenge has always presented problems for the building sector but the most often cited reason for not rising to the challenge is the relatively little demand for recycled and reclaimed materials. Particularly, this is experienced within the building industry with low-cost and low-profit margins. So, with the integration of the ISO 14001 EMS framework into this context, proper annual environmental audits and reviews could be achieved for sustainable growth (NIBS, 2006; Klotz *et al.,* 2007).

2.9 Life cycle assessment framework for building services infrastructure management

Life cycle assessment (LCA) is the global procedure applied to determine the environmental impact of building infrastructure systems. In recent times, research efforts to achieve sustainability in building services delivery have resulted in integrating the LCA framework within infrastructure systems management (ELC, 2006). LCA applications in this perspective have become a desirable and implementable tool in the current management of building infrastructure resources (MTP, 2009). Building services activities and building construction infrastructure projects alike, employ suitable LCA frameworks as indicators meant to provide effective evaluation of the energy utility resources (ISO, 2002; Cuellar, and Adisa, 2011). Energy, water, and wastewater resources utilisation are among other building services infrastructure components appraised for optimum and sustainable benefits through the incorporation of the LCA management.

Interestingly, the LCA frameworks due to their versatility provide useful and efficient management information regarding building services infrastructure performance with the ultimate aim of striking a balance among the three themes of sustainable development. In addition, a cradle to grave assessment regarding building services infrastructure services is made using the LCA technique (ISO, 1997; Blengini, 2009 Cuellar, and Adisa, 2011).

The integration of the LCA framework within this study has become imperative due to the pressure associated with the growing population and the increasing consumption of natural resources in the building sector. The pressures from the growing population and the existing modern lifestyle have placed a great burden on building infrastructure utilities, resulting in greenhouse gas (GHG) emissions, and climatic change (Eco Homes, 2003; ASHRAE, 2004).

2.9.1 The life cycle assessment framework

A study by Nebel (2006) has revealed the use of the LCA framework as being a standard practice in the building industry, as it provides a sound analytical framework for the systematic evaluation of environmental impact. Additionally, it allows for the examination of the raw materials processes, and the building services system throughout all the various stages in their respective life cycles, with a view to establishing best practice (Dutil *et al.,* 2011). Hence, it can be seen that the scope of the LCA framework extends from the extraction and processing of raw materials, right through to manufacture, delivery, use, and finally, to waste management. This continuum of processes, as indicated in the LCA framework, is often referred to as the 'cradle to grave' situation, and the LCA framework allows for its complete assessment (Nebel, 2006; ISO, 1997; Blengini, 2009; Cuellar and Adisa, 2011).

According to the ETBP (Environment Technology Best Practice, 2000), the building industry should be alert to the general direction of environmental regulations. Consumer pressure on building materials should be known and appreciated, and consequently, the LCA framework is valuable in providing useful data for identifying potential problems before they actually arise. Such an approach will promote the reduction in resources consumption, thereby saving costs (ETBP, 2000; ISO, 2002; Oritz *et al.,* 2009; GSGF, 2010). LCA appraisal in this situation considers building services infrastructure products from their 'cradle' stage, hence, paying attention to the natural resources from where the virgin (raw) building materials are extracted or acquired.

The process continues through to the entire construction and operation (use) to its 'grave' (disposal), and end-of-life (EoL) phases (Dutil *et al.,* 2011; GSGF, 2010). Figure 2.10 explains the life cycle assessment model with the causalities indicating the physical processes involved in the building materials life cycle stages. The flow processes within the system boundaries from the raw (virgin) materials acquisition through the EoL phases of building infrastructure activities. The LCA model as applied in this study is shown in Figure 2.10.

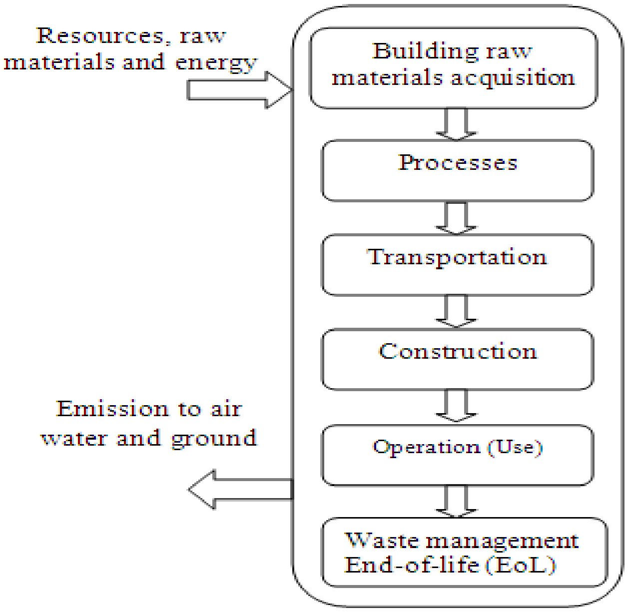


Figure 2.10: Life cycle assessment model (Richard, 1996; ISO, 2002).

There is also an indication of gases emission released into the air, water and ground (environment) generally. Environmental impact arising from the construction, operation (use), and maintenance phases of buildings within this context are the most important elements of sustainability in Figure 2.10. These environmental impact elements necessitate the LCA study. Therefore, the LCA evaluation in this case aims to address the environmental impact profile regarding building services infrastructure towards sustainability success (ISO, 2002; Oritz *et al.,* 2009).

2.9.2 The life cycle assessment techniques

This study adopted the generic LCA process (ISO, 1997) as shown in Figure 2.11. The LCA methodology comprises five successive stages of operation, these being: the goal and scope definition, inventory analysis, impact assessment, results interpretation, and application. These stages are briefly explained as follows:

- Goal and scope stage: This explains the intended application of the related environmental impact group within building services infrastructure systems, the rationale and the way of communicating the outcomes.

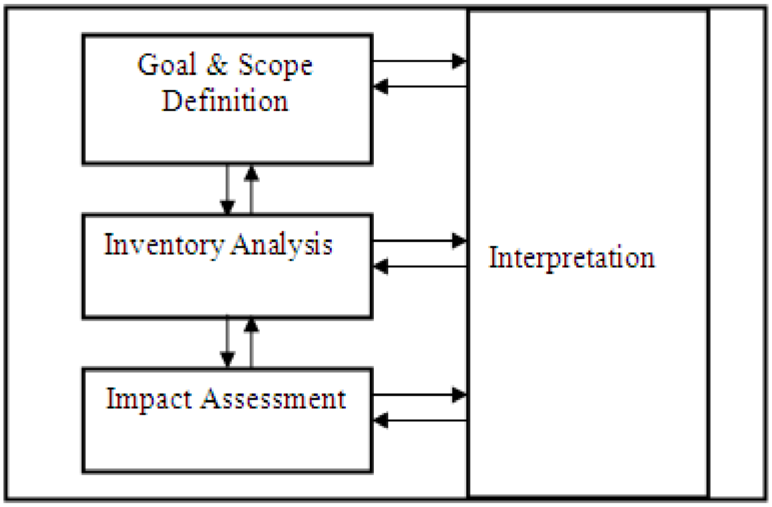


Figure 2.11: Life cycle assessment framework (ISO, 1997).

- Inventory analysis phase: This is aimed at creating a systems model according to the requirements of the goal and scope description. This stage also involves gathering quantifiable statistics relating to the material flows and energy inputs. Additionally, this analysis cuts across the whole life cycle of building materials and their associated emissions, discharges and wastes. It relates to all stages of the building life cycle from the 'cradle to grave'.
- Impact assessment: This stage of analysis focuses on the impact of the environmental loads quantified in the inventory study. The inventory result at this point is processed into more environmentally relevant information. Again, more focus on the environmental problem rather than emission or resources used within the building is evaluated. In this scenario, cognisance is taken of human health, resources, and the ecology factors (Richard, 1996).
- Interpretation Phase: This produces the results and is dependent on the goal of the study. It consists of three elements: identification of significant issues, evaluation, and conclusion of test (Paulson, 2001; ISO, 1997; Home *et al.*, 2009).

Table 2.1 displays the impact phases of the LCA and definition as applied in this study.

Table 2.1: Impact phases of LCA and definition (Guinea *et al.*, 2001).

Impact Phases	Definition
Selection of impact categories	Abiotic depletion, acidification, eutrophication, fresh water aquatic ecotoxicity, global warming, human toxicity, marine aquatic ecotoxicity, ozone depletion, photochemical oxidation and terrestrial ecotoxicity potentials.
Classification	Essentially addresses the grouping of the data in an inventory table into a number of impact categories.
Characterisation	Involves the quantification, aggregation and analysis of impact data within the investigated impact groups in the building.
Valuation phase	Accounts for the indicators result and can be further elaborated in the analysis. Normalisation: calculates the magnitude for each indicator result relative to reference level. Grouping: sorts or ranks the impact categories Weighting: aggregates the indicator results based on some value choice and numerical hierarchy (Cabal *et al.*, 2005).

Guinea *et al.* (2001) maintained that as a common practice in the LCA method, the impact assessment phase is often divided into four distinct stages as shown in Table 2.1. The choices of impact categories as applicable for the visualisation of the environment are chosen according to the scope and definition of the study.

Korkmaz *et al.* (2008) have researched decision-making frameworks for minimising the life cycle impact of building infrastructure systems using the LCA technique, primarily focusing upon building infrastructure examination and its benefits in realising sustainability. Environmental impact examinations of sustainable buildings have been studied using the LCA approach by the Environmental Literacy Council (ELC, 2006). The appraisal in this study was conducted with the consideration of all the building materials inputs and outputs throughout the life cycle of the building as a ‘cradle to grave process’. Additionally, the extraction of the raw materials, their production and use, are considered. A further dimension comprises the occupancy, maintenance, finally demolition and disposal of waste. The LCA approach in this situation accounts for the environmental, economic and social impact of materials during their life cycle.

However, this framework focuses on the environmental impacts with specific targets on emissions and waste management (ELC, 2006; Regal, 2005; Nebel, 2006).

An earlier study by the NSF (2005) overviewed the application of the LCA in assessing the building services infrastructure for sustainability, and in this circumstance, the concept of the LCA application was found adequate for evaluating the environmental impact and performance of different system components within buildings. Also, Bayer *et al.* (2010) have applied the LCA framework to examine both commercial and residential buildings. Their study has established the LCA is an emerging model that promises to aid in architectural decision-making. Moreover, industrial ecologists, engineers and chemists seeking to understand and to reduce environmental impact within the built environment have all developed the LCA framework for such purposes (Guinea *et al.*, 2001).

Recently, the LCA technique has been promoted as a paradigm for analysing the environmental impact of buildings and making decisions to reduce these impacts. The benefits of LCA advancement can offer a wide-ranging environmental footprint in building services infrastructure. These gains from the LCA application include utilities such as energy, water, and wastewater analysis. Other benefits of the LCA are the assessment of global warming potential, resource depletion, and toxic emissions in buildings (Patrick *et al.*, 2002; ISO, 1997; Varun, *et al.*, 2008).

2.10 Review of the life cycle cost (LCC) framework for building services management

The history of the life cycle cost (LCC) framework began in the United States Department of Defense (USDD) in the mid-1960s and 1980s (DIN EN, 2004). Later, attempts were made to adapt this model into building services infrastructure investments and construction projects. The LCC framework can be applied in many situations, and its economic benefits in building services assessment cannot be over-emphasised.

LCC is a technique applied to establish the "total cost of ownership", that is, the sum of all the costs associated with an asset or part thereof, including acquisition and installation. It also accounts for the operation (use), maintenance, refurbishment *and disposal costs related to the building services infrastructure and construction projects generally (Epstein, 1996; Langdon, 2007).*

Clift (2003) maintained that to a large extent, LCC is an estimation of the monetary costs of funding, design, and construction of building services infrastructure for sustainability success. However, it also involves the costs of operation, maintenance and repair, component replacement, and sometimes, the demolition of (facilities) buildings (Clift, 2003). The LCC application can deliver a new design, existing buildings, or can assess the residual life and value of a building. As such, with different maintenance, repair and replacement operations taking place at various times, incremental costs are converted to present-day value using a discounted cash flow approach (Flanagan *et al.*, 1989; ASTM, 2002).

2.10.1 The life cycle cost technique

The life cycle cost model could be applied at any stage of the building services infrastructure project management. Indeed, at the inception stage of building services infrastructure, the use of the LCC model can provide choices among alternatives in the design of sustainable homes (DIN, 2004; Flanagan *et al.*, 1989). Sustainability is now a critical consideration affecting the design, construction, operation and disposal of constructed building services infrastructure assets, and therefore, the LCC method is a key element in supporting improvements in the sustainability of buildings by providing a common means for all costs related to building assets (Klotz *et al.*, 2007). In LCC analysis, the selection of investment costs at the inception stage of the building services infrastructure project is a necessity and should be based on the client requirements and the services delivery. The costs are estimated in broad terms depending on the 'costs incurred' in similar historical building services infrastructure projects. Given differences in the design of the particular building services infrastructure involved, more detail is accumulated, and then the LCCs are estimated in view of the added or different features (Bakis, *et al.*, 2003). Figure 2.12 presents the algorithmic LCC process used in this study for the estimation of building services performance.

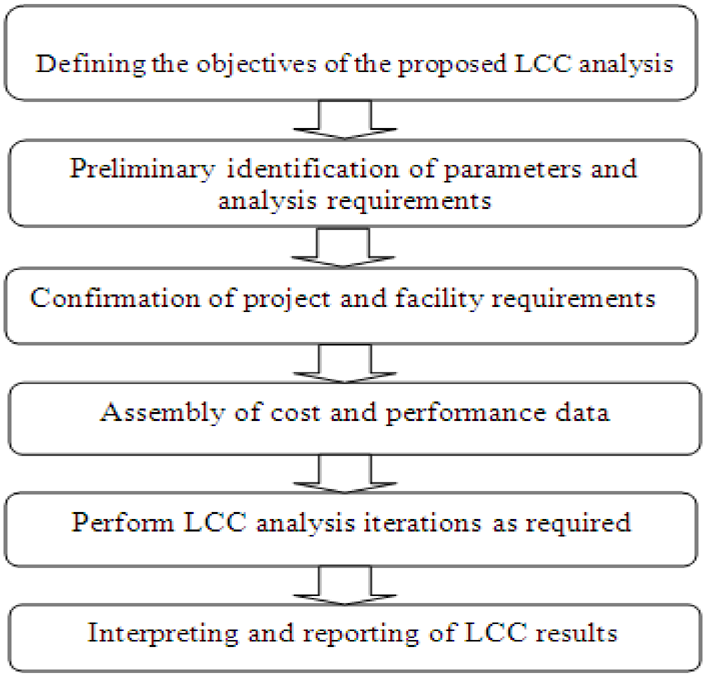


Figure 2.12: Algorithmic process of LCC framework (Home *et al.*, 2009).

Much later in the design phase, when the individual building components and fixtures are established, the LCC analysis is performed according to service delivery and costs data. In practical terms, LCC tests are performed when all the facts about the price and life expectancy of the building infrastructure components and fixtures and their associated costs are collated. But the process should also involve the maintenance and operation frequencies of the building services infrastructure generally. That is, the LCC of all the components together with the building services infrastructure costs such as energy, water, wastewater consumption and building data (Kirk and Dell'Isola, 1995; Bakis *et al.*, 2003, Flanagan *et al.*, 1989; Langdon, 2007).

In their LCC study, Flanagan *et al.* (1989) maintained that when appraising building services infrastructure, the estimated costs at each year of the building's life must be discounted. This to create proper allowance for time value of investment costs. Additionally, such provision will enable the comparison of the alternatives on a common basis using the LCC technique. This suggests the time value of money which is the amount of money spent to fix the building services infrastructure which is most likely to increase yearly by the relevant net inflation interest rate (DIN, 2004; Parnell, 2008).

2.10.2 Evaluating building services performance - life cycle cost

Economic life cycle costing related to building services infrastructure is a necessary component of the effort to achieve sustainable buildings, and in recent times, LCC analysis has become increasingly essential in the determination of building services infrastructure performance. Indeed, the introduction of LCC tests into building services infrastructure projects has offered best value for money in attempts to manage assets in the long term (Ellis, 2007). On this particular issue, Ashworth (1999) has argued that when investigating LCCs, analysts should set less money aside for current building services infrastructure projects, in order to meet higher expenditures in the future. In actual fact, the calculation of the LCC of building services infrastructure merely involves adding up the constituent costs. However, this is a simplistic evaluation since the timing of particular costs needs to be taken into account. This means that the costs of the building services infrastructure should first be converted into the present values and then added up to compare the different options on a common basis. The most familiar comparison measure used in the LCC analysis is the net present value (NPV) method (Gulch and Baumann, 2004).

Bakis *et al.* (2003) maintained that depending on the choice of LCC method used, the time perspective may differ, and this will affect the outcomes from the LCC computation when discounted to a NPV. Other LCC techniques which could be adopted in measuring the building services infrastructure performance, are the equivalent annual cost (EAC), payback period (PP), return on investment (RON), and saving to investment ratio (SIR). The five main economic evaluation methods for LCC, their application, advantages and disadvantages for building services infrastructure management are indicated in Table 2.2. It is evident from the literature that the most suitable approach for the LCC in this context is the NPV method.

In the course of examining the building services infrastructure performance using the LCC technique, the risk associated with each option should also be taken into account. Various risk assessment techniques are employed to evaluate the possible failure of attempts to achieve sustainability (Gulch and Baumann, 2004; Ellis, 2007; Dusart *et al.*, 2011). One way of performing such risk analysis is through the use of a sensitivity study as presented in Table 2.2.

Table 2.2: The LCC evaluation methods (Dusart *et al.*, 2011).

Method	Application	Advantage	Disadvantage
Simple payback (SP)	Rough estimation if the investment is profitable.	Quick and easy to calculate and interpret the results	Does not take inflation, interest or cash flow data into account.
Discount payback (DP)	Should only be used as a screening tool not a decision device.	Takes the time value of money into account.	Ignores all cash flow outside the payback period.
Net present value (NPV)	Most LCC models use the NPV. Not usable if the options incorporate different lifespan.	Takes the time value of money into account. Make the return equal to the market rate of interest.	Not usable when the compared options have diverse lifespan. Not easy to interpret.
Equivalent annual cost (EAC)	Different options with varied period can be compared (ISO, 2004).	Different options with diverse timescale can be compared (ISO, 2004).	Just gives an average number. But, it does not indicate the actual cost.
Internal rate of return (IRR)	Can only be used if the investments will generate an income.	Result is given in percentage which can be helpful.	Calculations need a trial and error procedure. IRR can only be calculated if the investments will produce an income.

A sensitivity study could be applied to assess the impact of a change in an input variable on the LCC of building services infrastructure projects. Monte-Carlo simulation is capable of testing the sensitivity of building services infrastructure data to obtain a range of possible values in this case. Another important benefit in the LCC examination is the costs broken down structure (CBS). The CBS system represents the method in which the LCCs of building services infrastructure are performed as presented in Table 2.2. Hence, the aim of LCC analysis is the comparison of options, since it enables information relating to costs involvement in the building to be shown in a way that enables proper judgment (Whyte *et al.*, 1999; Bakis *et al.*, 2003).

Bakis *et al* (2003) study has found the integration of the LCC method within building services infrastructure evaluation could yield more economic gain over several years after construction and operation alike. Such dividends cut across the technical lifetime of building services infrastructure, that is, the estimated number of years until the installed components, fixtures and applicable technologies are considered obsolete (Bakis *et al.,* 2003). Similarly, the physical lifetime of building services infrastructure explains the estimated period in which the building is physically assessed for use. The LCC can also be applied in measuring the building services infrastructure utilities lifetime as mentioned earlier. This aspect expresses the economic worth in estimating the actual time, in which the building services infrastructure can satisfy the established performance standards. Furthermore, LCC application is diverse in the quest for sustainability success, as it can also be used when forecasting, in tendering documents, and in bidding for building projects (TG4, 2003; Smith, 2008).

2.10.3 The barriers in the life cycle cost application

Recently, the building industry has relied heavily on the use of the LCC technique in its efforts to achieve delivery of sustainable projects. However, despite its economic importance and versatility in engineering and technology, there are still some limitations to its application. Contemporary studies have discovered that the LCC approach is commonly used in the implementation of building services infrastructure projects under private finance initiative (PFI) schemes at the procurement phase (BPC, 2010). Additionally, it is seen that most building construction organisations employ the LCC method for costs appraisal during the design phase for bidding (Landon, 2010). However, this is not to suggest that the LCC model cannot be successfully applied in other phases of operation (use)/maintenance, and the end-of-life stages (Sterner, 2000; Bakis *et al.,* 2003; BPC, 2010). There are, however, a number of reasons for the limited application of the LCC in building services infrastructure systems management so far. Some of these are either practical or political, depending upon the precise circumstances (Sterner, 2000; Bakis *et al.,* 2003).

In the practical dimension of LCC application, Bull (1993) revealed that capital costs and operating expenditure are usually met by different parties (client and contractors) before contract execution, and that there is no incentive on behalf of those responsible for building construction to reduce the subsequent costs-in-use (Bull, 1993). Figure 2.13 shows the two major constraints associated with the LCC application in building industry.

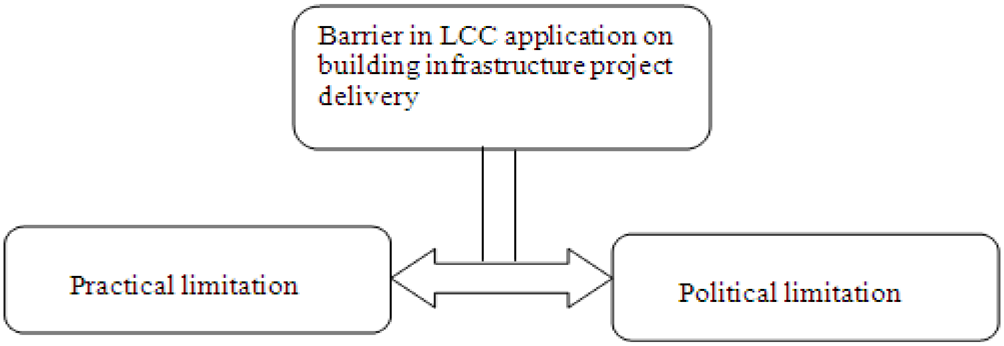


Figure 2.13: The major barriers in LCC application.

Another practical barrier to the use of the LCC method, is noted by Ferry and Flanagan (1991) as being the difficulty in forecasting building services infrastructure projects over a long period of time. Other factors are cited as the future operating and maintenance costs, and discount payback problem. Bakis *et al.* (2003) also itemised several reasons for the reluctance of the public sector to invest in the LCC technique in building construction. They include: (a) the tendency for the use of a building (facility) infrastructure to change in the near future, meaning that the LCC application would later be regarded as a waste of money; (b) the fact that building services infrastructure has a longer services delivery period than its life span as envisaged by the clients; (c) the unwillingness of government agencies to invest in the more expensive options when there are no solid technical data to guarantee any future savings on such building services infrastructure; and (d) the practice of many decision-makers using the LCC to opt for minimum initial investment (MIN) either to increase the return on investment or meet budgetary restrictions. These factors are considered as the practical obstacles in this situation (Landon, 2010; Kehily and Hore, 2012).

Kehily and Hore (2012) have also disclosed other practical barriers to the adoption of the LCC technique in building services infrastructure management. They are: (a) the complexity associated with the LCC application, and (b) the lack of sufficient data for computation. It is obvious that in such situations, a proper LCC evaluation could not be performed. One of the major setbacks in this case is the absence of frameworks or mechanisms for collecting and storing information. The accounting systems used by building managers and contractors seldom provide an alternative means to accurately identify the costs of maintenance and repair of specific components within a building. Moreover, the estimation of the LCC model is a rather complex exercise when applied manually, especially at the detailed design phase. An analyst has to estimate the LCC of each option for each building element such as energy, water, or the infrastructure utilities as a whole, and the LCC of each option might consist of several cost items. For each cost item, the related performance and cost data have to be retrieved (Clift and Bourke, 1999; NSA, 1999; Langdon, 2006).

Political barriers to LCC application lie in policy-making, and generally, the decision to apply the LCC model in building services infrastructure projects delivery is based purely on the client's inclination. Moreover, the lack of any legislative policy framework promotes a situation whereby there is no compelling obligation upon the client or the contractors to aim to deliver sustainable building services. Government legislation may, however, sometime affect both clients and other parties in integrating the LCC for cost analysis (Clift and Bourke, 1999; NSA, 1999; Bakis *et al.,* 2003; Langdon, 2007; Kehily and Hore, 2012).

2.11 Engineering sustainability in building services management

Engineering sustainability is a catalyst for building services infrastructure growth. The promotion of its principles yields economic benefits and resources which all help in the effort to achieve sustainable development. However, such sustainability depends upon the development of business strategies that can be effectively implemented. Two main factors underpin the demand and rationale for eco-buildings believed to be achieved through green growth incorporation within building services infrastructure advancement goals. These factors are: (a) the growing concerns about the environmental unsustainability of past and current economic growth patterns; and, (b) the risk of irreversibly altering the environmental base needed to sustain economic prosperity (ESCAP, 2011). Increased awareness of a potential future climate crisis has made it clear that the environment and the economy can no longer be considered in isolation.

These concerns point to the need for substantial change of consumption behaviour, industry structures, and technologies (OECD, 2010; OCED, 2011; ESCAP, 2011).

2.11.1 The green growth model

Within the built environment, the green growth model is now commonplace in sustainable building services infrastructure systems development (ESCAP, 2006). Green buildings could be defined as building services infrastructure that promotes the reduction of harmful effects on the environment and construction activities as a whole (Eco Homes, 2003). The sustainability model has been the beacon for sustainable development. Moreover, the interdisciplinary engineering fields and social science are included in the drive to integrate innovative models into the management of building services infrastructure systems for sustainability purposes (Yudelson, 2008; Broers, 2005).

It is an established fact that much benefit has resulted from engineering sustainability approaches within the context of building services infrastructure, but there still remains a demand for more progress in this respect. Consequently, other proactive measures are adopted, including: (a) concepts of reduce, reuse and recycle, (b) eco-efficiency, (c) the public–private partnership drive, (d) educational awareness, and (e) the use of mathematical modelling tools (OCED, 2003; ESCAP, 2006; Girouard, 2011). In this study, the concept of green growth could better be described as:

> *Green growth practice is capable of maintaining the economic expansion necessary for enhancing the quality of life in this context. This practice will simultaneously minimise pressure on the available resources consumption, thereby, improving the eco-efficiency within building industry (WBCSD, 2000; ESCAP, 2006).*

The green growth approach to sustainable building services infrastructure management has been found effective in promoting engineering sustainability. Consequently, it fosters eco-efficiency of building services infrastructure development, creating more value with fewer resources and less impact (ESCAP, 2006b). Building services infrastructure development has traditionally been the responsibility of the public sector, and in measuring eco-efficiency, it is necessary to enlist government efforts. Government must determine both economic and environment-related issues in respect of building services infrastructure expansion since these are the major elements of eco-efficiency schemes in engineering sustainability. Such determination is essential during each stage of building services infrastructure development, such as planning, design, and construction (OECD, 2009a). Typical of the measures adopted, are those indicated in Figure 2.14.

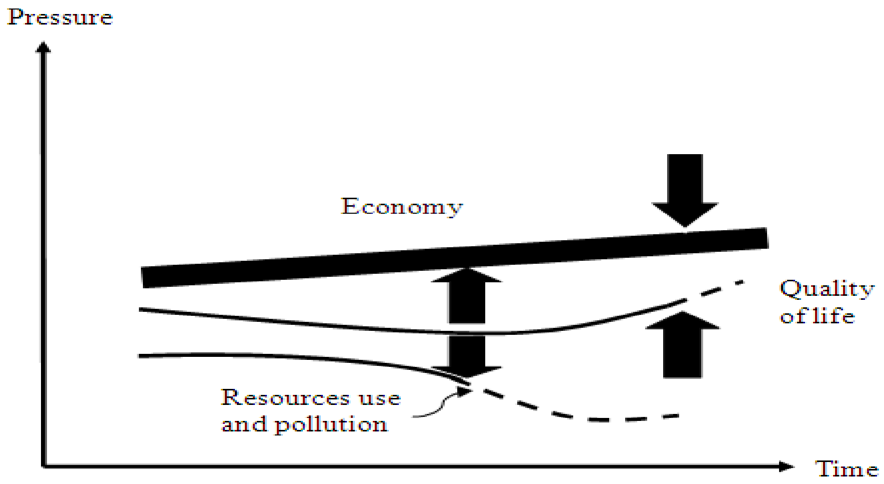


Figure 2.14: Eco-efficiency and its impact on the economy (WBCSD, 2000).

Figure 2.14 demonstrates the governmental measures of eco-efficiency schemes considering engineering sustainability objectives in respect of building services infrastructure advancement. The notion that there is an upward pressure on the economy and quality of life, with much emphasis on the resources utilisation and pollution released to the environment, underpins the model. As such, the green growth approach can facilitate the viable recovery of building services infrastructure development with environmentally and socially-stable economic growth (WBCSD, 2000). The WBCSD (2000) study indicates that eco-efficiency involves increasing services while reducing material and energy intensity. This approach has hitherto been mainly applied in building services infrastructure (water and energy) management, but it may also offer far greater sustainability benefits when applied to other economic aspects. For example, it may provide increased energy, water, and wastewater utilities, with less use of material and other resources, thereby, enabling 'green growth' and socio-economic development as shown in Figure 2.14 (OECD, 2009b; OCED, 2011; ABS, 2012).

Several frameworks have been identified for the promotion of the green growth strategy. In this respect, policy mixes with research and developments (R&D) need to be closer to the best practice from the concept of green growth (OECD, 2010; GSGF, 2010). The factors are being identified as key elements of the economic framework to determine the profitable efficiency and sustainable development integrity (WBCSD, 2000). Legislative policy formulation with appropriate educational awareness through R&D could simulate a trade-off at both national and international levels (OECD, 2010).

2.11.2 Engineering sustainability through eco-efficiency methods

Eco-efficiency is achieved in building services infrastructure by the integration of environmentally-sound technologies and fundamentally new systems solutions for the services delivery. Progressively, such principles will reduce the ecological impacts and resource intensity throughout the life cycle of building services infrastructure systems to the bare minimum level. Hence, more value is created at the same time as there is less use of the building services infrastructure utilities, and less environmental impact (WBCSD, 2000; Eco Homes, 2003). UNCTAD (2003) has argued that the term eco-efficiency can be expressed as the ratio of the added value to the building infrastructure network and its environmental impacts.

It can be seen, therefore, that the concept of eco-efficiency when successfully implemented with the building industry, is capable of yielding financial benefits. Indeed, it can also support government in deriving a national strategy for the success of the sustainable development agenda. The practices associated with eco-efficiency could establish healthy frameworks to promote innovation, and transparency that allows for responsibility sharing among the stakeholders. Furthermore, the initiative can amplify eco-efficiency ethics for the economy and deliver progress in respect of sustainability goals (WBCSD, 2000; ESCAP, 2011; Eco Homes, 2003; Janssen and Hendriks, 2002; WB, 2010). The basic principles needed for the promotion of eco-efficiency in building services infrastructure are shown in Table 2.3.

Table 2.3: Principles for promoting eco-efficiency of building infrastructure (ESCAP, 2006).

Factors	Benefits of eco-efficiency
Use resources efficiently	To obtain greater value from fewer resources and to reduce waste and impacts within the building.
Minimise externalities	When considering market failures, including life cycle costs and the social benefits of policy tools such as utility bills.
Use both mandatory and voluntary systems	For assessing and reducing environmental impacts, including raising awareness of policy makers and the public on building infrastructure usage.
Promote the use of eco-efficient indicators	To measure environmental sustainability for building infrastructure development.
Promote appropriate technology tools	For eco-efficient infrastructure in the region focusing on local and renewal energy, climate responsive design for building, waste management and treatment.
Promote effective multi-stakeholder partnership	Involving key actors in the building industry.
Use innovative financing and procurement methods	Such as cost sharing and partnering in building industry.
Promote demand-side management	Targeted at service-focused approach keeping in mind the end users' needs for building infrastructure sustainability.

On the whole, the employment of eco-efficient policies will sustain a long-term building services infrastructure lifespan and green growth initiative. This drive is capable of maintaining sound and healthy building services infrastructure systems for the present and future generations (WCED, 1987; ESCAP, 2011).

2.11.3 The 3R approach

The reduction, reuse, and recycling of materials within the context of this study is termed the 3R approach. Environmentally-sound practices achieved through 3R can be considered and applied as best practice in building services infrastructure development. Minimising waste generation through source reduction, separation, reuse, recycling, and recovering goods and materials, will promote sustainability success. This approach not only responds to the problems of increasing waste generation, but may also provide significant gains from the reuse and recycling of waste (Eco Homes, 2003). Promoting this approach requires establishing 3R-related policies along with environmentally-sound recycling mechanisms that will support and improve informal waste recycling (DEFRA, 2011).

The use of financial incentives in the form of government subsidies for recycling technologies and harnessing market forces is another engineering sustainability measure that is adopted in the development of building services infrastructure. The 3R approach could also involve public awareness and waste composting practices for energy generation (Eco Homes, 2003; ESCAP, 2006b; Sabol, 2008; DEFRA, 2010; WRAP, 2011). Figure 2.15 depicts a typical 3R process in engineering sustainability through waste management.

Figure 2.15: Best practice in waste management (WRAP, 2011).

2.11.4 Public-private partnership

The public-private partnership (PPP) scheme has been found to deliver sustainable buildings, and therefore this is one of the robust approaches currently employed in engineering sustainability efforts in respect of building services infrastructure development (Friesecke, 2006). A study by Tetrevova (2006) has established the PPP contribution towards sustainable building services infrastructure as being significant and laudable. Indeed, the gain from this practice includes investment projects implemented in the public interest using financial resources from the private sector. To implement these projects, not only do the financial resources from private companies count, but the expertise, managerial know-how, organisational and innovational potentials are also used (Broers, 2005; ASHRAE, 2004). Expert abilities and experience relating to building services management and funding are the core mechanisms in the delivery of the sustainability agenda. Consequently, PPP has become a ground-breaking, and strategic approach in the services delivery of sustainable building services infrastructure worldwide (ESCAP, 2006).

PPP programmes can be developed through co-operation between governments, non-governmental organisations (NGOs), community-based organisations (CBOs), and other private entities in managing building projects for sustainability. The PPP agenda can also deliver in the procurement of the public building sector, thereby increasingly gaining more ground in the effort to achieve sustainability (ESCAP, 2011). The synergy of the PPP initiative in the building services industry is evident, especially in an economic climate where fewer resources (utilities) are available for public service needs (Friesecke, 2006; Fernandez, 2010).

2.11.5 The use of mathematical modelling theories

Engineering sustainability in the context of building services infrastructure development can be delivered through suitable mathematical modelling. Contemporary studies have revealed the integration of mathematical methods in measuring the economic, social, and environmental values that can enhance the potential of achieving sustainability. Such techniques contribute to a variety of decision-making processes, ranging from the planning, design, and construction stages of the building services infrastructure (Gulch and Baumann, 2004). These analytical techniques can also offer efficient managerial pathways in appraising the maintenance, operation, and EoL of building infrastructure projects (Yudelson, 2008; Nebel, 2006; Langdon, 2007).

2.11.5.1 The sustainable engineering infrastructure (SEI) model

The SEI model is one of the latest mathematical models applied in analysing building services infrastructure performance. A recent study by Okon *et al.* (2010) found such novelty through the integration of an SEI model in evaluating a shopping mall. The SEI model analyses the total building services infrastructure project life cycle with an allowance for on/offsite recycling processes. All aspects of conceptual design, procurement, materials handling, construction, renovation, disposal, decommissioning, hazardous materials, and demolition with recycling procedures, are addressed for their sustainability impacts. Additionally, appropriate metrics for the engineering project life cycle are incorporated in the SEI model functions to manage issues bordering on building services infrastructure project viability, performance, reliability, and deliverability. Furthermore, the maintenance and use of buildings, EIA and the return-on-investment among other parameters, are integrated into a common design and analysis pool function for the overall building services infrastructure growth (Hill and Bowen, 1997; Ellis, 2007).

Interestingly however, the SEI model also addresses and normalises sustainability values (Suv) within ranges of $0 \leq Suv \leq 1$ by applying the probability (P) and set theory paradigm into sustainability. Thus, accurate and reliable indices of sustainability can be qualified and quantified. Typically, for an ideal building services infrastructure project situation, the Suv is 1. But this is impracticable in the real engineering projects situation. Similarly, the reliability and regression analysis models (RRAM) are among the effective methods integrated in assessing building services infrastructure growth (Stroud, 2001). These theories have been applied in evaluating building services infrastructure utilities (water, energy maintenance), and other ancillary practices. The outcomes from these methods are reliable (Okon *et al.,* 2010; Okon and Elhag, 2011).

2.11.6 Summary

In this Chapter of the thesis, a comprehensive coverage of the literature related to the aims and objectives of the study has been provided. Consequently, a full review of literature concerning building services infrastructure and building construction activities has been made. The review has concentrated on issues relating to sustainability-driven buildings, and has identified the theoretical basis, gaps, drivers and limitations in sustainability practices in order to create more awareness regarding the study. Through reviewing the related literature, the researcher has identified several appropriate sustainability management frameworks (ISO 14001 EMS, LCA and LCC) and engineering sustainability models that have been established and used in the context of building services development and management. Chapter Three presents detailed information concerning the methodology adopted for the empirical work in the study.

Chapter Three

3.0 Research methods: sustainable building services infrastructure systems management

3.1 Introduction

Building services infrastructure systems are typically characterised by complexity, diversity, operational context, and their non-standardised nature (CIOB, 2003; CIB, 2004; Wood, 2006). Consequently, it becomes necessary to design suitable and implementable frameworks for the proper determination and review of the extent to which sustainability is integrated in this context (NSA, 1991; ASTM, 2002). The CIB (2004) has maintained that building services infrastructure systems constructed in a well-planned and designed manner, will account for the well-being of people, natural resources, and the environmental impact (Koskela, 2009; ASHRAE, 2004; BREEAM, 2008; Gigg, 1988). However, the effective management of such building infrastructure systems upon completion and during use, is currently posing great challenges (Boyle, 2005). Problems arising in this respect, are the lack of prudent management regarding the infrastructure resources, and environmental impact issues resulting in the threat of climate change (GSGF, 2010; Shah, 2007). Building services infrastructure resources are water, energy, and wastewater, all of which need to be properly maintained and require more strategic appraisal due to worldwide insatiable demands (Cheshire and Maunsell, 2007; GSGF, 2010; ASHRAE, 1999).

However, it is not possible to effectively appraise building services infrastructure use and their impact upon sustainability without clearer and more consistent standards and principles of performance (BREEAM, 2008; CIB, 2004; ASTM, 2002). These ethics and frameworks must be developed for use by the practitioners in this context. The building planners, engineers, architects, and other experts who are all involved in encouraging sustainability are therefore, responsible for considering the long and short-term economic, social and the environmental implications (BREEAM, 2008; GSGF, 2010). There is also need for a mix of technological, political and innovative models. Such models need to be tailored so that they can achieve best practices in the performance of eco-efficient and green growth buildings so that sustainable development goals can be realised (Eco Homes, 2003; Dutil *et al.*, 2011; CIOB, 2010).

3.2 Research design

This section presents the methods and systematic approaches used in the study. The research problem statement is indicated, and the methods for assessing sustainable building services infrastructure systems practices are presented. Likewise, survey information and detail of the pilot survey used, are given. Figure 3.1 shows the approach to research design, indicating the steps between the identification of the research problems, and the eventual discussion of the results obtained after the fieldwork.

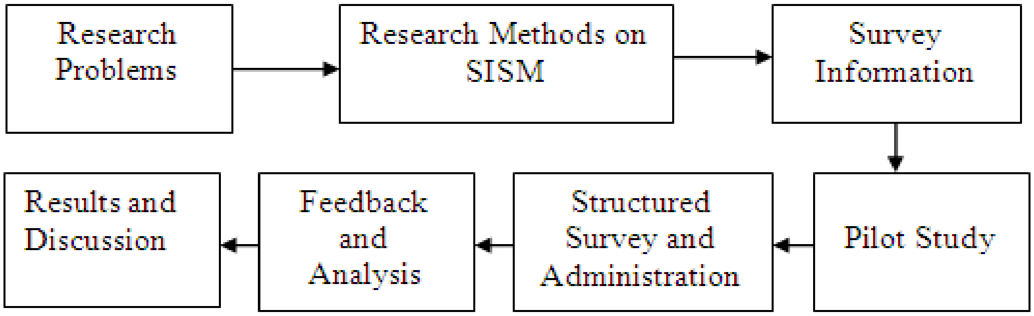


Figure 3.1: The research design approach

Table 3.1 depicts the seven phases (I–VII) of the study and the methods adopted during each phase. The table further explains how these methods were applied in each phase to achieve the overall objectives of the research.

Table 3.1: Phases of study and the applied methods.

Phases of Study	Research Title	Adopted Method
I – IV	Building services infrastructure characteristics	*Methods used for the survey information, pilot study and administration were; Akin and Wing (2007); Yin (1984); Yin (2003); O' Leary (2004) and Last (2003). *Elhag *et al.* (2005) approach was used for the feedback analysis. *Also, Okon *et al.* (2010) method was applied to study the sustainability indices.

V	LCA and LCC evaluation	*The method according to O'Leary (2004) and Last (2003) were adopted for the pilot study and the structured survey administration respectively. *The LCA study employed ISO (1997) and Home *et al.* (2009) methods. *Impact assessment study was conducted via CML (2007) approach. *Guinea *et al.* (2001) and Cabal *et al.* (2005) methods were applied to normalise the environmental impact test. *The statistical analysis on the LCA was studied using Devellis' (1991), and Field's (2006) methods. *LCC study was conducted through Landon, (2007) method and Romm (1994) approaches were applied for the LCC analysis. Also, the statistical software package version (SPSS 19.0) was employed for the LCC study.
VI	Energy & utilities management	*The UK, FOI medium was used for contacts within the health and education sectors before a pilot study. *The methods used for the pilot study and structured survey were O'Leary (2004) and Last (2003). *The averaging study were according to Smith (1998) and Stroud (2001) methods. *In studying the percentages outcomes, Stroud (2001) approach was used. *Carbon footprint evaluation was conducted in line with Azapagic (2010) method. *Also, the probability analysis study was carried out using Hansen (2005) and Montgomery *et al.* (1998) methods. *However, permutations and combinations function alongside the statistical analysis were studied to establish the sustainability indices through Stroud, (2001) approach.
VII	Interviews	*Interviews approaches as used in the study were according to Kumar (1999); Kvale (1996) and McCracken (1988).

3.3 Presenting the research methods

Suitable methods were decided upon, and later applied within the seven phases of the study as shown in Chapters Four, Five, Six and Seven respectively. These methods were focused on achieving the overall aim and objectives of the research in each scenario. Four phases (I–IV) implement a common approach in addressing the building services infrastructure characteristics evaluation. Phases V and VI employ different methods for the studies as specified in the subsequent sections. The interview sessions as contained in Chapter Seven (phase VII) and details of the methods used and their application are also reported in the appropriate sections of this thesis.

3.4 Survey information in study phases I – IV

Tables 3.2–3.5 present a summary of the survey distribution within study phases I–IV as contained in Appendix I. The achievable data from these surveys were later analysed and used for the investigation. Information in these tables provides an overview of the different survey cases within the UK and Nigeria. The analyses arising from the surveys are contained in Chapter Four of this thesis.

Table 3.2: Summary of survey distribution within Commercial Buildings

Survey Inventory	Lot	Period of administration	Response time (month)
Survey produced	100	September, 2009	-
Survey administered	100	September, 2009	-
Survey received after completion	25	September, 2009	January, 2010
Survey returned unanswered	22	December, 2010	February, 2010

Table 3.3: Summary of survey distribution in Buildings Construction Companies

Survey Inventory	Lot	Period of administration	Response time (month)
Survey produced	100	September, 2009	-
Survey administered	100	September, 2009	-
Survey received after completion	35	September, 2009	January, 2010
Survey returned unanswered	16	December, 2009	March, 2010

Table 3.4: Summary of survey distribution within ALSCON Building/Facility

Survey Inventory	Lot	Period of administration	Response time (month)
Survey produced	100	May, 2010	-
Survey administered	100	May, 2010	-
Survey received after completion	48	September, 2010	January, 2011
Survey returned unanswered	8	March, 2011	February, 2011

Table 3.5: Summary of survey distribution in MPN Building/Facility

Survey Inventory	Lot	Period of administration	Response time (month)
Survey produced	100	May, 2010	-
Survey administered	100	May, 2010	-
Survey received after completion	30	September, 2010	March, 2011
Survey returned unanswered	17	March, 2011	March, 2011

3.5 Research method in study phases I – IV

The research method is tailored towards contributing to the overall body of knowledge regarding building services infrastructure systems management and building construction activities. In this context, the UK and Nigerian scenarios were appraised. Atkin and Wing (2007) explained that in order to achieve such a contribution in a systematic way, it is necessary to approach a study with suitable and logically accepted techniques. At the same time, Yin (1984, 2003) argues that a case study method provides a rational approach to a research project. Consequently, the research method consists of a combination of strategies, which involve a two-stage method: an in-depth literature search of previous studies concerning current practices in this field, and a survey to collect primary data.

The literature review was aimed at identifying the gaps within the management procedures. The survey was aimed at obtaining the views of the experts in the practical situation. As already shown in Chapter Two, the literature search was focused on illuminating all the background issues relating to the sustainability agenda and identifying best practices in terms of policy and implementation in respect of sustainable building development. The evaluation of the sustainability agenda and its application in respect of building services infrastructure systems and building construction activities have been thoroughly studied.

The survey was administered through email, regular mail, and personal contact. The regular mail survey was found to be more productive, due to its wider coverage (BAJR, 2007). Building services and building construction experts were the major respondents to the survey.

3.6 Research process used in study phases I–IV

This section addresses the research processes employed. The three different processes involved in administering the questionnaire are presented, these being: the pilot study, the survey itself, and the methods of analysis.

3.6.1 Pilot study in phases I–IV

A pilot survey was prepared and administered within two shopping malls and five building construction companies in the UK. This was aimed at investigating the key parameters affecting the management of building services infrastructure systems in both the private and public sector. The pilot study was meant to provide background information for the restructuring of suitable surveys for the main study. The pilot survey was comprised of structured questions to capture respondents' observations on the suitability of the proposed methods. The potential usefulness of the survey approach in research is indicated by O'Leary (2004), and Last (2003) who suggested its suitability for use within the social sciences. In total, 400 paper copies of the main survey were produced and administered by hand and through the mail. Soft copies of the survey were also emailed to the organisations indicated in Tables 3.2–3.5. Appendix I is a sample copy of the survey for study in phases I–IV respectively.

3.6.2 The structured survey administration in study phases I–IV

The feedback from the pilot study established a group of six characteristics which were subsequently structured into survey and administered within the four phases, I–IV of study, Appendix I. These characteristics include: energy, water resources management, maintenance management practices, infrastructure design, projects characteristics, and external factors. Provisions were also made for the respondents to return the survey either by hand or email as indicated in the appendices. More details on these surveys are indicated in Section 3.6.3.

3.6.3 Survey feedback and methods used for analyses, phases I–IV

Within the main survey 50 characteristics were found, and grouped into the six different categories already identified, and as contained in Appendix I. These are:

- Energy resources management characteristics;
- Water resources management characteristics;
- Maintenance management practices;

- Infrastructure design characteristics;
- Infrastructure project characteristics; and,
- External factors affecting infrastructure management.

The method employed for the survey in Appendix I was to rank and evaluate these factors according to their influence and significance in terms of this study. The survey in Section 3.4 was produced and specifically administered to the maintenance/ operations managers within the chosen organisations. The response rates for the survey in the four sectors studied are within 25–48%, Tables 3.2–3.5. This rate is higher than the normal rate of 20–30% for most surveys posted through the regular mail or hand-delivered (Elhag *et al.*, 2005). More interestingly, the survey feedback indicated that 65% of respondents had between 5 and 20 years, and over 20 years, of related professional working experience. The remaining respondents had between 1 and 4 years such experience. This wealth of experience was in the organisations studied or within a related building/facility or company.

All respondents were happy with the survey technique, and some recommended ways for improvement as presented in the results and discussion section. To calculate the degree of influence of each variable from the survey feedback, a three-point scale was used (Elhag *et al.*, 2005), as follows:

1 = not significant
2 = moderately significant
3 = highly significant

For further analysis, the determinant factors described in sub-sections 3.6.3.1 and 3.6.3.2 were applied.

3.6.3.1 Analysis and ranking of determinant management factors

The factors were ranked according to their significance in examining energy and water resources management characteristics. Also, maintenance management practices, infrastructure design, project characteristics, and external factors influencing the proper delivery of sustainable building projects were investigated. A severity index (SI) computation was used for ranking the associated factors according to their significance (Elhag *et al.*, 2005). Mathematically, the severity index analysis is given by Equation (1):

$$\textbf{SI} = \left(\sum_{i=1}^{3} w_i x f_i\right) x \frac{100}{n} \qquad (1)$$

Where *i* represents the ratings 1 – 3, *fi*, the frequency of the responses, *n*, the total number of responses and *wi*, the weights for each rating. Appendix II is the worked examples for the severity index analysis. Chapter Four outlines the summary of findings regarding the statistical analysis for the severity index results.

3.6.3.2 Measuring respondents' concordance

This was targeted at determining the variation of responses for each factor. The coefficient of variance (COV) allows for the comparison of variables between two or more different variables. Therefore, Elhag *et al.* (2005) defined the coefficient of variation as the ratio of standard deviation to the mean of a given data set. This is shown in Equation (2). The respondents' concordances were analysed using Figure 3.2.

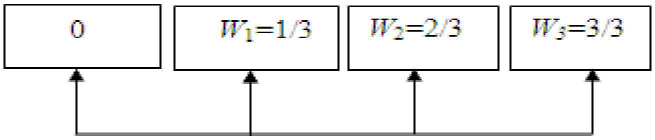


Figure 3.2: Weight for each rating (Elhag *et al.*, 2005).

The characteristics in Tables 3.2–3.5 were determined through the application of the COV in the analysis as indicated in Equation (2).

$$\textbf{COV} = \frac{S}{\bar{X}} x100\% \qquad (2)$$

where *COV* represents the coefficient of variation, *S* denotes the standard deviation and $\overline{X}$ the weighting mean sample. The *COV* in this case, expresses the standard deviation as a percentage of the mean and is useful in comparing the relative variability of different responses with values calculated using Equation (2). Appendix II is the worked examples for the coefficient of variation analysis.

In computing for the category ranking analysis, this is usually the product of the severity index results. As such, the order of sequence of 1st, 2nd, 3rd, are followed. But, a constant of 1.5 is usually added onto the prceeding order of sequence when similar (overlapping) results are achieved. For instance, in category ranking analysis where the order of sequence is 4th, then, the next overlapping severity index results of two value equal to 5th. This order of sequence will eventually change to 6th considering the specified constant (Elhag *et al.,* 2005). The overall ranking accounts for the evaluation of the severity index results in order of their magnitude. Interestingly, the different methodologies as applied in this study have already been presented in internationally refereed journals (Okon *et al.,* 2010; Okon and Elhag, 2011). The rationale behind this approach was to provide an in-depth understanding of the benefits of incorporating sustainability into the context of this study. It is also tailored at more widely improving the building infrastructure project performance.

3.7 Other research approaches used in study phases I–IV

In this study, some basic theoretical models were incorporated for analysing building services infrastructure performance. This becomes necessary as other researchers have not exploited these fundamental mathematical components in addressing sustainability generally. They include: (a) the set theory; (b) the probability theory: and, (c) the SEI model development. Information regarding the application of these models in this research is presented in the relevant sections of this thesis.

3.7.1 The set theory method

Set theory application attempts to test the veracity of the data in this study. The use of set theory in data analyses is to provide for the suitable management of the acquired information in any given circumstance or event (E), (Stroud, 2001: Hansen, 2005). A set theory has wider application ranging from engineering, science and humanities settings just to mention but a few. The sustainable development theme revolves around the economic, social, and environmental values. These trio factors reveal a balance among the three themes of sustainability and can be appraised through the set theory. Indeed, a set theory is a collection of elements (Hansen, 2005). Also, if an element x is contained in or belongs to the set E: it could be expressed as,

$$\boldsymbol{x \in E} \tag{3}$$

Then, if A is a collection of elements all belonging to E; the expression is as follows:

$$\boldsymbol{A \subseteq E} \tag{4}$$

Equation (4) indicates A is a sub-set of E. Thus, A in itself is a set included in the largest set of E. Therefore, the complement of A, denoted as A^C within E, is a set of elements in E that do not belong to A. This argument, however, has yielded:

$$\boldsymbol{A^C = \{x \in E \mid x \notin A\}} \tag{5}$$

But, if $A, B \subseteq E$ are two sub-sets of E, this will define a union. Hence;

$$\boldsymbol{A \cup B = \{x \in E \mid x \in A\} \text{ or } \{x \in B\}} \tag{6}$$

From Equation (6) the intersection gives:

$$\boldsymbol{A \cap B = \{x \in E \mid x \in A \text{ and } x \in B\}} \tag{7}$$

$$\text{Also,} \quad \boldsymbol{A/B = A \cap B^C} \tag{8}$$

Equation (8) defines the set of elements in A that do not belong to B.

The set theory according to James *et al.* (1996), explains it is basically concerned with the identification of one or more common characteristics among objects called elements (members of the set). These members of the sets are usually presented in capital letters, typically: A, B, C and the sub-sets, a, b, c respectively. Smith (1998), argues that set theory has been one of the fundamental means of sorting objects into certain similar groupings. In addition, the letter *(U)* denoting universal is always applied for the set theory in the Venn diagram. Therefore, a finite set is one that contains only a finite number of elements (1, 2, 3…….n) while an infinite set is one consisting of an infinite number of elements (Stroud, 2001). These infinite sets in this case are economic, social and environmental values of sustainable development.

In this thesis, environmental values are represented by (E_{nv}), social values (S_{oc}), economic values (E_{co}) and sustainable development is denoted by (S.D). However, the two Venn diagrams in Figure 3.3 depict the set theory representation.

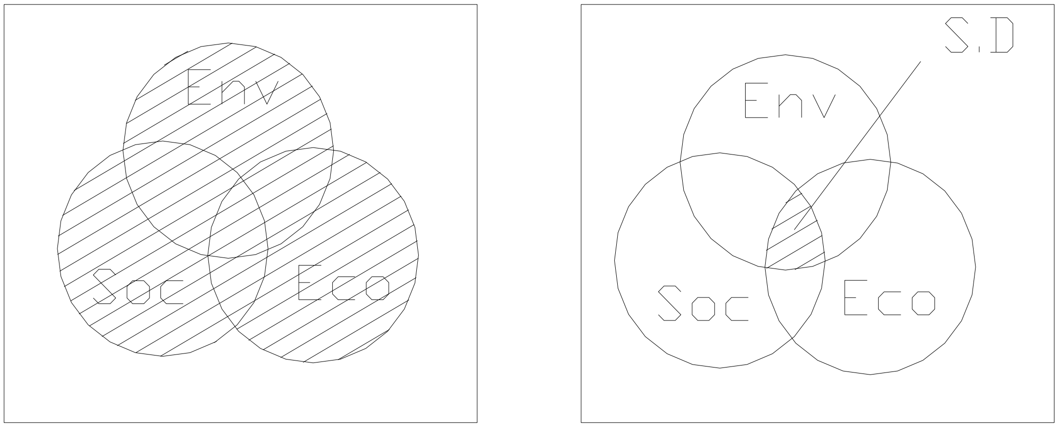


Figure 3.3: Venn diagram showing the intersection and union of set elements.

Hence from Figure 3.3, the set theory equation is expressed in Equation (9):

$$\mathbf{E_{nv} \cap (S_{oc} \cap E_{co})} \tag{9}$$

It is indicative from Equation (9) that the triple factors of sustainable development belong to the same universal set theory. Consequently, set theory also holds as indicated in Equation (10):

$$\mathbf{S_{oc} \cap (E_{co}\ U\ E_{nv}) = (S_{oc} \cap E_{co})\ U\ (S_{oc} \cap E_{nv})} \tag{10}$$

The incorporation of set theory into sustainability originates from the inter-relation among the three themes of sustainable development. The economic, social, and environmental values are classified as sets. The sub-sets are equitability, viability, and bearability values of sustainability. Evidently, set theory is capable of evaluating sustainability along with the building services infrastructure systems management as contained in Figure 2.2 on page 44 (Okon *et al.*, 2010). The set theory model has generated into the Venn diagram given in Figure 3.3 and is used for evaluating building infrastructure services delivery.

3.7.2 The probability theory method

Probability theory aims to measure the achievable data in this study. The increasing use of probability theory is to quantify the chance or possibility that sample test measurement results or data fall within some set of values (Hansen, 2005). Probability theory is usually expressed in terms of random variables during information presentation (Montgomery *et al.*, 1998). Accordingly, probability theory can provide the foundation for evaluating statistical inference in any research. Probability theory is found as the main conceptual origin of statistics and a mathematical framework for discussing experiments with an outcome that is uncertain (Smith, 1998; Stroud, 2001). However, probability theory is used to address the mathematical aspects of uncertainties and is calculated theoretically by specifying what properties such quantification represents (Hansen, 2005).

The application of probability (P) theorems from the Venn diagram in Figure 3.3 is expressed as follows:

$$\boldsymbol{P(X \in R) = 1} \qquad (11)$$

where (*P*) is the probability of random variables, (*R*) is the set of real variables (E) elements and (*X*) denotes data information from this study;

$$\boldsymbol{0 \leq P(X \in R) \leq 1 \text{ for any set E}} \qquad (12)$$

Contextually, it be could stated that the environmental, social and economic values still hold with the sustainability values (S_{uv}). Then the boundary condition in Equation (14) was applied within the entire study analysis. Hence,

$$\boldsymbol{P(X \in E) = S_{uv} = P(E_{cv} \cap E_{nv} \cap S_{ov})} \qquad (13)$$

Therefore, the model as applied in this study becomes:

$$\boldsymbol{P(X \in E) = 0 \leq S_{uv} \leq 1} \tag{14}$$

3.7.3 The sustainable engineering infrastructure (SEI) model use

The research aim and objectives concern the proper management of building services infrastructure resources, and a generic model has been produced to assist in this respect. Specifically, the SEI model is developed through the interpretation of the three themes of sustainable development, and it addresses the inter-disciplinary engineering fields, systems, sub-systems, devices along with components application, technologies and architectures requiring sustainability success. The term values in this case can also imply indices. Hence, the following abbreviations are applied in this study:

S_{ov} – Social values
E_{qv} – Equitability values
E_{nv} – Environmental values
E_{cv} – Economic values
V_v – Viability values
B_v – Bearability values
S_{uv} – Sustainability values

The Venn diagram intersection in Figure 3.3 yielding sustainable development among the three themes is translated into a mathematical model called the SEI model. This application is found in Chapter Four of Appendix III. Thus;

$$\mathbf{n(E_{cv}) \cup n(E_{nv}) \cup n(S_{ov}) = n(E_{cv}) + n(E_{nv}) + n(S_{ov}) - n(E_{cv} \cap E_{nv}) - n(E_{cv} \cap S_{ov}) - n(E_{nv} \cap S_{ov}) + n(E_{cv} \cap E_{nv} \cap S_{ov})} \tag{15}$$

But:

$$\left.\begin{aligned} &\mathbf{n(E_{cv} \cap E_{nv}) = n(V_v)} \\ &\mathbf{n(E_{nv} \cap S_{ov}) = n(B_v)} \\ &\mathbf{n(E_{cv} \cap S_{ov}) = n(E_{qv})} \\ &\mathbf{n(E_{cv} \cap E_{nv} \cap S_{ov}) = n(S_{uv})} \end{aligned}\right\} \tag{16}$$

Therefore, substituting Equations (16) into (15) yields;

$$\mathbf{n(E_{cv})\ U\ n(E_{nv})\ U\ n(S_{ov}) = n(E_{cv}) + n(E_{nv}) + n(S_{ov}) - n(V_v) - n(B_v) - n(E_{qv}) + n\ n(S_{uv})} \tag{17}$$

Equation (17) is the final mathematical representation of the sustainability model by the application of set theory. It implies that in order for the sustainability goals of engineering projects to be attained, relevant indices or values of sustainability must be defined and modelled as a set of integrated systems. Then, the sustainability engineering standpoint should promote a rigorous interaction for a balance amongst the three themes of sustainable development. The SEI model also addresses and normalises sustainability within the ranges of $0 \leq S_{uv} \leq 1$ by applying the probability (*P*) theory into sustainability (Stroud, 2001). The SEI model limits $[0 \leq S_{uv} \leq 1]$, thereby explaining the underlying principles associated with the efficiency of a machine, including building services operations. The building services operation contains systems, sub-systems (equipment) installation which can be measured in performance terms (RICS, 2008; Ashworth, 1999; IPMVP, 2002; Cheshire and Maunsell, 2007). The efficiency of a building in this case underscores the ratio of measured and ideal services delivery within a building (Cengel *et al*., 2008; ABS, 2012; Stroud, 2001; NIBS, 2006).

Once constructed, and fitted with equipment, a building yields the efficiency of 1. This logically expresses the ideal condition of such a building. But, when a building is put to use (operation), the efficiency will increasingly reduce over time tending towards 0. Also, this situation accounts for the fact that when the installed equipment is measured within the building, depreciation occurs due to deformation, friction, wear and tear, and that parts require maintenance if services are to be delivered (Cengel *et al*., 2008; CIOB, 2010; BREEAM, 2008; RICS, 2000). With the SEI model limits, accurate and reliable indices of sustainability can be qualified and quantified. An ideal building project is expected to have the S_{uv} value of 1. However, this is found impracticable in the real engineering project context (Smith, 2008; BREEAM, 2008; Cengel *et al*., 2008). The proposed SEI model reported in this study has defined and normalised S_{uv} values to unity for building services infrastructure application. The SEI model is expected to serve as a design, development, implementation, and management platform for the sustainable engineering community. Indeed, the different methods as applied in this study have been discussed earlier (Okon *et al.*, 2010; Okon and Elhag, 2011).

3.7.4 Partial differential equation method

The partial differential equation method, according to Stroud (2001), has also been applied to study buildings (facilities) as shown in Chapter Four. This method was used for the determination of the sustainability index (SI) and the building infrastructure performance (IP) within the investigated buildings (facilities) services. The application of this technique accounts for the initial and temporal (final) boundary conditions in the analysed buildings (facilities) with respect to their lifespan. The considered boundary conditions are:

- Initial building lifespan (t) boundary condition, ($t = 0$);
- Temporal (final) building lifetime boundary condition, ($t = \alpha$).

where α expresses the infinity status within the investigated buildings (facilities) and the building services infrastructure activities during the construction phase is represented by (E). In addition, the building services infrastructure activities during use (operations) and maintenance are denoted by (IU) and the sustainability index is represented by (SI) in this analysis. It is also noted that all parameters in this analysis are normalised values, therefore:

$$\mathbf{SI(t) = IP(t) + E.IU} \tag{18}$$

Let μ = buildings (facilities) infrastructure capacity (variables) factors, then;

$$[\mathbf{0 \leq \mu \leq 1}] \tag{19}$$

But, α = buildings (facilities) infrastructure usage (variables) factors, then;

$$[\mathbf{0 \leq \alpha \leq 1}] \tag{20}$$

For the sustainability index analysis within the investigated building (facilities) infrastructure at the initial construction (c) time, before operation (o) or use:

$$[0 \leq \mathbf{SI_o} \leq 1] \qquad (21)$$

Considering the highlighted parameters for the investigated buildings (facilities), the governing model for the analyis was established as presented in Equation (21).

$$SI^{1}_{0C}(t) = SI_{0}\,\ell^{-t/\alpha\mu} \qquad (22)$$

In this situation, ℓ represents the exponential constant in the analysis. The model in equation (22) was derived and subsequently applied for the analysis. Plots in Figure 3.4 illustrate the building services infrastructure at the construction and operational phases.

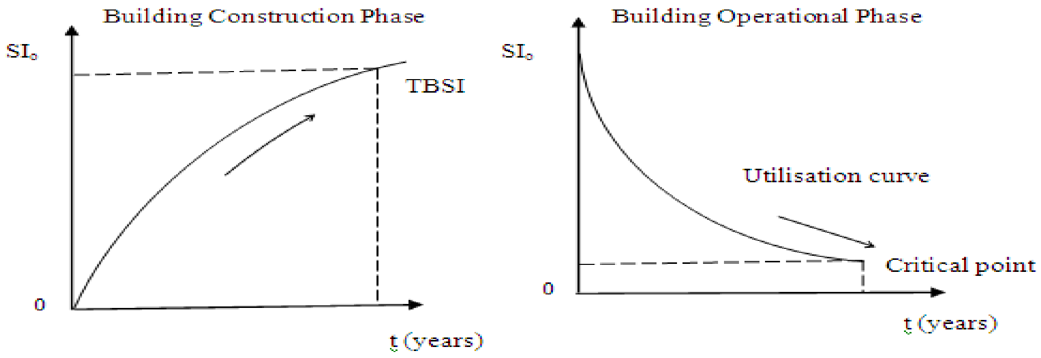


Figure 3.4: Construction and operational phases of building infrastructure.

In Figure 3.4, the point marked TBSI signifies the targeted building sustainability index at the construction phase of the building infrastructure (Barret, 1995; Chanter and Swallow, 2000; Bayer, *et al.,* 2010). The critical point in the operational phase of a building is where decommissioning is suggested as applicable in this study. More details regarding this analysis are reported in Appendix III.

3.8 Research methods used in study phase V

The research evaluates sustainable building services infrastructure systems within residential and office buildings. In this study also, the life cycle analysis (LCA) and life cycle cost (LCC) within six ongoing constructed buildings in the UK were appraised. This investigation was performed on six new high-rise buildings, and focused on their building infrastructure services delivery and management procedures. The results are presented in Chapter Four of this thesis.

3.8.1 Pilot study in phase V

The pilot study was conducted with three project managers handling building construction project activities. The feedback from these experts was able to provide very useful and important information leading to the preparation of structured surveys for the study (O'Leary, 2004). The various materials supply chains involved in this study were the energy utilities, water, waste, and building materials consumed at the construction, operation, maintenance, and end-of-life phases. Other details regarding this phase of the study are considered in the results and discussion section.

3.8.2 The structured survey administration in study phase V

Structured surveys were prepared and administered to twelve project managers within the building construction industry across the UK. Out of this number, six project managers were able to give measured field data from their organisation inventory for the analysis as shown in study phase V in Chapter Five. The suggested research methods by Last (2003), and O'Leary (2004), were adopted for the study, as they were believed to assist in achieving the study's goals. In the main, the research sought information on the construction, operation (use), maintenance, and EoL phases of the buildings services infrastructure systems. It was possible for respondents to return their surveys either by hand, email and regular mail as shown in Appendix IV. More details of this phase of tests are reported in Chapter Five.

3.8.3 Survey information and feedback in study phase V

Table 3.6: Summary of survey distribution in Buildings Construction Companies

Survey Inventory	Lot	Period of administration	Response time (month)
Survey produced	10	July, 2010	-
Survey administered	10	July, 2010	-
Survey received after completion	6	September, 2010	August, 2011
Survey returned unanswered	4	August, 2011	September, 2011
Participating companies	6	See *A – F	-

*A –Wates Construction Company, UK

*B –GallifordTry Construction Company, UK

*C –John Turner Construction Company, UK

*D –Northern Group Build Limited, UK

*E – Overburry Construction Company, UK

*F –Shepherd Building Group, UK

3.8.4 Methods used for sustainability evaluation in study phase V

This study found it necessary to find suitable methods to evaluate the data obtained from the survey feedback presented in Section 3.8.3. The features of sustainability were analysed in three parts each using a different method as indicated in Table 3.7.

Table 3.7: Features of sustainability and evaluation approach.

Features of Sustainability	Methods	Environmental Impact
Environmental Values	LCA	Energy Demand: * ADP, AP, EP, FAETP, GWP, HTP, MAETP, ODP, POCP, TETP.
Economic Values	LCC/value added	Life cycle costs and value added potentials. This will be adopted as related to the sector.
Social Values	LCA	It may include the building infrastructure delivery and benefits to the users generally.

*ADP –Abiotic Depletion Potential

*AP –Acidification Potential

*EP –Eutrophication Potential

*FAEP –Freshwater Aquatic Ecotoxicity potential

*GWP –Global Warming Potential

*HTP –Human Toxicity Potential

*MAETP –Marine Aquatic Ecotoxicity Potential

*ODP –Ozone Layer Depletion Potential

*POCP –Photochem Ozone Creation Potential

*TETP – Terrestric Ecotoxicity Potential

3.8.5 Method used for the LCA study in phase V

In this phase of study, the methods of ISO (1997), and Home *et al.* (2009) were used in the investigation. In the LCA analysis, the bills of materials data were exported and modelled using the Gabi 4 software package (Guinee *et al.*, 2001; CML, 2007). The rationale behind this approach was to identify the 'hot spots' (impact) and data gaps across the supply chain from the measured field data. The process flow diagram used for the LCA inventory analysis is shown in Figure 3.5.

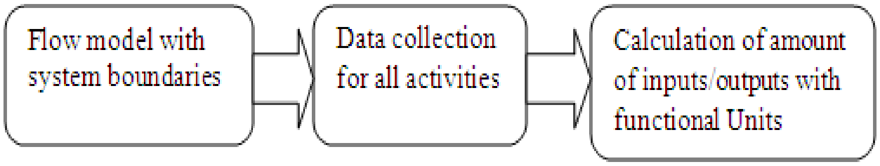


Figure 3.5: LCA inventory analysis process.

In this research, ten listed environmental impacts associated with the supply chain regarding building services infrastructure systems were evaluated using the CML assessment method in Guinee *et al.* (2001). CML is a method developed in the Centre of Environment Science of Leiden University in the Netherlands and is the best fit for impact examination study. The impact evaluation was studied and these include both characterisation and weighting steps in accordance with the ISO 14044 standard (Guinee *et al.*, 2001; REGENER, 1997; ISO, 2002) This standard is the EU's normalisation technique in Appendix V according to the CML package (Guinee *et al.*, 2001; Szalay *et al.*, 2011; Bayer *et al.*, 2010; Cabal *et al.*, 2005). The LCA appraisal also employs a mathematical approach according to ACLCA (2008), and Stroud (2001) to evaluate each characteristic's impact on the analysis as shown in Equation (23):

$$\textbf{Impact analysis} = \frac{(HHB - LHB, \ldots XBn)}{HHB} x100 \tag{23}$$

where HHB is the high hot spot in the studied buildings, LHB is the low hot spot, and *XBn* signifies any of the buildings in this situation (Lee and Burnett, 2008). The overall impact results in each case are presented as a percentage of the total estimation.

3.8.6 Methods used for the LCC in study phase V

In this study, the Langdon (2007) approach was used for the costs examination. This method was essential to evaluate the total cost of the building services infrastructure /facility ownership and to integrate the economic value for sustainability benefits. The appraisal in this context accounts for the cost of acquisition, owning, and disposing of the entire building services infrastructure systems. Furthermore, it addresses the overall costs of building services infrastructure projects alternatives, and selects the suitable design for the services delivery (Epstein, 1996). The LCC also aimed to ensure that the buildings infrastructure services will deliver at the lowest cost of ownership, whilst keeping its quality and function steady over the life cycle (Romm, 1994).

Romm (1994) maintained that in practical terms, over a 50 year period of a building's lifetime, the initial cost should account for just 2% of the total expenditure. At the same time, the operation (use) and maintenance costs should be worth about 6%, and the personnel costs equal to 92% of the total investment (Muto *et al.,* 2006). LCC appraisal in this case was based on the supplied field data as contained in Tables 5.40 and 5.41 that appear in Section 5.22. Davis Langdon and Jacobs' engineering costs assessment companies assisted in providing the current materials valuation for this study as shown in Appendix IV. In analysing the building infrastructure services, the related costs usually fall into the following classes (Muto *et al.,* 2006; Romm, 1994; Epstein, 1996):

- Initial costs – purchase, acquisition costs
- Fuel costs – operation, maintenance and repairs
- Replacement costs (Residual values – resale or salvage values or disposal cost)
- Finance charges – loan, interest payments and the non-monetary benefits or costs

At this stage in the study, the mathematical expression shown in Equation (24) was employed for the LCC analysis:

$$\textbf{LCC = Acquisition costs + Ownership costs + Disposal costs} \qquad (24)$$

Similarly, considering the total life cycle costs analysis in the investigated buildings infrastructure, Equation (25) was applied in the study:

$$\mathbf{LCC = I + Repl. - Res. + E + W + OM\&R + O} \qquad (25)$$

Where:

I = Investment cost
Repl. = Replacement cost
Res. = Residual cost
E = energy cost
W = water cost
OM & R = operation, maintenance and repairs
O = other associated costs incurred.

Similarly,

LCC = Total economic life cycle costs (£) in present value (PV) of a given alternative regarding the building infrastructure. Therefore, in terms of present value the component can be defined as follows:

I = PV of investment costs if incurred at the base date, they do not need to be discounted.

Then;

Repl. = PV of capital replacement costs
Res. = PV of residual value (resale value, salvage value) less disposal costs
E = PV of energy costs
W = PV of water costs
OM & R = PV of non-fuel operating, maintenance and repair costs
O = PV of other costs especially the contract cost (Muto *et al.*, 2006 and Romm, 1994).

Further analysis in this study also accounts for the other building infrastructure evaluation criteria. Thus, the lowest economic LCC for the purpose of finding costs effectiveness associated with the building infrastructure considering the indicated parameters. Then, the following parameters are defined for the building infrastructure (Epstein, 1996; Park and Tippett, 1999 and Muto *et al.*, 2006). The abbreviations are:

NS – Net savings: operational savings less difference in capital investment costs.

SIR – Saving-to-investment ratio: ratio of operational savings to difference in capital investment costs. However, other parameters include:

AIRR – Adjusted internal rate of return: annual yield of alternative over the study period, taking into account reinvestment of interim returns at discount rate.

SPB – Simple payback: time required for the cummulative savings from an alternative to recover its initial investment cost and other accrued costs without taking into account, time value of money (TG4, 2003). Also;

DPB – Discounted payback time required for the cummulative savings from an alternative to recover its initial investment cost and other accrued costs, taking into account the time value of money (Gulch and Baumann, 2004; Ellis, 2007).

3.9 Research methods used in study phase VI

This study evaluates sustainable building services infrastructure management to include water and energy utilities, waste, and carbon emissions, within hospitals and schools in the UK. Hospitals are regarded as the National Healthcare Services (NHS) and schools are generally considered as the Education sector. In addition, the study employed a two-stage method that being an initial literature review, subsequent empirical work in the form of the administration of surveys. The literature review was aimed at discovering the gaps within the management procedures and the survey targeted the experts' views on the issues raised in the literature. The research was tailored to determine the building services infrastructure management professionals' opinions on the existing standards and best practices for improved services delivery. Other methods applied in this phase of study are also indicated.

3.9.1 Pilot study in phase VI

Pilot surveys were prepared and administered to two facility managers in a college and university within the UK. Additionally, three operation and estate managers within the hospitals (NHS) were contacted for information regarding this context. These experts were able to supply very useful and significant information leading to the preparation of structured surveys for this research (O'Leary, 2004). This method was tailored towards achieving the overall aim of the study. The energy and utilities consumption together with the waste and other data from these organisations are presented under the structured survey in Section 5.4.

3.9.2 The structured survey administration in study phase VI

The structured survey produced in Appendix VI was produced and administered to the facilities, and operation and estate managers within hospitals and schools (colleges and universities) across the UK. These professionals were able to supply measured data from their individual organisations' inventories for the analysis. In the operation and maintenance phases of the activities, the focus was on the energy utilities such as water, electricity, natural gas, heating and fuel/oil use. The statistics from the maintenance and refurbishment phases centred on the materials flow and their recycling contents respectively. The waste management list includes segregated and non-segregated waste, recyclable, landfill, incinerated and other waste. On this basis, O'Leary's (2004) method was adopted as it sought to achieve the same overall goals as the study's objectives.

Last (2003) is supportive of the survey approach, observing that it is often applied, and particularly so in social science research. In this study, respondents were able either to return their completed survey by hand, email and regular postal mail as indicated in Appendix VII. More details regarding this phase of the study are contained in Tables 6.2 and 6.3 of Section 5.4.

3.9.3 Survey information and feedback in study phase VI

The statistical information in Table 3.8 presents a summary of the survey distribution in study phase VI as the requisite data was subsequently analysed and used for the investigation. Information in Table 3.8 accounts for the data acquisition process in both the healthcare and education sectors within the UK as shown in Appendix VII. The analyses and discussion from the survey are contained in Sections 5.4 of the thesis. The response rates for the surveys in the healthcare and education sectors are 22% and 34% respectively, as indicated in Table 3.8. These are high rates, being above the norm of 20–30% for most posted and hand-administered surveys (Elhag *et al.*, 2005).

Table 3.8: Summary of survey distribution - healthcare and education sectors

Survey inventory	Total number of survey per sector		Period per sector (months)	
	Health	Education	Health	Education
Survey produced	100	100	Feb. 2011	Feb. 2011
Survey administered	100	100	Feb.- June 2011	Feb. – June 2011
Survey received after completion	34	22	March-Oct. 2011	March- Oct. 2011
Survey returned unanswered	11	17	March-Oct. 2011	March- Oct. 2011

3.9.4 Averaging method

Averaging is a scientific approach to analysing data, and this was used in respect of the data obtained from the health and education sectors, shown in Appendix VII. In this connection the methods advocated by Smith (1998) and Stroud (2001) for finding average statistical information were adopted in the analysis. Equation (26) was applied for the investigation. Average analysis is the ratio of summation *(∑)* of all the energy and utilities and the total number of utilities consumption.

$$\textbf{Average test} = \frac{\sum(EU1+EU2....EUn)}{TU} \tag{26}$$

Hence, *EU* is the energy and utility and *TU* signifies the total number of utilities. The analysis outcomes are contained in Section 5.4 of this study.

3.9.5 Percentages method

The application of the percentages method becomes imperative for analysing the individual energy and utility consumption within the healthcare and education sectors as shown in Appendix VII. Stroud's (2001) method in determining the percentages analysis was used in this study. Percentages evaluation of energy and utilities consumption was also calculated using Equation (27) thus:

$$\textbf{Percentage} = \frac{Individual\ Energy\ Utility}{Total\ No.\ of\ Energy\ Utilities}\ x\ 100 \qquad (27)$$

The results obtained from this method are reported in Section 5.4.

3.9.6 Carbon footprint analysis method

In this study, a carbon footprint evaluation was also conducted using the carbon calculator (CcalC) software package formulated by Azapagic (2010) as shown in Section 5.8.2. The study adopted this method as contained in the CcalC package due to its wide application within the building industry and other field activities. The CcalC tool is a user friendly package allowing for quick and easy estimations of environmental impacts and value added along the supply chain in this research. Appendix VIII of this thesis contains the analysis from the CcalC software package.

3.9.7 The concept of probability theory

Probability theory applications in this study seek to quantify the data acquired from the health and education sectors. Hansen (2005) explains that probability theory is used to quantify the chance or possibility that sample test, and measurement results or data fall within some set of values. The methods suggested by Hansen (2005), and Montgomery *et al.* (1998) were used in examining the data, and the results obtain are presented in Section 5.9.1.

3.9.8 Sustainability index model with permutations and combinations functions

This study employed the sustainability index (SI) model with the permutations and combinations functions (PCF) methods for data analysis. The sustainability index model was applied due to its ability in arranging and sorting of the obtained data in this phase of study. Moreover, the achievable data from the healthcare and education sectors were measured through this approach. Stroud's (2001) method was then used to verify the best match energy utilities among the variables. In buttressing the test, the SEI model approach of Okon *et al.* (2010) was adopted alongside the PCF methods for addressing the sustainability index evaluation in this phase of study. Equation (28) is the governing principle of PCF in this analysis. Thus:

$$\mathbf{NC_m} = \frac{NPm}{m!} = \mathbf{1} \tag{29}$$

$$\mathbf{5C_5} = \frac{5P_5}{5!} = \mathbf{1} \tag{30}$$

$$\mathbf{5C_3} = \frac{5P_3}{3!} = \mathbf{1} \tag{31}$$

where N is the number of energy and utilities = 5, and C is the combination factors = 3. Also, P denotes the permutation factor = 3. The outcomes of these methods are reported in Section 5.10 of this thesis.

3.10 Interviews: Qualitative method – study phase VII

Chapter seven of this thesis reports on the structured interview sessions that were conducted with two sustainability professionals within the UK as indicated in Appendices IX and X. The individuals involved were: (a) the Director of Building Services and Construction Projects Management Programme at the Liverpool John Moores University; and (b) the Director of Sustainability at the company BDP. The interview evaluation was in line with the aim and objectives of this research. In addition, the structured interviews were expected to validate the results from the administered surveys discussed elsewhere in the thesis. The achievable information (data) in this phase of study was of a qualitative type which adds value to all the objectives of the research (Maxwell, 1996; McCraken, 1998).

3.10.1 Interview approach in study phase VII

The associated problems or research issues connected with engineering management in building services infrastructure systems and building construction activities, involve the measurement of data that are not easily quantified. Building infrastructure projects' scope definition, management capability, project complexity, and delivery services are all concepts that have proven to be essential for the successful management system (Armstrong, 1987; Grigg, 1987; GSGF, 2010; Ding, 2008). However, these constructs have posed difficulties for researchers in evaluation efforts. As a consequence, the research intention was to assess the parameters affecting building services infrastructure and building construction.

Maxwell's (1996) method was applied in this case as it offers a qualitative investigation approach to data collection through person-to-person interaction. This medium of data acquisition was adopted with two different management experts as indicated in Chapter Seven of this thesis. A tape recording system was also used by the interviewer to document the entire conversations for reference purposes. According to Kumar (1999), the advantages of the interview are as follows: the interview is more appropriate for complex analysis; hence, in situations where in-depth information is required, interviewing is the preferred method of data collection. Interviews can also vary in their form, ranging from the highly structured, to the unstructured type, distinguished by the degree of flexibility in the interview session. The unstructured interview is extremely useful in situations where either in-depth information is needed or little is known about the area. As this approach provides detailed information, many researchers use the technique for gathering rich background information, and subsequently developing a structured research instrument. This form of interview achieves its desire for flexibility, broad and detailed information from the responses.

In contrast, *"In a structured interview the investigator asks a pre-determined set of questions, using the same wording and order of questions as specified in the interview schedule. One of the main advantages of the structured interview is that it provides uniform information, which assures the comparability of data"* (Kumar, 1999).

Both methods have their advantages, but the semi-structured interview is characterised by the best of both worlds, and was, therefore, adopted in the study. The interview session was conducted by inviting the interviewees to share their opinions in an honest encounter with the researcher.

In accordance with Kvale (1996), *"The interviewee should be provided with a context of the interview by a briefing before. The context is introduced with a briefing in which the interviewer defines the situation for the subject; briefly tells about the purpose of the interview, the use of tape recorder; and asks if the subject has any question before starting the interview"*. Consequently, written lists of questions were sent to the interviewees in advance together with a clear explanation by the researcher of the need for conducting interviews (McCracken, 1988). The interview questions were open-ended with the purpose of achieving integrated information from the experts.

Obviously, the different method as applied in this study had previously been presented at the internationally-refereed conference (Okon and Elhag, 2011).

3.10.2 Summary

In this Chapter, the research methods employed for the study have been presented and discussed. This Chapter began with a short introduction regarding sustainable infrastructure systems management and proceeded to illustrate the approach taken to research design. In order to clarify the situation, the methods applied in the different phases of the study have been tabulated. Additionally, general information concerning the research processes in study phases I–IV, V, VI and VII have been highlighted, from which it is understood that a mixed methods approach has been adopted, with quantitative research methods being employed in phases I–IV, V and VI of the study, and a qualitative method being adopted in phase VII. This qualitative dimension to the empirical work has been indicated as a method to test the veracity of the results from the other phases of study (I–IV, V and VI) respectively.

Interestingly, various sustainability management models (LCA and LCC) are among those techniques that were identified through the related literature survey and have been applied in this study. The SEI model and a partial differential equation method were developed and subsequently used in the research. These management models have offered systematic advancement towards the attainment of sustainability success in buildings (facilities) projects and implementation.

Chapter Four

4.0 Results and discussion of the research

4.1Introduction

The results and discussion are presented in two broad phases as revealed in Figure 4.1. Sections 4.2–4.6 consider the building services infrastructure characteristics in commercial buildings (facilities), these being mainly, the operations and maintenance (OM) practices, and building construction companies within the UK. In Sections 4.12–4.13, the buildings (facilities) services infrastructure characteristics analysis from the Aluminium Smelter Company of Nigeria (ALSCON), and Mobil Producing Nigeria (MPN) scenarios are presented. The four phases of this study are namely; **1**) Commercial buildings: the operations and maintenance (OM) – Phase I; **2**) Building construction companies (BCC) – Phase II; **3**) ALSCON – Phase III; and **4**) MPN – Phase IV. The comparative analyses results from the UK and Nigerian scenarios are also reported. The pattern of the study is shown in Figure 4.1.

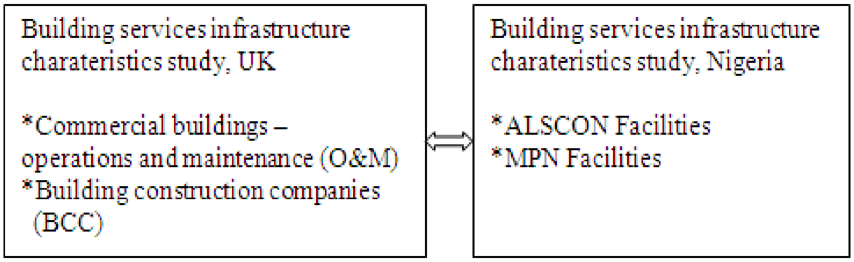


Figure 4.1: The results and discussion pattern of the study.

4.2 Study Phase I: Commercial Buildings - O&M evaluation

4.2.1 Presenting the phase of study

Commercial buildings: the operations and maintenance (O&M) activities of the building services infrastructure in the Arndale Centre, and Liverpool One (shopping malls in Manchester, and Liverpool respectively), in the United Kingdom were examined. The maintenance/operations and information desk managers provided the building services infrastructure statistics through the survey, and the results obtained appear in Sections 4.3–4.20 of the thesis.

4.2.2 Goal and scope definition

The goals were specifically concerned with the operations and maintenance stages of the building services infrastructure performance. Basically, water, energy, heating, and the maintenance culture, were the services addressed. Additionally, the characteristics leading to effective services delivery and the sustainability of the building infrastructure over its life cycle were appraised.

4.3 Results and discussion in study phase I

In this study, the following abbreviations are used: severity indices (SI), coefficient of variation (COV), category ranking (CR), and the overall ranking (OR).

The outcomes from the energy resources management characteristics in phase I are presented in Table 4.1.

4.3.1 Energy resources management characteristics

Table 4.1: Energy resources management characteristics

FACTORS	SI	COV	CR	OR
1)Use of efficient and energy saving fixtures	82.7	19.2	3	11
2)Use of modern technological (energy) concepts	80.0	26.6	4	15
3)Use of sensor based lighting systems for energyconservation in building/facility	79.7	27.5	5	16
4)Use of the renewable energy source in building/facility	68.0	36.0	10	31
5)Use of HVAC for energy efficiency/conservation	72.7	30.5	9	26
6)Employment of solar panels/photovoltaic technology	55.6	45.7	11	36
7)Installation of modern energy saving accessories in building/ facility	78.8	30.4	6.5	17
8)Energy management via good operating efficiency in buildings /facility	87.5	18.8	1	6
9)Energy management via good maintenance policy framework in building/facility	86.9	19.1	2	7
10)Educational awareness drive on the sustainable energy usage in building/facility	78.8	24.6	6.5	17
11) Application of building regulation Part L for energy conservation in building/facility	75.8	33.8	8	22

From Table 4.1 it can be seen that the group of respondents identified 11 factors. The severity indices range from 55–88%. The result shows that these factors have relatively weighty degrees of influence on building infrastructure energy and utilities management in terms of cost and service delivery. For instance, 87% of the respondents strongly agreed with (a) the use of efficient and energy saving fixtures in building infrastructure for cost savings. The class maintained coefficients varying between 18% and 46% which are relatively low and show a good concordance level between the respondents. The category ranking range is 1st–11th.

This indicates strong agreement on (b) the application of energy management through good operating efficiency and maintenance policy factors. However, (c) the employment of solar panels, and (d) the renewable energy source in the building, are ranked least in the category scale. Their overall ranking ranges are 6th–36th. There are exceptions of nine variables perceived by most respondents as not being highly significant in this investigation, as shown in Table 4.1.

4.3.2 Water resources management characteristics

Findings from the water resources management characteristics in study phase I, are shown in Table 4.2.

Table 4.2: Water resources management characteristics

FACTORS	SI	COV	CR	OR
1)Use of efficient water fixtures, sensor flow taps	66.7	39.2	6.5	32
2)Use of modern technological concepts; water recycling practice in building/facility	59.1	41.8	9	35
3)Use of water conservation techniques; grey water in building/facility	59.4	46.5	8	33
4)Installation of automatic shut-off faucets for water conservation in building/facility	69.6	41.3	4	29
5)Installation of accessories/dual flush toilet/wireless urinals in building/facility	78.3	27.9	2	18
6)Prevention of water wastage/losses via leakages in the building/facility	81.2	24.5	1	14
7)Achieving DEFRA standard 2007/use of 125 litres of water/head/day in building/facility	68.2	40.2	5	30
8)Educational awareness drive towards sustainable water usage in building/facility	77.3	36.9	3	20
9)Building of On-site/Off-site (sewage) effluent plant in building/facility	67.7	46.3	6.5	32

This category includes nine factors, as indicated in Table 4.2. Seven of these factors achieved severity indices within the range 60–81%. Some of these factors are: (a) the use of efficient water fixtures (sensor flow taps), (b) the installation of automatic shut-off faucets for water conservation, (c) the educational awareness drive on the sustainable water usage, and, (d) the prevention of water wastage. This shows these variables have higher degrees of influence and they are considered to be of top priority in water resources management delivery. The category maintained a coefficient of variation between 24% and 46% which is relatively low, signifying a strong level of agreement between respondents.

Two factors recorded a coefficient of variation of 46%. These are: (a) the use of grey water concept, and (b) the provision of an effluent treatment plant. This indicates that these factors are less important among others. Moreover, in the category ranking they are 1st–9th. Hence, a good level of concordance is revealed from the respondents' perspective. However, the overall ranking category contains the top two of the 10 factors, these being: (a) the prevention of water wastages/losses through leakages, and (b) installation of accessories and dual flush toilet and wireless urinals. These results demonstrate that priority should be given to these factors in the quest for sustainability and improved services delivery in the infrastructure systems (Table 4.2).

4.3.3 Maintenance management practices

The statistics from the maintenance management practices in study phase I, appear in Table 4.3.

Table 4.3: Maintenance management practices

FACTORS	SI	COV	CR	OR
1)Employment of technical /skilful expertise	82.7	26.3	4	12
2)Adoption of team working approach	89.5	23.3	1	3
3)Adoption of innovative driven concepts	73.6	35.3	6	25
4)Predictive maintenance practice	82.6	26.9	5	13
5)Preventive maintenance practice	88.9	19.1	2	4
6)Corrective maintenance practice	86.1	25.8	3	8
7)Maintain as-we-go philosophy	57.6	47.9	7	34

The questionnaire consists of seven factors as shown in Table 4.3. In this category, six factors achieved severity indices ranging between 73% and 89%, thereby revealing a relatively high degree of influence from these factors on the maintenance management practices. The other factor, (a) the maintain-as-we-go philosophy, gained a severity index of 57%. There are indications from the respondents that this factor is insignificant and should be discarded during planning and policy implementation. In this category, the coefficient of variation for the six most influential factors ranged between 19% and 35%. These coefficients of variation are relatively low and indicate a strong agreement level between respondents in their ranking. Hence, it could be adduced these factors are crucial in enabling proper maintenance practices in all factors except for the maintain-as-we-go approach.

At the top of the category ranking is: the adoption of a team working approach in addressing the maintenance culture. This demonstrates a strong agreement amongst the respondents on the influence of this factor. Furthermore, the preventive, and the corrective maintenance factors were ranked 2nd and 3rd respectively, whereas the other factors in this category were considered more subjective and less influential. The top overall ranked factor in this group (see Table 4.3) still remains (d) the team working approach in addressing infrastructure management systems. The remaining factors within this category do not obtain results that show them as having a strong degree of influence. However, the entire results are consistent throughout the scale of examination.

4.3.4 Infrastructure design characteristics

In this thesis, data obtained from the infrastructure design characteristics in study phase I are presented in Table 4.4.

Table 4.4: Infrastructure design characteristics

FACTORS	SI	COV	CR	OR
1)Design/drawings/envelope/specification	74.6	37.1	4	24
2)Feasibility of the design framework	75.8	36.4	3	22
3)Variation orders/cost/interference	69.8	36.7	6	28
4)Design quality/specification	80.0	36.8	2	15
5)Inspection/testing/approval/commissioning	83.3	29.6	1	10
6)Infrastructure/design/planning	73.3	37.1	5	25

The category has six factors as shown in Table 4.4. Two of these factors attained severity indices between 80% and 83%, these being: (a) the design/quality/specification and, (b) the inspection/testing/approval/commissioning. This outcome reveals the high degree of influence held by these variables in respect of the decision-making concerning the infrastructure design characteristics. Moreover, the severity indices of the other four remaining factors are between 69% and 75%, showing that their levels of influence are also strong in this respect. However, their perceived importance from the respondents' perspective should not be ignored, and in this connection, the coefficients of variation range from 29–37%, meaning that the effects of these factors are low in the pursuit of infrastructure systems design, as seen in the overall ranking.

The implication of an infrastructure design that has appropriate characteristics is that it enhances effective service delivery, and the just-in-time maintenance culture. In the category ranking, the top ranked factor within the group was: the inspection/testing and commissioning, and the second top ranked factor was: the design quality/specification and feasibility of the design framework (see Table 4.4). Clearly, these two factors are accorded high importance in building services infrastructure systems. In the overall ranking, this category generally came low since the factors included are considered to be expensive, time-consuming, and harder to implement in building projects.

4.3.5 Infrastructure project characteristics

The results from the infrastructure project characteristics in phase study I are presented in Table 4.5.

Table 4.5: Infrastructure project characteristics

FACTORS	SI	COV	CR	OR
1)Type of building/facility /industrial/residential/ commercial/ offices	76.2	34.3	5	21
2)Size of building/facility area	74.2	33.8	7	25
3)Height/number of stories	71.4	39.8	9	27
4)Complexity of building/facility	77.8	31.3	2.5	19
5)Structure type (steel, brick etc)	74.6	37.1	6	24
6)Construction method/technology	77.3	36.2	4	20
7)Accessibility to the building/facility	72.7	34.4	8	26
8)Intensity/complexity of the building/facility	77.8	34.1	2.5	19
9)Site topography/location	76.2	34.3	5	21
10)Quality of finishing	78.8	35.9	1	17

Table 4.5 outlines ten factors, with severity indices ranging between 71% and 79%, thereby revealing that more than 70% of all respondents strongly agreed with the need to tackle all these factors. These are quite clearly perceived as having a substantial degree of influence on infrastructure project characteristics in terms of time management, materials, cost, and service delivery. However, in this category the coefficients of variation of the entire range of factors is between 31% and 40%, indicating that they have gained a very low level of influence within this context. The category ranking ranges from 1st–9th, thereby showing a good level of concordance on the influencing factors regarding the sustainable infrastructure projects characteristics. The category ranking contains three of the top 10 factors ranked 1st–3rd.

These factors are: 1) the quality of finishing, 2) the complexity of building, and 3) the intensity of the building/facility (Table 4.5). Hence, the respondents are in strong agreement in their ranking of these factors. The overall ranking scale expresses more concern on: the quality of finishing, the complexity of the building alongside, and the intensity of the building/facility. The quality of finishing as highlighted by the respondents promotes aesthetics in the engineering infrastructure projects delivery systems. The other two overlapping results also play vital roles in the building infrastructure systems domain.

4.3.6 External factors affecting sustainable infrastructure management (SIM)

Survey information regarding the external factors affecting SIM in study phase I, is presented in Table 4.6.

Table 4.6: External factors affecting SIM

FACTORS	SI	COV	CR	OR
1)Users’ attitude towards the building/facility	84.9	26.4	4.5	9
2)Availability of safety equipment/fume extractors installation	88.9	21.7	3	5
3)Supply performance	84.9	26.4	4.5	9
4)Weather condition	75.4	33.3	6	23
5)Government policies (OHSAS, EMS)	84.9	26.4	4.5	9
6)Quality of equipment/installation	90.5	20.7	2	2
7)Sustainability of the building/facility	90.9	20.2	1	1

The questions in this category referred to seven factors as indicated in Table 4.6. This group demonstrates high severity indices ranging between 75% and 91%, confirming that the degree of influence of these variables is extensive after the commissioning, operation and maintenance of building infrastructure systems delivery. The two topmost severity indices are over 90% score, these being 1) the quality of equipment/installation, and 2) the sustainability of the building/facility. In addition, the severity indices of the other remaining five factors are between 75% and 89%, meaning their levels of influence are also very strong. Obviously, three of these factors have severity indices of 85% overlapping each other.

The group include: (a) the users' attitude towards the building; (b) the supply performance; and (c) the implementation of government policies. This signifies a strong correlation between the degree of their influence on building infrastructure systems from the respondents' viewpoints. In the coefficient of variation ranking, the top ranked factors are: 1) the weather conditions; 2) the users' attitude towards the building; and, 3) the supply performance. The implementation of government policies has also made this list. Similarly, this group category ranking is from 1st–6th. Apart from: the sustainability of the building, and the quality of equipment and installation factors, which are ranked 1st and 2nd respectively, three other characteristics have corresponding rankings as shown in Table 4.6. These outcomes indicate a strong degree of concordance and the fact that these factors have significant impacts.

Furthermore, on the overall ranking list within this category, first is the sustainability of the building, and second is the quality of equipment and installation factors. Three other factors have overlapping results within the ranking of 9th as shown in Table 4.6. This demonstrates their significant impacts upon the standard practices and safety of the building services infrastructure system. The entire results emerge from the respondents' perceptions of the infrastructure system management success.

4.4 Constraints in study phase I

Certain factors affected the data acquisition process during the research as follows:

- Difficulties in gaining access to some offices and members of staff for audience and subsequent administration of the survey.
- Delays from some respondents in completing and subsequently returning the questionnaire for data analysis and evaluation.
- Administrative bureaucracies within organisations which posed difficulties in the acquisition of data for evaluation.
- Data disclosure and information brokering as a result of which some members of staff expressed fear of divulging the company's confidential information in the process of completing the survey.

4.5 Conclusion to study phase I

The analysis indicates that 15 factors maintained severity indices ranging from 80–90%, and that 36 factors sustained severity indices in the range 55–79%. This shows that 15 factors are regarded as being highly relevant for improved, efficient and sustainable infrastructure systems delivery. They include: (a) energy management through good policy; (b) prevention of water/wastage/losses through leakages in the building/facility; and (c) the preventive maintenance practices. The other remaining factors gaining severity indices between 80–90% also count.

At the same time, 36 factors need to be improved upon to realise efficient infrastructure management practices. The results further revealed the coefficient of variation indices for 22 factors were 78–90% with: (a) the sustainability of the building infrastructure characteristic factor being ranked first, and the second and third ranking factors being: (b) the quality of equipment/installation, and (c) the availability of safety equipment within the shopping malls, respectively. In the respondents' opinions, these factors require more prioritisation if enhanced service delivery is to follow.

The category ranking in this phase of study emphasised those characteristics in each group placed first and second, since these are very strongly rated in terms of their necessity for building services and construction management success.

On the overall ranking scale, it is observed that the top priority was the sustainability of the building infrastructure characteristic factor. The second priority was the quality of equipment/installation; and the third was the adoption of team working approach factors. Therefore, the research suggests very strong agreement on the part of the respondents regarding the high level of significance on these factors. At the same time, the ‘maintain-as-we-go’ philosophy achieved 47% indicating a good degree of conformity on the negative impact of this factor from the respondents’ point of view. The result further signifies a strong correlation on the identifiable and outstanding factors in the building services infrastructure decision-making and implementation processes.

Generally, the result is akin to the views of Grigg (1988), and Hill and Bowen (1997), although there are substantial indications of this position from the results on the implementation of government policies on the sustainability programme, preventive maintenance practices, technical/skilful expertise, and the building infrastructure users’ attitude. Moreover, the design quality/specification, supply performance and prudent resources management need a more pragmatic approach to guarantee optimum services delivery within this context.

4.6 Study Phase II: Building construction companies (BCC)

4.6.1 Presenting the phase of study

The research also investigated the building construction sector and identified five major construction/engineering/design companies within the UK involved in sustainable construction projects. These companies are front line practitioners regarding sustainable construction and development. They are: Laing O’ Rourke Group, Atkins Global, MWH, BDP and BAM Company. A brief description of these companies is presented together with the results of the surveys administered within them.

(I) Laing O’Rourke construction group is the largest privately owned construction firm in the UK and was established in 2001. The company’s offices are located in various countries which include Germany, India, Australia, United Arab Emirates, and the UK and it has over 31,000 employees worldwide. The organisation uses an integrated method of delivery with capabilities across all elements of the projects life cycle within the built and infrastructure environment.

The company's projects expertise extends to feasibility studies, to development options, and investment opportunities. Additionally, it is expert in technical fields, for example in delivering excellent design, engineering, innovative construction, and manufacturing of products. Moreover, activities such as testing, commissioning, handing over, operations, maintenance, and decommissioning of the sustainable infrastructure services, are also undertaken by the company. Through self-delivery capabilities, the Laing O'Rourke group is able to deliver a broad range of services that drive out waste, mitigate risk management, and allow for the integration of efficient and effective project resources, thereby increasing productivity (Laing O'Rourke, 2012).

(II) Atkins Global is the UK's largest engineering and design consultancy and the world's 11th largest design firm. The organisation possesses a depth and breadth of expertise to respond to the most technically challenging and time-critical infrastructure projects. Moreover, the urgent transition to a low-carbon economy is a specific area of focus with the company's policy. Issues regarding construction, from the concept for a new skyscraper, upgrading of infrastructure, modelling of a water system, improvement of a management process, and many more are undertaken by the organisation. Its capabilities span planning, designing, construction, and building, and enable solutions within the built environment (Atkinsglobal, 2012).

(III) The MWH global organisation is driving the wet infrastructure sector globally, and is leading the world in results-oriented management, technical engineering and construction services to build a better world. The wet infrastructure sector encompasses a variety of water-related projects and programmes ranging from water supply, treatment and storage, to water resources management, and coastal restoration. The company embarks on the design and construction of hydropower and renewable energy facilities to full environmental services.

Furthermore, it recognises wet infrastructure covers a broader range than simply water. Therefore, global mega trends including climate change, scarcity of resources, aging infrastructure and technical innovation are all tied to the firm's efforts in providing sustainable solutions that reflect the best practices in wet infrastructure knowledge, experience and innovation (MHW, 2012).

(IV) BDP is the largest interdisciplinary practice of architects, designers, engineers and urbanists in Europe. The organisation was founded in 1961 and currently employs more than 1,000 architects, designers, engineers, urbanists, sustainability experts, lighting designers, and acoustics specialists in 16 studios across the UK, France, Ireland, Netherlands, and United Arab Emirates. The firm works closely with users, clients and the community to create special places for living, working, shopping, culture and learning across Europe, Africa, Asia, and Australia.

BDP has a leading track record in all major sectors including health, education, workplace, retail, urbanism, heritage, housing, transport and leisure. The organisation combines expertise across disciplines, locations, sectors and all major building types to deliver a truly integrated way of working, resulting in high quality, effective and inspiring built spaces. In addition, BDP Company has won numerous accolades including sustainable designer and consultant of the year in the 2008 Sustainable Building Awards. The firm’s delivery of a holistic sustainable design remains its topmost design philosophy within the built environment (BDP, 2012).

(V) The Royal BAM Group has been a European construction enterprise since 1847. The organisation’s expertise provides a seamless service in construction, property development, design, engineering, facilities management and plant hiring services. Moreover, BAM Company has a large network of offices covering England, Scotland and Wales, and projects in the education, retail, mixed-use development, health, office, leisure, and the law and order sectors. The Company has a strong commitment to collaboration and offers unique benefits of health and safety, sustainability, innovation and end users’ satisfaction legacy for future generations (Royal BAM Group, 2012).

4.6.2 Goal and scope definition

As the main aim of the study is to examine and value five building construction companies within the UK (Section 4.2.2), with a specific focus on the design and construction stages of the building infrastructure, the scope of this dimension of the empirical work concerns the infrastructure services performance. That is to say, water, energy, heating, quality of equipment installation, and the maintenance culture in all these areas were considered in the study. Additionally, the characteristics leading to effective services delivery and the sustainability of the infrastructure over its life cycle were evaluated.

4.7 Results and discussion in study phase II

4.7.1 Energy resources management characteristics

The findings from the energy resources management characteristics in phase II are presented in Table 4.7.

Table 4.7: Energy resources management characteristics

FACTORS	SI	COV	CR	OR
1)Use of efficient and energy saving fixtures	96.5	21.4	3	6
2)Use of modern technological (energy) concepts	98.4	20.1	1	1
3)Use of sensor based lighting systems for energy/ conservation in building/facility	96.4	22.8	4.5	7
4)Use of the renewable energy source in building/facility	94.7	26.1	7.5	14
5)Use of HVAC for energy efficiency/ conservation	92.4	28.9	11	24
6)Employment of solar panels/photovoltaic technology	95.4	33.4	6	13
7)Installation of modern energy saving accessories in building facility	94.7	25.6	7.5	14
8)Energy management via good operating efficiency in buildings /facility	98.3	20.1	2	2
9)Energy management via good maintenance policy framework in building/facility	92.6	28.4	10	22
10)Educational awareness drive on the sustainable energy usage in building/facility	96.4	23.8	4.5	7
11)Application of building regulation Part L for energy conservation in building/facility	92.9	26.5	9	21

It can be seen in Table 4.7, that 11 separate factors are identified, with severity indices ranging between 92% and 98%. These factors can be appreciated as having relatively high degrees of influence on building infrastructure management in terms of the cost and service delivery. In fact, more than 92% of the respondents strongly agreed that all the identified characteristics in the building construction industry had an impact upon cost savings. Within this overall categorisation, coefficients of variation between

20% and 33% were maintained, representing a relatively low percentage, and thereby indicating a good level of concordance among respondents. The category ranking suggests strong agreement on the use of modern energy concepts and management factors, and very low agreement on the employment of HVAC.

However, their overall rankings are 1st–24th. There are exceptions of three variables perceived by most respondents as not being highly significant in this investigation. They include: (a) the building regulation Part L for energy conservation in the building/facility; (b) the energy management through good maintenance policy/policy framework; and (c) the application of HVAC for energy efficiency/conservation within the building/facility. The other remaining factors in the study are rather significant in this perspective as demonstrated in Table 4.7.

4.7.2 Water resources management characteristics

Data collected from the water resources management characteristics in study phase II are presented in Table 4.8.

Table 4.8: Water resources management characteristics

FACTORS	SI	COV	CR	OR
1)Use of efficient water fixtures, sensor flow taps	92.8	28.7	3.5	22
2)Use of modern technological concepts; water recycling practice in building/facility	98.2	22.8	1	4
3)Use of water conservation techniques; grey water in building/facility	92.8	28.7	3.5	22
4)Installation of automatic shut-off faucets for water conservation in building/facility	81.9	38.2	6	35
5)Installation of accessories/dual flush toilet/wireless urinals in building/facility	92.8	28.7	3.5	22
6)Prevention of water wastage/losses via leakages in the building/facility	90.9	30.5	5	27
7)Achieving DEFRA standard 2007/use of 125 litres of water/head/day in building/facility	79.1	38.1	7	36
8)Educational awareness drive towards sustainable water usage in building/facility	96.3	25.1	2	9
9)Building of On-site/Off-site (sewage) effluent plant in building/facility	75.6	39.5	8	38

This category includes nine factors as shown in Table 4.8. Six of these factors achieved severity indices within the range 90–98%. Included in these factors are: (a) the prevention of water wastage/losses through leakages; (b) the use of energy saving fixtures (sensor flow taps); and (c) the grey water techniques. This demonstrates these variables have higher degrees of influence and are considered to be of top priority in water resources management delivery. Moreover, the other remaining three factors have severity indices ranging from 75–81%. Among these characteristics are: (a) the DEFRA standard 2007, and (b) the provision of effluent treatment plant.

The list also contains: (c) the installation of automatic shut-off faucets within the building/facility. The group has coefficients of variation between 22% and 39%, which are relatively low, signifying a strong agreement level between respondents. Four factors were recorded with the coefficient of variation ranked 30–39%, indicating these factors are of less importance. They are: (a) the DEFRA standard 2007, (b) the provision of effluent treatment plant, (c) the installation of automatic shut-off faucets, and (d) the prevention of water wastage/losses through leakages. Category ranking ranges from 1st–8th with the use of water recycling technology leading, and the educational awareness drives on the sustainability success coming next. The other remaining factors in this class are shown in Table 4.8. These results indicate a good level of concordance from the respondents' perspective regarding building construction management goals.

The overall ranking category contains two of the top 10 factors. The top two ranked factors within this group are: the water recycling concepts, and the educational awareness drive on sustainable water usage in the building construction projects sites. This result emphasises the significance of these factors in the search for sustainable water management practice.

4.7.3 Maintenance management practices

Information gathered from the maintenance management practice characteristics study in phase II is presented in Table 4.9, which shows seven factors. In this category, five factors achieved severity indices ranging between 92% and 94%. Among these factors are: (a) the innovative driven concepts, and (b) the team working approach between the maintenance personnel. Furthermore, (c) the employment of technical/skilful expertise, (d) the adoption of preventive maintenance, and (e) the predictive maintenance culture are also listed. This indicates a relatively high degree of influence of these factors on the maintenance management practices. The other two factors are within the severity indices ranging between 62% and 87%.

Table 4.9: Maintenance management practices

FACTORS	SI	COV	CR	OR
1)Employment of technical /skilful expertise	94.3	25.0	1	16
2)Adoption of team working approach	92.4	29.1	3	24
3)Adoption of innovative driven concepts	93.9	27.4	2	18
4)Predictive maintenance practice	92.2	29.4	5	26
5)Preventive maintenance practice	92.3	29.3	4	25
6)Corrective maintenance practice	87.5	33.7	6	31
7)Maintain as-we-go philosophy	62.8	50.3	7	39

There are indications from the respondents that one factor, namely the corrective maintenance practice is equally important. However, the maintain-as-we-go philosophy is regarded as a minor.

Nevertheless, in this group the coefficients of variation of six factors range between 25% and 33%, confirming that the factors are relatively low, and that a strong agreement level exists between respondents in their ranking of these factors. As a consequence, it can be appreciated that these factors are crucial in enabling proper maintenance practices. Notably, one factor has a coefficient of variation 50%. Specifically, this is the maintain-as-we-go philosophy factor which is found to be insignificant in this case, indicating that it should not form part of the maintenance policy framework on building construction management growth.

At the top of the category ranking is: (a) the employment of technical or skilful expertise in addressing maintenance culture. This first-place ranking demonstrates a strong agreement amongst the respondents on the influence and importance of this factor. Furthermore, the factors relating to the innovative driven concepts, and the team working approach between the maintenance personnel, were ranked second and third respectively as seen in Table 4.9. The other factors were considered more subjective with less influence in this class. The top ranked factor in this group still remains: the employment of technical/skilful expertise in building construction projects. Other factors in this group do not gain a strong degree of influence in terms of their building infrastructure management accomplishment.

4.7.4 Infrastructure design characteristics

Statistics from the infrastructure design characteristics in phase II are provided in Table 4.10.

Table 4.10: Infrastructure design characteristics

FACTORS	SI	COV	CR	OR
1)Design/drawings/envelope/specification	98.2	18.2	1	3
2)Feasibility of the design framework	96.1	24.9	3	12
3)Variation orders/cost/interference	87.9	33.0	6	30
4)Design quality/specification	96.4	21.1	2	7
5)Inspection/testing/approval/commissioning	94.6	25.2	4	15
6)Infrastructure/design/planning	89.2	31.2	5	29

This category has six factors, Table 4.10. Four of these characteristics attained severity indices between 94% and 98%. Among these factors are: (a) the inspection/ testing/approval/commissioning, (b) the design quality/specification, and (c) the feasibility of the design framework. The group also includes: (d) the design/drawings /envelope/specification in handling building infrastructure challenges. These variables have a high degree of influence in the decision-making process in the building infrastructure design stages. Moreover, the severity indices of the two other remaining factors are in the range 87–89%. These factors are: (e) the variation orders/cost/interference, and (f) the infrastructure/design/planning. Consequently, it can be understood that their level of influence is equally very strong within this context. However, according to the respondents' opinions, they should not be discarded. The coefficient of variation is between 18% and 33% (Table 4.10), showing that the effects of these factors are comparatively low. The implications are that in terms of infrastructure design characteristics, they enhance effective building service delivery and promote a just-in-time maintenance culture in respect of infrastructure systems management.

In the category ranking, the top ranked factors include: the design/drawings envelope and specification, and the design quality/specification, which were ranked first and second respectively, and hence regarded as highly important. In the overall ranking scale, three factors came top, which are: (a) the building infrastructure design/planning, (b) the quality/specification, and, (c) the feasibility of the design framework.

Accordingly, it can be seen that the remaining factors are considered to be expensive, time-consuming and more difficult for implementation in the building construction projects.

4.7.5 Infrastructure project characteristics

Data from the infrastructure project characteristics in study phase II are presented in Table 4.11, from which it can be seen that ten factors are identified. The severity indices range from 86–96%. Specifically, characteristics such as the construction method/technology, and the complexity of the building/facility, represented the two top identifiable factors in this group. Others such as: the intensity/complexity of the building, the building type, and site topography, were also cited. Over 86% of all respondents strongly agreed with the need to address these factors.

Table 4.11: Infrastructure project characteristics

FACTORS	SI	COV	CR	OR
1)Type of building/facility / industrial/ residential/ commercial/ offices	94.1	27.0	6	17
2)Size of building/facility area	92.6	28.9	5	23
3)Height/number of stories	86.7	34.9	9	33
4)Complexity of building/facility	96.2	34.2	2	10
5)Structure type (steel, brick etc)	86.3	24.4	10	34
6)Construction method/technology	96.3	35.1	1	8
7)Accessibility to the building/facility	90.9	24.6	7	28
8)Intensity/complexity of the building/facility	94.3	27.3	4	16
9)Site topography/location	94.6	26.4	3	15
10)Quality of finishing	87.0	34.1	8	32

Only three factors recorded severity indices ranging from 86–87%. They are: (a) the structure type, (b) the height/number of storeys, and (c) the quality of finishing characteristics. The results show these factors to have a relatively substantial degree of influence on building services infrastructure projects quality in terms of time, materials and costs.

In this category the range in the variation of the coefficients of all the factors is 24–35% (Table 4.11). Hence, these factors can be understood to have an important impact on the building construction industry. The categories are ranked from 1st-10th thereby indicating a good level of agreement on the factors influencing the sustainable building construction projects characteristics. The category ranking contains two of the top 10 factors ranked 1st and 2nd, these being: (a) the construction method/technology, and (b) the complexity of the building/facility. The reason why the construction method/technology achieved the top rank was because it serves costs, materials, and wastage among others.

4.7.6 External factors affecting SIM

Statistics regarding the external factors affecting SIM in study phase II are shown in Table 4.12, from which it can be seen that the questions in this group concerned seven factors. This category demonstrates high severity indices ranging between 79% and 94%, indicating that the variables have a wide-ranging degree of influence after the commissioning, operation (use), and maintenance of building infrastructure systems delivery. The topmost severity index at 94% and ranked first is the sustainability of the building/facility, while the second highest ranked in the category is users' attitude (see Table 4.12).

Table 4.12: External factors affecting SIM

FACTORS	SI	COV	CR	OR
1)Users' attitude towards the building/facility	87.2	23.3	2	16
2)Availability of safety equipment/fume extractors installation	86.0	24.3	3	19
3)Supply performance	82.5	22.2	6	26
4)Weather condition	79.2	26.4	7	31
5)Government policies (OHSAS, EMS)	82.9	24.0	5	25
6)Quality of equipment/installation	85.2	13.3	4	22
7)Sustainability of the building/facility	94.4	19.4	1	2

The severity indices of the remaining five factors range between 79% and 86%, also indicating that their levels of influence are relatively strong. Four of these factors have severity indices overlapping each other. These factors include the supply performance, and the implementation of government policies, signifying the respondents' perception that they have a strong influence on the building construction industry.

In the coefficient of variation ranking, the top ranked factors are: (a) the weather, and (b) the availability of safety equipment/fume extractors as shown in Table 4.12. Also included is (c) the implementation of government policies. After the weather, the sustainability of the building/facility factor is ranked first, with other factors gaining individual ranks of 2nd–7th indicating a strong degree of concordance, and their significant impact within this group regarding the building services and construction management.

On the overall ranking list the sustainability of the building/facility is ranked second. The other factors are considered very prominent, but were perceived as less significant in this study. Generally, the other remaining factors have less influence on the building services and construction practices as shown in the study.

4.8 Constraints in study phase II

There were limiting factors affecting the data acquisition during the study, these being:

- Delays from some respondents in completing and subsequently returning the survey for data analysis and evaluation.
- Expression of lack of time in their work schedule for either holding interviews or completion of the survey by the experts, technical directors, and stakeholders within these organisations.
- Administrative bureaucracies within the organisations posed difficulties in the acquisition of the envisaged data for evaluation.
- Some members of staff expressed fear of divulging the company’s confidential information in the process of completion of the questionnaire.

4.9 Conclusion to study phase II

The analysis of the results showcases 20 factors maintaining severity indices between 93% and 98%. Nonetheless, 31 factors gained severity indices in the range 75–92%. This indicates that 20 factors are perceived by the respondents as being relevant for achieving improved, efficient, and sustainable building construction. Similarly, 31 factors are considered very important characteristics within this case study. Therefore, the respondents’ remarks are based on their degree of severity indices and at 75% and over, these are high. Hence, their level of influence is significant for the building construction industry and these factors should be promoted, with the once exception of the build/maintain as-we-go philosophy. The analysis further indicates the coefficients of variation resulting in 36 factors being in the range of 17–30%. The remaining characteristics gained 31–41% in this respect, signifying a strong degree of agreement in the study on these factors.

Notably, the build/maintain as-we-go philosophy achieving 50% indicates a good degree of concordance from the respondents’ viewpoints, and remains an insignificant factor in building construction practice. In the category ranking, five factors obtained 94–98%. Some factors have overlapping results within the highlighted range although they were placed second. Interestingly, five factors were very exceptional, gaining a category ranking of 98%. These are: (a) the quality of equipment/installation, (b) the sustainability of the building and the design/drawings/envelope/specification, (c) the water recycling technology, (d) energy management through good operating efficiency, and (e) the use of modern technological energy concepts within the building construction industry.

The overall ranking scale recorded: (a) the use of modern technological energy concepts, and (b) the energy management through good operating efficiency. Moreover, (c) the design/drawings/envelope/specification has been identified within the top scale 1st–3rd, while (d) the maintain as-we-go philosophy is found as the least in this class. The research shows a very strong degree of conformity in the respondents’ views concerning the high level of significance of these factors in sustainable building practices.

On this premise, this finding suggested that in recent times, the building construction industry has been making a more progressive impact on the integration of the sustainability model. Also, the utilisation and management of resources in this sector incorporates synergies of new hi-tech measures towards sustainable building construction success. This confirms the situation outlined in the literature, particularly by Miyatake (1996), and Hill and Bowen (1997) on the need to adopt sustainability in building construction projects for the present and future generations (WCED, 1987).

4.10 Comparative analysis between O&M and BCC studies

The research illustrates (in Figures 4.2–4.6), the comparative analysis outcomes between the commercial buildings - (O&M) infrastructure and the building construction companies (BCC) in the UK. Additionally, the graphs of parameter rankings (%) against the identified factors (-) are plotted to examine their level of significance in each case.

4.10.1 Severity indices analysis (SIA)

Severity indices results are shown in Figure 4.2. The O&M respondents' evaluation is not strongly in favour of four characteristics, which scored 50–60%. These characteristics are: (a) the employment of solar panel/photovoltaic technology, (b) the water recycling practice application within the building/facility, (c) the use of grey water technology, and (d) the maintain-as-we-go philosophy approach. On the 60–70% benchmarks, the O&M respondents identified six factors, which are: (a) the use of renewable energy source in the building, (b) the use of efficient water fixtures; sensor flow tap, (c) the installation of automatic shut-off faucets for water conservation, (d) the use of DEFRA standard 2007, (e) the provision of effluent treatment plant, and (f) the variation orders/cost/interference at the execution stages of the building/facility. On the other hand, the BCC respondents' rated one factor within this scale, which being the maintain-as-we-go philosophy approach, in handling building infrastructure challenges. There are strong indications from the respondents' perception that the factors in the 60–70% band have a significant impact in this matter.

The severity index ranking information on the 70–80% score shows the O&M and BCC have achieved 23 and four factors respectively. This result from the O&M is accounted for by: (a) the use of sensor-based lighting systems, and (b) the use of HVAC for energy efficiency and conservation within the buildings. Also in this class, and among other factors are: (c) the installation of modern energy saving accessories, (d) the use of innovative driven concepts, and the (e) complexity of the building/facility. Similarly, factors identified in the BCC scenario include: (a) the use of DEFRA standard 2007 for water management, (b) the provision of effluent treatment plant, and (c) the weather condition. Accordingly, a strong degree of influence is noticed within these factors in concordance with the respondents' views towards the services delivery in building infrastructure systems as shown in Figure 4.2.

Certainly, the O&M and BCC respondents have ranked 18 and 45 factors respectively with the sustainability index scale 80–90% above. On this basis, some of the characteristics appearing from both result trends are: (a) the use of efficient and energy saving fixtures within the building/facility, (b) the prevention of water wastages/losses through leakages in building/facility, and (c) the adoption of preventive maintenance culture.

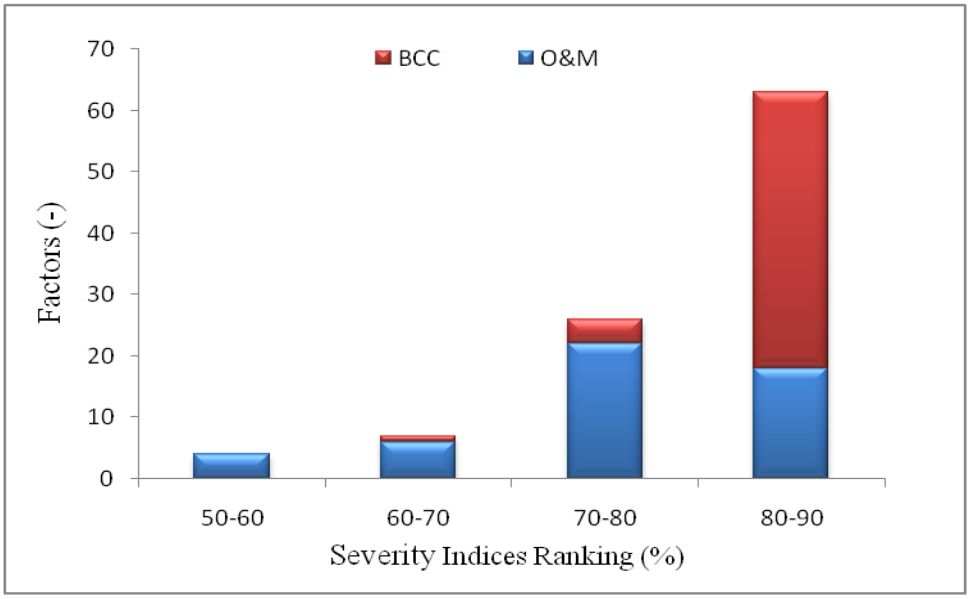


Figure 4.2: Relationship between factors and severity indices ranking

Other factors are (d) the design quality/specification, (e) the implementation of government polices (OHSAS, EMS), and (f) the quality of equipment and installation. The other remaining factors in this group are highly rated and are crucial to this research.

4.10.2 Coefficient of variation (COV) analysis

The result in this phase of the study (Figure 4.3) demonstrates that the O&M and BCC respondents ranked the COV factor as COV 10–20% respectively. However, the O&M respondents proposed four characterises as: (a) the application of energy management through good operating efficiency, (b) the maintenance policy framework,

(c) the use of efficient and energy saving fixtures, and (d) the preventive maintenance culture. These were considered to be the best practices to lead to the achievement of sustainability goals. The BCC respondents identified factors such as: (a) the proper design/drawing/envelope/specification, and (b) the sustainability of the building /facility. This indicates that the characteristics with lower COV strongly encourage sustainability principles in the building infrastructure services delivery as depicted in Figure 4.3.

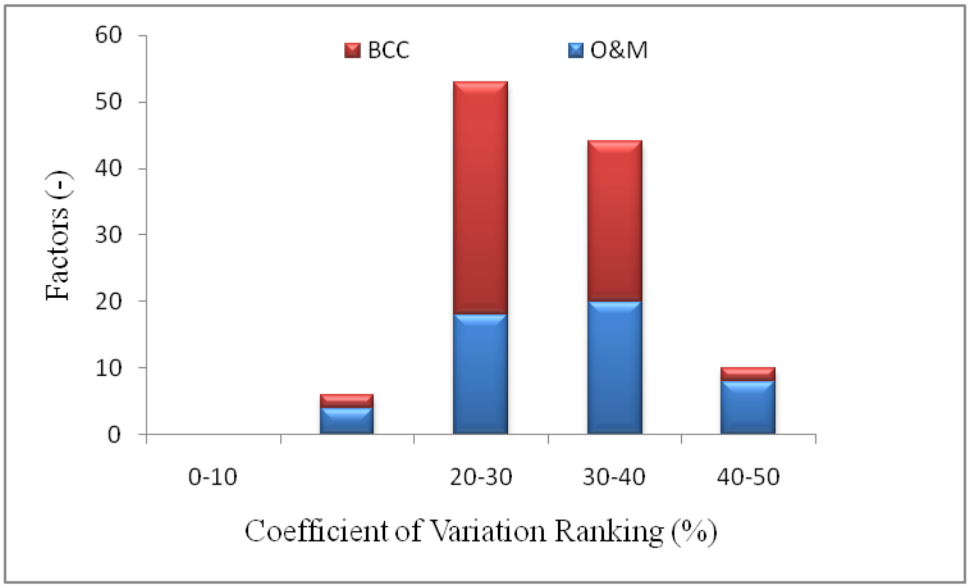


Figure 4.3: Relationship between factors and COV ranking

The COV analysis further expresses the O&M and BCC opinions, achieved 18 and 35 factors with 20–30% marks respectively. Some of the characteristics identified by the O&M respondents are: (a) the use of sensor-based lighting systems for energy/conservation in the building facility (as shown in Figure 4.3), (b) the installation of accessories/dual flush toilet/wireless urinals in building/facility, (c) the corrective maintenance practice, (d) the users' attitude towards the building/facility, and (e) the quality of equipment installation among others. BCC respondents have likewise noted some factors to include: (a) the use of efficient and energy saving fixtures, (b) the prevention of water wastages/losses through leakages in building/facility, (c) the employment of technical/skilful expertise, (d) the accessibility of the building/facility, and (e) the supply performance of the installed equipment. These outcomes express the level of consciousness of the respondents from both scenarios regarding the importance of sustainability success relative to building infrastructure systems goals.

In the COV scale of 30–40%, the O&M and BCC have achieved 20 and 11 factors The O&M respondents indicated characteristics such as: (a) the use of HVAC for energy efficiency/conservation, (b) the educational awareness drive on the sustainable water usage in building/facility, (c) the adoption of innovative driven concepts, (d) the construction method, and (e) the weather condition among others factors in this group. Further analysis shows the BCC respondents indicated characteristics to include: (a) the employment of solar panels/photovoltaic technology, (b) the use of DEFRA standard 2007 for water management, (c) the implementation of corrective maintenance practice, (d) the construction method, and (e) the complexity of building/facility, as shown in Figure 4.3.

There are strong perceptions from the respondents' viewpoints that factors within this benchmark are very significant and the scores are quite reasonable. The COV statistics at 40–50% grades indicate that the O&M and BCC have gained eight and two characteristics respectively. The O&M identifiable factors in this case are: (a) the employment of solar panels/photovoltaic technology, (b) the use of water conservation techniques; grey water in building/facility, (c) the provision of effluent treatment plant, (d) the maintain-as-we-go philosophy, and (d) the grey water conservation technique. BCC respondents have maintained characteristics such as: (a) the maintain-as-we-go philosophy approach, and (b) the weather condition, but these are not encouraged as such. Hence, these factors are either moderately or less significant to the study as illustrated in Figure 4.3.

4.10.3 Category ranking (CR) analysis

In the category ranking evaluation, the O&M respondents produced four factors with a score of 50% as shown in Figure 4.4. These include: (a) the employment of solar panels/photovoltaic technology, (b) the grey water conservation technique, (c) the use of modern technological concepts, water recycling practice in the building/facility, and (d) the maintain-as-we-go philosophy approach. The statistics on the 60% ranking indicate that the O&M respondents have achieved six characteristics, which are: (a) the use of renewable energy sources in the building/facility, (b) the use of efficient water fixtures and sensor flow taps, (c) the installation of automatic shut-off faucets for water conservation in building/facility, (d) the provision of effluent treatment plant, (e) the variation orders/cost/interference, and (f) the use of DEFRA standard 2007 for water management also made this list. However, the BCC respondents only scored one factor in this category, which was the maintain-as-we-go philosophy approach in the execution of building infrastructure. Nonetheless, the result established a very good correlation between the two scores of the different experts in assessing these characteristics as shown in Figure 4.4.

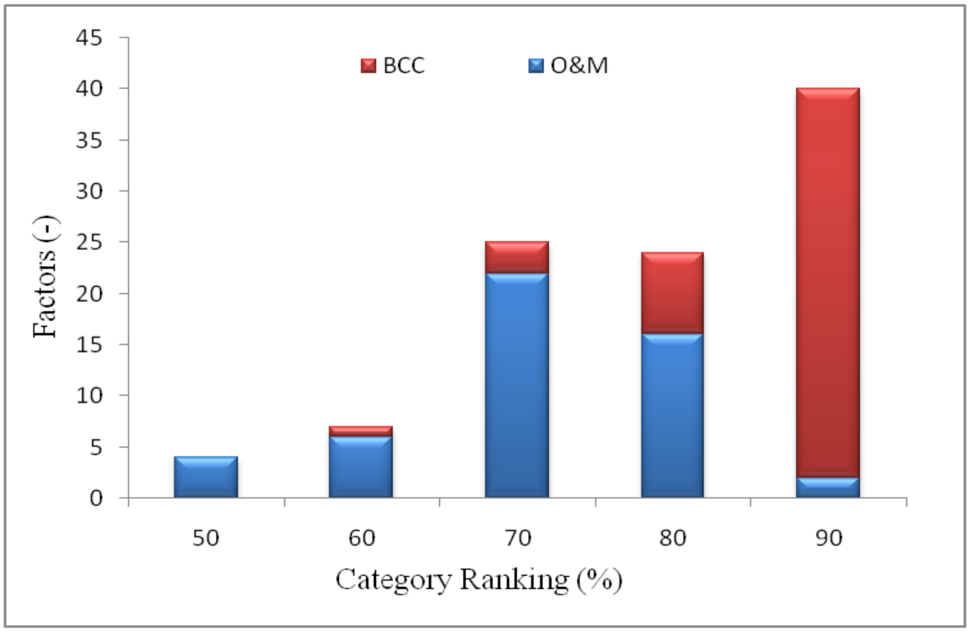


Figure 4.4: Relationship between factors and CR

The O&M respondents were leading on the 70% benchmark with 21 factors. The characteristics among these include: (a) the installation of modern energy saving accessories, (b) the installation of accessories/dual flush toilet/wireless urinals in building /facility, (c) the adoption of innovative driven concepts, (d) the type of building/facility, and (e) the feasibility of the design framework. Similarly, the BCC respondents identified: (a) the use of DEFRA standard 2007 for water management, (b) the provision of effluent treatment plant, and (c) the weather condition, as characteristics within the 70% grade. These results confirm that according to the appraisals of both types of expert, these factors are crucial.

The analysis in Figure 4.4 further explains that the O&M respondents gained 18 factors on the 80% score. Some of these factors are: (a) the use of modern technological (energy) concepts, (b) the prevention of water wastages/losses via leakages in building /facility, (c) the adoption of predictive maintenance practice, (d) the design quality/specification, and (e) the provision of safety equipment in the building/facility. The BCC respondents achieved eight characteristics. Among these are: (a) the installation of automatic shut-off faucets for water conservation in the building/facility, (b) the application of corrective maintenance practice, (c) the variation orders/cost/interference, (d) the structure type, and (e) the availability of safety equipment in the building/facility. This result explains the level of significance between these factors and their role within the building services infrastructure and building construction field.

On the 90% scale, the O&M and BCC respondents have two and 38 characteristics respectively. From the O&M perspective, these factors are: (a) the quality of equipment/installation and, (b) the sustainability of the building. From the BCC viewpoint, the factors include: (a) the use of HVAC for energy efficiency/conservation, (b) the educational awareness drive on the sustainable water usage in the building/facility, (c) the adoption of innovative driven concepts, (d) the construction method, and (e) the installation/design quality/ specification. Accordingly, a strong degree of influence is noticed within these factors in concordance with the views of the respondents from both scenarios. These results further reveal a very high correlation between the scores of the two types of professional in respect of their level of awareness of sustainability concepts. The application of these concepts and the quality of equipment installed with a view towards improving service delivery within the infrastructure systems is explained in Figure 4.4.

4.10.4 Overall ranking (OR) analysis

An examination of the overall ranking was conducted in order to gain a comparison of outcomes from the O&M and BCC companies. In this evaluation, the correlations between the top and bottom marked factors with their overall rankings are illustrated in Figures 4.5 and 4.6.

4.10.5 Top marked factors

Figure 4.5 shows the evaluation of the top marked factors. This became necessary in order to find the most significant characteristics in the study. As a result, the O&M sector in the OR assessment was seen to identify five top marked factors, at approximately 89–91%. The factors include: (a) the availability of safety equipment /installation, (b) the preventive maintenance culture, and (c) the adoption of a team working approach in addressing building services infrastructure problems.

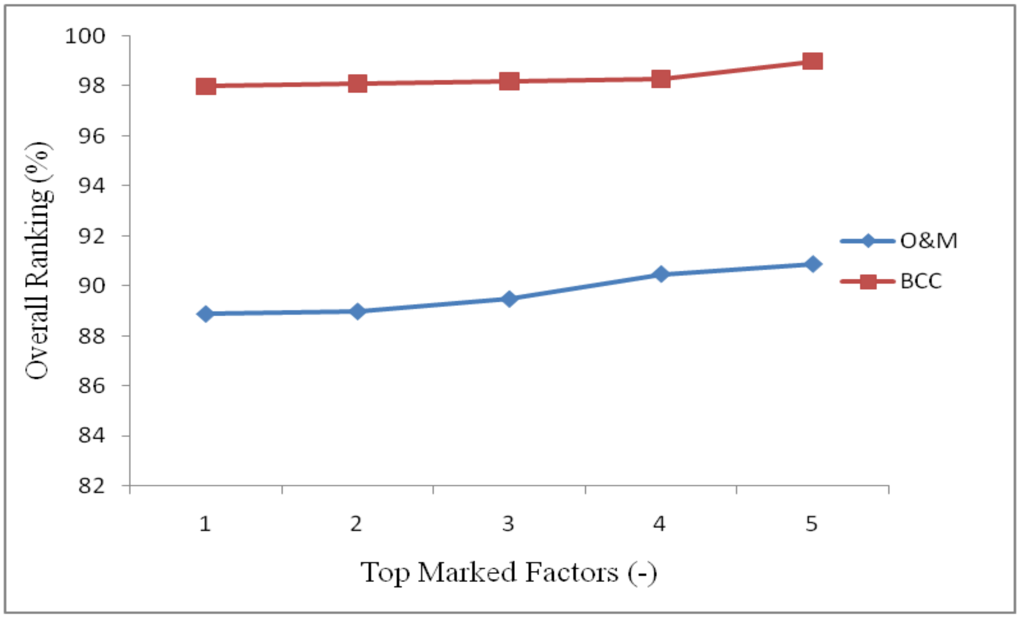


Figure 4.5: Correlation between top marked factors and OR

The group also contains: (d) the quality of equipment/installation, and (e) the sustainability of the building/facility. This expresses the significance of these characteristics and their function in respect of the attainment of sustainable building services infrastructure. Certainly, the factors are considered very significant before other issue regarding the improved performance on this domain. Consequently, the quality of equipment/installation factor also has a crucial role in terms of maximisation of the resources use within the building/facility. On the top scale from the BCC are five characteristics scoring 98–99%. They include: (a) the use of modern technology energy concepts; (b) the energy management through good operating efficiency in building/facility (Figure 4.5); (c) the design/drawings/envelope/specification; (d) the quality of equipment/installation; and (e) the sustainability of the building/facility. The outcomes again emphasised the significance of these characteristics when trying to provide for quality equipment installation in the building/facility. With these features in place, sustainable building services infrastructure delivery can be achieved.

4.10.6 Bottom Marked Factors

The bottom marked factors are depicted in Figure 4.6, from which it is seen that the O&M placed five factors with scores of 67–56% at the bottom. They are: (a) the provision of an effluent treatment plant; (b) the use of efficient water fixtures (the sensor flow taps factor gained overlapping results); (c) the application of the grey water technology; (d) the maintain-as-we-go philosophy approach; and (d) the employment of solar panels/photovoltaic technology in the building/facility. The BCC respondents identified five characteristics with 82–63% as the bottom scores. These factors are: (a) the installation of automatic shut-off faucets for water conservation in building/facility; (b) the use of DEFRA standard 2007 for water management; (c) the weather condition; (d) the provision of effluent treatment plant; and (e) the maintain-as-we-go philosophy approach.

This result demonstrates an overlapping interest between these factors and their level of significance within the building services infrastructure management. In these two sectors, the O&M and BCC experts perceived that these characteristics are either moderately or less significant to the study. The result further identifies that the build/maintain as-we-go philosophy approach in both cases is unacceptable and should be totally avoided if sustainability success is to be achieved (Figure 4.6).

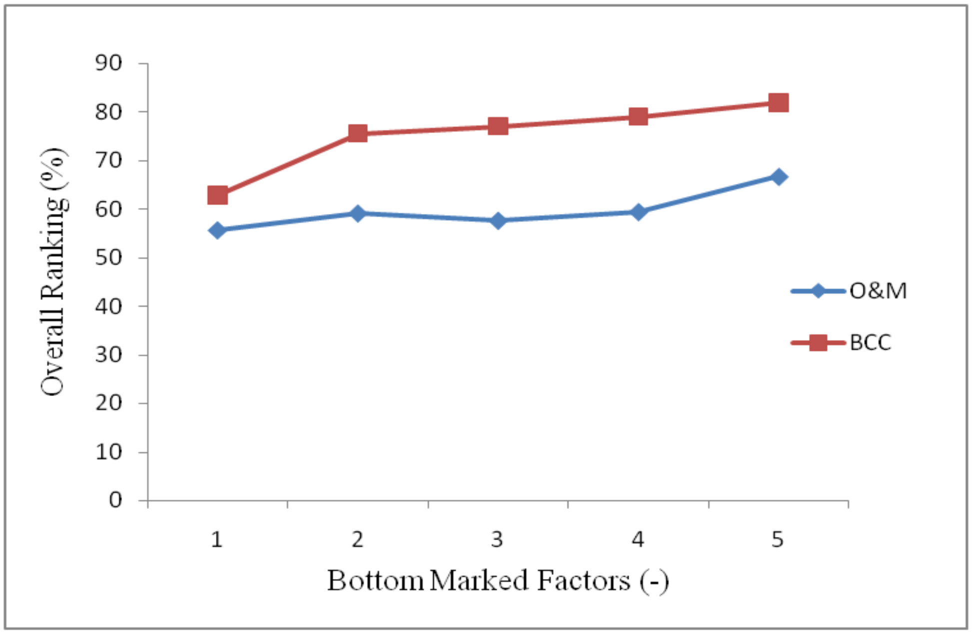


Figure 4.6: Correlation between bottom marked factors and OR.

Notwithstanding, this result is reasonable expressing a very strong degree of agreement between these factors in comparative terms. Also, sustainability is increasingly becoming the watchword for building services infrastructure delivery within building/facilities at large. On this basis, it could be concluded that the research methodology is capable of validating the two phases of the study. This discovery is akin to the views expressed by Hill and Bowen (1997), and Grigg (1988).

4.11 Validating the two phases of study using the SEI model

In validating the two phases of study, the SEI model was applied to determine the level of building infrastructure management performance within these companies. This implies that for the sustainability goals of building services infrastructure systems to be achieved relevant indices must be met. These indices and values of sustainability must be defined and modelled as a set of integrated systems parameters. Hence, the sustainability engineering stand-point should promote rigorous interaction to achieve a balance amongst the components on the triple bottom line of sustainable development.

The SEI model also concentrates on, and normalises sustainability to be within ranges of $0 \leq S_{uv} \leq 1$ by applying the probability (P) theory concept. Thus, accurate and reliable indices of sustainability can be qualified and quantified. On this basis, an ideal project will have the S_{uv} value of 1, although, this is found to be impracticable in the real engineering infrastructure systems context as presented in Section 3.7.3 of this thesis. Hence, for the O&M sector, the probability function of 5/6, 4/5 and 6/7 from the economic, environmental and social values respectively give a S_{uv} factor of 0.54 as the sustainability index result. From the BCC sector, the probability function of 8/9, 6/7 and 7/8 from the economic, environmental and social values correspondingly give a S_{uv} factor of 0.70 as the sustainability index result.

The study contributions from both the O&M and BCC sectors have presented results that could be regarded as the acceptable sustainability indices for the building infrastructure systems performance given the intervening factors of interest.

4.12 Study Phase III: ALSCON Company

4.12.1 Presenting the phase of study

The building services infrastructure characteristics were studied in the Aluminium Smelting Company of Nigeria, ALSCON. The company is located in Ikot Abasi local government area of Akwa Ibom State in Nigeria. ALSCON Company is the major producer of aluminium metal ingots, which are consumed locally within Nigeria and sent for export to other parts of the world. The study objectives related to the company’s maintenance, operation, project managers, and design engineers.

4.12.2 Goal and scope definition

The main goal of the study is to examine and value the building services infrastructure in ALSCON in Nigeria (Section 4.2.2). The services relate to the ALSCON smelting facility, water pumping station, harbour house, power station, and production areas, among other buildings. The goals are specifically targeted at the operations and maintenance stages of the building services infrastructure performance. Water, energy, and the maintenance culture are some of the services addressed with factors leading to effective services delivery and the sustainability of the infrastructure over their life cycle also being appraised.

4.12.3 Results and discussion in study Phase III

In this phase of the study, the results and discussion regarding ALSCON are reported. Statistics from the energy resources management characteristics in study phase III are shown in Table 4.13.

4.12.4 Energy resources management characteristics

Table 4.13 presents 11 factors, showing severity indices ranging from 69–91%. The result shows that these factors have relatively weighty degrees of influence on the building infrastructure systems in terms of costs and building services delivery. About 91% of the respondents strongly agreed with the use of modern technological energy concepts as being crucial, and 87% believed that energy management via good maintenance policy frameworks in buildings/facilities for cost savings is also very significant.

Table 4.13: Energy resources management characteristics

FACTORS	SI	COV	CR	OR
1)Use of efficient and energy saving fixtures	85.7	19.5	3	20
2)Use of modern technological (energy) concepts	90.8	16.6	1	7
Use of sensor based lighting systems for energy/ conservation in building/facility	82.9	22.4	6	25
3)Use of the renewable energy source in building/facility	76.7	33.0	8	37
4)Use of HVAC for energy efficiency/ conservation	70.5	35.9	9	39
5)Employment of solar panels/photovoltaic technology	70.1	34.1	10	40
6)Installation of modern energy saving accessories in building/ facility	78.3	28.2	7	33
7)Energy management via good operating efficiency in buildings /facility	83.7	25.4	5	24
8)Energy management via good maintenance policy framework in building/facility	87.4	20.6	2	15
9)Educational awareness drive on the sustainable energy usage in building/facility	85.4	23.2	4	21
10)Application of building regulation Part L for energy conservation in building/facility	69.0	38.0	11	41

The other remaining characteristics are, however, also important as the least index is almost 70%. The class maintained coefficients of variation ranging between 16% and 38%, which are relatively low and reveal a good level of concordance between the respondents. In this category ranking are 1st–11th. This indicates strong agreement on factors to include: (a) the use of modern technological energy concepts; (b) the energy management via good maintenance policy framework in building/facility; (c) the use of efficient and energy saving fixtures; (d) the application of building regulation part L for energy conservation in building/facility (which was the least ranked among the entire factors).

Although this standard is common practice within the UK and other parts of the world, it is not very important in the Nigerian context. However, the overall rankings are 7th–41st, with the use of modern technological energy concepts leading. Apart from the use of efficient and energy saving fixtures, the other remaining factors are perceived by most respondents as being moderately significant. The overall results are very reliable based on the experts' perception of the investigated characteristics.

4.12.5 Water resources management characteristics

Statistics from the water management characteristics in study phase III are displayed in Table 4.14. This category includes 10 factors, eight of which achieved severity indices within the range 78–91%. This shows these variables have higher degrees of influence and are considered to be of top priority in water resources management delivery. One factor scored a severity index slightly below 70%, that is, (a) the use DEFRA standard 2007 for water resource practice. Findings revealed the entire characteristics are very highly rated from the respondents' feedback.

The category maintained coefficients of variation in the range 18–38% which are relatively low, signifying a strong agreement level between the respondents. Three factors also recorded the coefficient of variation 30–38%, these being: (a) the installation of accessories/dual flush toilet/wireless urinals in building/facility; (b) the use DEFRA standard 2007 for water resource practice; and (c) the educational awareness drive towards sustainable water usage in building/facility. The indication is that these factors are of importance to sustainable water resource management. Moreover, the category rankings are 1st–10th. This points towards a good level of concordance from the respondents standpoint, showing (a) the prevention of water wastages/leakages being the top marked factor. However, (b) the use of DEFRA standard 2007 for water resource practice was classed as the bottom marked characteristic.

Table 4.14: Water resources management characteristics

FACTORS	SI	COV	CR	OR
1)Use of efficient water fixtures, sensor flow taps	89.1	22.7	2	11
2)Use of modern technological concepts; water recycling practice in building/facility	81.8	28.4	4	27
3)Use of water conservation techniques; grey water in building/facility	78.0	29.6	7	35
4)Installation of automatic shut-off faucets for water conservation in building/facility	84.6	25.1	3	23
5)Installation of accessories/dual flush toilet/wireless urinals in building/facility	77.8	31.6	8	36
6)Prevention of water wastage/losses via leakages in the building/facility	90.8	18.6	1	7
7)Achieving DEFRA standard 2007/use of 125 litres of water/head/day in building/facility	68.5	38.5	10	42
8)Educational awareness drive towards sustainable water usage in building/facility	79.2	31.2	6	31
9)Building of On-site/Off-site (sewage) effluent plant in building/facility	81.0	29.0	5	30

The overall ranking category contains one of the top 10 factors - (a) the prevention of water wastages/leakages, showing the belief that it represents a crucial factor in this group. The other remaining characteristics are ranked to show a moderate influence according to the respondents. The results suggest that priority should be given to these factors in the quest for sustainability and improved services delivery within the building infrastructure systems.

4.12.6 Maintenance management practices

Data received from the maintenance management practices in phase III is presented in Table 4.15, which reveals seven factors, six of which achieved severity indices ranging from 88–97% while one obtained only 68%. This presents the belief that a relatively high degree of influence of these factors is brought to bear the maintenance management practice.

Table 4.15: Maintenance management practices

FACTORS	SI	COV	CR	OR
1)Employment of technical /skilful expertise	93.8	14.0	2	3
2)Adoption of team working approach	91.9	17.7	3	5
3)Adoption of innovative driven concepts	90.0	19.1	4	9
4)Predictive maintenance practice	84.6	28.4	6	23
5)Preventive maintenance practice	97.6	9.0	1	1
6)Corrective maintenance practice	88.9	19.7	5	12
7)Maintain as-we-go philosophy	68.4	33.9	7	43

The factor with the least severity index of 68% is the maintain as-we-go philosophy, indicating the respondents perceived this to be insignificant. Indeed, there are indications from the respondents that this factor should be discarded during the planning and policy implementation. The coefficients of variation range of six of the factors are 9–34, confirming that the factors are relatively low, and pointing to strong agreement between respondents in their ranking. Hence, these characteristics are essential in facilitating proper maintenance practices (Table 4.15).

The category ranking list is as follows: (a) the preventive maintenance practice, (b) the employment of technical/skilful expertise in addressing infrastructure systems, (c) the adoption of a team working approach, (d) the implementation of innovative driven concepts. All of these factors were considered as being effective in tackling infrastructure challenges. The maintain as-we-go philosophy was rated least in this group, thus confirming the earlier views of the respondents.

This outcome demonstrates a strong agreement amongst the respondents on the influence and importance of the factors, with the maintain as-we-go philosophy being further confirmed as being the least influential.

4.12.7 Infrastructure design characteristics

Data from the infrastructure design characteristics in study phase III are shown in Table 4.16.

Table 4.16: Infrastructure design characteristics

FACTORS	SI	COV	CR	OR
1)Design/drawings/envelope/specification	92.2	17.9	1	5
2)Feasibility of the design framework	88.3	20.3	5	13
3)Variation orders/cost/interference	91.2	16.3	2	6
4)Design quality/specification	89.2	21.9	4	10
5)Inspection/testing/approval/commissioning	78.1	27.1	6	34
6)Infrastructure/design/planning	90.5	19.1	3	8

Table 4.16 outlines six factors, four of which can be seen as obtaining severity indices ranging from 80–90%. The topmost in this category are: (a) the design/drawings/envelope and specification; (b) the variation orders/cost/interference; and, (c) infrastructure/design/planning. This indicates that these variables have high degrees of influence in the decision-making in infrastructure design characteristics. In addition, the severity index of the remaining factor - the inspection/testing/ approval/commissioning is almost 80%, thereby expressing the fact that its level of influence is also very strong in this situation.

The coefficient of variation is slightly above 16–27%. It is noteworthy that the effects of these factors are low. This suggests that suitable building infrastructure design characteristics should be tailored towards effective services delivery and that a just-in-time maintenance culture should be promoted. Additionally, proper design for the installation of quality equipment is suggested.

In the category ranking, the top ranked factors comprise: (a) the design/drawings envelope/specification, and, (b) the variation orders/cost/interference as first and second respectively. These factors are considered to be of high value, although the other remaining factors are equally significant. In the overall ranking scale, three factors came top, these being: (a) the design/drawings/envelope/specification; (b) the variation orders/cost/interference; and, (c) the infrastructure/design/planning. There is no doubt that these infrastructure characteristics are crucial to the study as their rankings are evident in all the four stages of examination as shown in Table 4.16.

Accordingly, it could be suggested that the remaining factors are considered as being expensive, time-consuming and more complex to implement in this scenario. On this basis, it could be adduced that the achievable results are reliable indications of the respondents’ perspectives regarding infrastructure system management goals.

4.12.8 Infrastructure project characteristics

The infrastructure project characteristics information in study phase III is illustrated in Table 4.17, which indicates ten factors and their analysis. The severity indices range is approximately 80–94%. Eight characteristics achieved very top marks and the top three of these are: (a) the quality of finish; (b) the site topography/location; (c) the structure type. Two factors obtained the bottom scores, these being the type of building, and the height and number of storeys. That said, the respondents believed that all the factors had a very strong influence in managing building services infrastructure project activities.

Table 4.17: Infrastructure project characteristics

FACTORS	SI	COV	CR	OR
1)Type of building/facility / industrial/ residential/ commercial/ offices	78.8	29.2	9	32
2)Size of building/facility area	81.5	23.3	8	29
3)Height/number of stories	77.8	24.6	10	36
4)Complexity of building/facility	81.6	29.2	7	28
5)Structure type (steel, brick etc)	86.8	19.5	4	17
6)Construction method/technology	87.7	21.2	3	14
7)Accessibility to the building/facility	86.3	21.6	5.5	18
8)Intensity/complexity of the building/facility	86.3	24.1	5.5	18
9)Site topography/location	88.9	20.4	2	12
10)Quality of finishing	93.5	15.6	1	4

On the coefficient of variation appraisal, all the factors are in the range 16–29%, showing that they all have an important impact on the building infrastructure systems and construction generally. Two characteristics gained the topmost and similar outcomes and were: (a) the height/number of storeys, and (b) the complexity of building/facility. The quality of finish scored the least. These results demonstrate a good level of concordance among respondents on the influencing factors in terms of the sustainable building construction projects characteristics. The category ranking contains four of the top 10 factors ranked 1st–4th. These factors are: (a) the quality of finish, (b) the site topography/location, (c) the construction methods, and (d) the structure type (Table 4.17). This again demonstrated the strong degree of agreement between the respondents in their ranking of these factors. On the top of the overall ranking scale, was the quality of finish, whereas the other remaining factors were not highly rated.

These outcomes represent the experts' opinions regarding the building infrastructure project characteristics implementation.

4.12.9 External factors affecting SIM

Information received concerning the external factors affecting SIM in phase III is shown in Table 4.18.

Table 4.18: External factors affecting SIM

FACTORS	SI	COV	CR	OR
1)Users' attitude towards the building/facility	87.2	23.3	2	16
2)Availability of safety equipment/fume extractors installation	86.0	24.3	3	19
3)Supply performance	82.5	22.2	6	26
4)Weather condition	79.2	26.4	7	31
5)Government policies (OHSAS, EMS)	82.9	24.0	5	25
6)Quality of equipment/installation	85.2	13.3	4	22
7)Sustainability of the building/facility	94.4	19.4	1	2

The study in Table 4.18 presents seven characteristics, with severity indices in the range of 80–94%. In this category: (a) the sustainability of the building/facility, and (b) the users' attitude towards the building services infrastructure were perceived by most respondents as being very significant. Also (c) the availability of safety equipment, and (d) the quality of equipment/installation were rated highly. The indication is that these factors are paramount in the building services infrastructure success. On the coefficient of variation analysis, all results are in the range 13–26%.

Topmost in this group include: (a) weather condition, (b) the availability of safety equipment, and (c) the implementation of government regulated polices. Accordingly, the least scores went to the following factors: (a) the quality of equipment/installation, and (b) the sustainability of the building/facility. This result is reasonable because the respondents' accorded priority to these factors based on their experience on the infrastructure management.

The category ranking reveals three factors at the top, these being: (a) the sustainability of the building/facility; (b) the users' attitude towards the building; and (c) the availability of safety equipment installation. The weather condition achieved the lowest evaluation as the respondents from the company considered it insignificant given that in Akwa Ibom State, Nigeria, the temperature remains stable, being on average, 15 degrees Celsius throughout the year. Therefore, this factor does not really have much impact on the investigated scenario.

However, whilst the overall ranking for the weather condition was not found to be significant, the respondents did observe that the rainfall may be problematic. In most cases, heavy rainfall occurs between the months of May and August, and this is likely to affect the pace of construction activities. However, the other remaining characteristics in this class achieved moderate rating, all being of equal significance.

4.13 Study Phase IV: MPN Unlimited

4.13.1 Presenting the phase of study

A case study regarding the building services infrastructure characteristics was undertaken in the oil and gas sector, using Mobil Producing Nigeria (MPN) as the company for investigation. This company has facilities (platforms) located in Eket and Ibeno local government areas in Akwa Ibom State, Nigeria. MPN is involved in oil and gas exploration and has several facilities (platforms) situated on land and at sea. The study sites involved both on and off-shore oil facilities within the company's operational base. The individuals targeted by the survey were the maintenance, operation, and project managers, and the design engineers, among others.

4.13.2 Goal and scope definition

The main purpose of the study was to analyse and value the MPN Nigeria facility as indicated in Section 4.2.2. The goals were mainly to address the operation and maintenance stages of the building services infrastructure performance within the company. Therefore, the building services infrastructure operations such as water, energy, heating, maintenance culture and the ancillary activities at these stages were measured in the study. Furthermore, the features leading to effective services delivery and the sustainability of the infrastructure over their life cycle were assessed.

4.13.3 Results and discussion in study phase IV

The results and discussion from this phase of study are presented.

4.13.4 Energy resources management characteristics

The energy management resources characteristics data within study phase IV are shown in Table 4.19, which shows that 11 factors were explored. High severity indices ranging from 61–79% were obtained, with the top marked factors being: (a) the energy management through good maintenance policy framework, and (b) the energy management via good operating efficiency in building/facility. The inventory also includes: (c) the educational awareness drive on the sustainable energy usage, and (d) the use of modern technological energy concepts, among other factors.

These ranges verify that the variables have a wide-ranging degree of influence on the operation and maintenance of the building services infrastructure delivery. The bottom marked factor with the severity index of 61% was: (e) the use of renewable energy sources in the building/facility. Obviously, the result is logical because this innovative concept is not commonly practised in Nigeria, as confirmed by the respondents.

The class in Table 4.19 also maintained coefficients of variation about 30–42%, which are relatively low and state a good conformity level between the respondents' opinions. The two topmost characteristics are: (a) the application of building regulation part L for energy conservation; and (b) the use of renewable energy sources in the building/facility.

Table 4.19: Energy resources management characteristics

FACTORS	SI	COV	CR	OR
1)Use of efficient and energy saving fixtures	68.9	31.0	9	33
2)Use of modern technological (energy) concepts	77.4	36.9	3	21
3)Use of sensor based lighting systems for energy/conservation in building/facility	72.0	29.5	6	29
4)Use of the renewable energy source in building/facility	61.1	40.7	11	36
5)Use of HVAC for energy efficiency/ conservation	71.4	32.7	7	30
6)Employment of solar panels/photovoltaic technology	66.7	37.4	10	35
7)Installation of modern energy saving accessories in building facility	73.6	32.9	5	26
8)Energy management via good operating efficiency in buildings /facility	78.5	33.9	2	18
9)Energy management via good maintenance policy framework in building/facility	78.9	35.9	1	17
10)Educational awareness drive on the sustainable energy usage in building/facility	76.2	34.9	4	24
11)Application of building regulation Part L for energy conservation in building/facility	70.7	41.6	8	31

The bottom scale comprises: (c) the use of sensor-based lighting systems; and (d) the application of efficient and energy saving fixtures within the building/facility. The result is consistent because some respondents within the company expressed lack of knowledge regarding the use of part L standard of practice in energy management.

Category ranking information also emphasised: (a) the energy management through good maintenance policy framework; and (b) the energy management via good operating efficiency in building/facility. At the same time: (c) the use of modern technological energy concepts; and (d) the educational awareness drive on the sustainable energy usage were maintained as crucial On the other hand, the lowest in this category was: (a) the use of renewable energy source; and (b) the employment of solar panels photovoltaic technology in the building/facility. The interpretation to be made from these outcomes is that the models discussed are not commonplace in this company. In the overall ranking assessment, all the factors are 17th–36th. Energy management through a good maintenance policy framework and operating efficiency infacilities is regarded as essential, but the other remaining factors are less, important.

4.13.5 Water resources management characteristics

Information received concerning the water management resources characteristics in study phase IV is presented in Table 4.20.

Table 4.20: Water resources management characteristics

FACTORS	SI	COV	CR	OR
1)Use of efficient water fixtures, sensor flow taps	79.0	30.2	2	16
2)Use of modern technological concepts; water recycling practice in building/facility	69.9	41.5	8	32
3)Use of water conservation techniques; grey water in building/facility	72.4	37.0	7	28
4)Installation of automatic shut-off faucets for water conservation in building/facility	78.9	32.3	3	17
5)Installation of accessories/dual flush toilet/wireless urinals in building/facility	72.8	38.2	6	27
6)Prevention of water wastage/losses via leakages in the building/facility	80.5	30.4	1	15
7)Achieving DEFRA standard 2007/use of 125 litres of water/head/day in building/facility	68.2	38.4	9	34
8)Educational awareness drive towards sustainable water usage in building/facility	76.5	31.5	4	23
9)Building of On-site/Off-site (sewage) effluent plant in building/facility	73.8	35.5	5	25

Table 4.20 indicates nine factors associated with the sustainable water resources management, with severity indices between 68% and 81%. Prevention of water wastage/losses through leakages in the building/facility gained a severity index 81%. This is followed by: (a) the use of efficient water fixtures (sensor flow taps); and (b) the installation of automatic shut-off faucets in the company buildings. On the whole, the other remaining characteristics are very strongly considered as important by the respondents in view of this evaluation. Also, the coefficient of variance shows a range of 30–42%, signifying strong agreement among the respondents in their appraisal of these factors. Specifically, they see the necessity for: (a) the prevention of water wastage/losses through leakages in the building/facility, and the use of water recycling technology; (b) the use of efficient water fixtures (sensor flow taps); and (c) the installation of dual flush toilet accessories as the best practice.

In the category ranking, the results are 1st–9th. The prevention of water wastage/ losses through leakages in the building/facility leads in the overall rating, and is followed by: the use of efficient water fixtures (sensor flow taps), and the installation of automatic shut-off faucets within the company facility. The use of DEFRA standard 2007 attained the lowest score. The respondents maintained that the practice is not very common within the area of study, as shown in Table 4.20. The overall ranking was 15th-34th, thereby indicating strong agreement on factors such as: (a) the prevention of water wastage/losses through leakages; (b) the use of efficient water fixtures; and (c) the installation of automatic shut-off faucets in the company facility, since these practices were believed to promote effective building services success.

The lowest mark was awarded to: (a) the application of DEFRA standard 2007 procedure factor, which is not surprising given that the respondents confirmed this as an unusual company practice in respect of buildings (facilities) management.

4.13.6 Maintenance management practices

The maintenance management practices data in study phase IV are shown in Table 4.21.

Table 4.21: Maintenance management practices

FACTORS	SI	COV	CR	OR
1)Employment of technical/skilful expertise	89.8	18.4	1	4
2)Adoption of team working approach	84.4	24.5	4	10
3)Adoption of innovative driven concepts	77.4	32.2	5	21
4)Predictive maintenance practice	85.6	24.0	3	9
5)Preventive maintenance practice	87.8	23.0	2	6
6)Corrective maintenance practice	83.9	29.3	6	11
7)Maintain as-we-go philosophy	68.9	39.6	7	33

The study showcases seven factors (Table 4.21) with severity indices in the range of 69–90% for all the factors. The leading characteristics are: (a) the employment of technical/skilful expertise, and (b) the application of preventive maintenance culture in handling infrastructure challenges. Apart from these two factors, (c) the adoption of predictive maintenance practice, is also perceived by most respondents as achieving greater impact. The only characteristic with less influence within this category is the maintain-as-we-go philosophy. Statistics concerning the coefficient of variation demonstrate that the variables are in the range 18–40%. Whilst the scores are very small comparatively, this indicates a good concordance level between the respondents in ranking these characteristics.

Specifically, the most favoured coefficient of variation factors are: (a) the employment of technical/skilful expertise, and (b) the preventive maintenance culture. The maintain-as-we-go philosophy is not strongly supported in this case, essentially not being encouraged within the company in the quest for sustainable building services infrastructure. In respect of the category ranking, (a) the employment of technical/skilful expertise, and (b) the application of preventive maintenance culture are highlighted. Also, included in this category are: (c) the adoption of predictive maintenance practice; and (d) the adoption of a team working approach. The maintain-as-we-go philosophy was again reflected as a minor factor in the study.

The overall ranking of the group presents three characteristics gaining the topmost impacts (Table 4.21). They are: (a) the employment of technical/skilful expertise; (b) the application of preventive maintenance culture; and (c) the adoption of predictive maintenance practice in managing infrastructure systems. The result is reasonable as the incorporation of these measures will make the infrastructure network sustainable and reliable over the life cycle of the network.

4.13.7 Infrastructure design characteristics

The infrastructure design characteristics information in study phase IV is highlighted in Table 4.22.

Table 4.22: Infrastructure design characteristics

FACTORS	SI	COV	CR	OR
1)Design/drawings/envelope/specification	86.2	28.3	4.5	8
2)Feasibility of the design framework	88.5	23.1	3	5
3)Variation orders/cost/interference	90.8	19.4	1	2
4)Design quality/specification	90.5	22.1	2	3
5)Inspection/testing/approval/commissioning	81.0	26.1	6	14
6)Infrastructure/design/planning	86.2	26.4	4.5	8

The six factors analysed demonstrated severity indices ranging between 81% and 91%. The top marked factors are: (a) the variation orders/cost/interference; (b) the quality/specification; and (c) the feasibility of the design framework. In reality, the other remaining characteristics gained higher marks. This is an expression of consistency on the respondents in assessing these factors. The coefficient of variation is in the range 19–28%. Notably, the influence of these factors is very low. Consequently, the experts believe that building services infrastructure design should address the need for successful services delivery, and therefore, encourage the efficient installation of equipment, and a just-in-time maintenance culture.

The category ranking statistics showed the three top factors as being: (a) the variation orders/cost/interference; (b) the design quality/specification; and (c) feasibility of the design framework. Also, in this class are: (d) the design/drawings/envelope with specification; and (e) the infrastructure/design/planning, both of which achieved overlapping results. Inspection/testing/approval/commissioning gained the least score in the category ranking evaluation. The overall ranking analysis indicates three factors coming top with: (a) the variation orders/cost/interference; (b) the quality/specification; and (c) the feasibility of the design framework, occupying these positions. The outcome in the overall raking appraisal is a true reflection of the category ranking as contained in Table 4.22. This result is reliable, confirming a strong degree of concordance from the respondents in the study.

4.13.8 Infrastructure project characteristics

In this study, the infrastructure project characteristics record in phase IV is presented in Table 4.23. This result accounts for the investigation of 10 characteristics, with severity indices ranging from 77–84%. The result shows that these factors have relatively weighty degrees of influence on building infrastructure project management in terms of cost and service delivery. In addition, 84% of the respondents strongly concur with: (a) the intensity/complexity; and (b) the quality of finishing of the building/facility as significant factors.

Similarly: (a) the construction methods/technology; (b) the accessibility to the building; and (c) site topography/location gained approximately 83%. The other remaining factors results are far greater than 70%.

Table 4.23: Infrastructure project characteristics

FACTORS	SI	COV	CR	OR
1)Type of building/facility/industrial/residential/ commercial/offices/other	78.2	32.2	4.5	19
2)Size of building/facility area	76.7	34.1	7.5	22
3)Height/number of stories	78.2	32.1	4.5	19
4)Complexity of building/facility	76.7	25.5	7.5	22
5)Structure type (steel, brick etc)	77.8	29.7	6	20
6)Construction method/technology	82.8	25.2	3	12
7)Accessibility to the building/facility	82.8	24.4	3	12
8)Intensity/complexity of the building/facility	83.9	25.8	1.5	11
9)Site topography/location	82.8	26.9	3	12
10)Quality of finishing	83.9	24.3	1.5	11

This shows a good level of agreement from the respondents regarding the impacts of these characteristics towards the success of building services infrastructure delivery. Also, in the coefficient of variance records are 24 – 34%. The trend of the result is declining signifying a strong agreement from the respondents in their assessment concerning these factors. The group maintained: (a) the size of building/facility area; (b) the type; and, (c) the height of building are highly rated. But, less emphasis was attached to (d) the quality of finish the building/facility.

In this category the ranking range is 3rd–7th, indicating strong agreement on factors to include: (a) the intensity/complexity; (b) the quality of finishing of the building/facility; (c) the construction methods /technology; (d) the accessibility to the building; and (e) the site topography/location of the building/facility. The other remaining factors in this class gained corresponding results. The overall rankings are 11th–22nd with: (a) the intensity/complexity, and (b) the quality of finishing in the building/facility having the same results. Three factors in this group had overlapping results, these being: (c) the construction methods/technology, (d) the accessibility to the building, and (e) the site topography/location of the building/facility.

The bottom marked factors in this case are: (f) the size, and (g) the complexity of the building/facility (Table 4.23). Most respondents perceived the top marked characteristics as being significant and the bottom group as less significant. This is because the most significant named factors are crucial for building services operations, whereas, the less significant factors are sometimes regarded as being hard to envisage in the execution of infrastructure systems project activities.

4.13.9 External factors affecting SIM

Data related to the external factors affecting SIM in study phase IV are presented in Table 4.24.

Table 4.24: External factors affecting SIM

FACTORS	SI	COV	CR	OR
1)Users' attitude towards the building/facility	85.6	25.9	4	9
2)Availability of safety equipment/fume extractors installation	81.6	28.8	7	13
3)Supply performance	85.1	22.4	5	10
4)Weather condition	86.2	23.1	3	8
5)Government policies (OHSAS, EMS)	86.7	22.4	2	7
6)Quality of equipment/installation	84.4	22.1	6	10
7)Sustainability of the building/facility	93.3	14.5	1	1

The data comprises seven factors with severity indices in the range of 80–90%. In this group the top rated are: (a) the sustainability of the building/facility; (b) the implementation of government policies; and (c) the weather condition factors. In the lowest score band is: (d) the availability and installation of safety equipment within the building/facility. The respondents contend that the other remaining characteristics are equally significant. In the coefficient of variation analysis, all results are within the range 15–29%. Uppermost in this group are: (a) the availability and installation of safety equipment, (b) the users' attitude towards the building/facility, and (c) the weather conditions.

The lowest grade is achieved by: (d) the sustainability of the building/facility. A consistent and strong agreement in ranking has been established by the respondents in this assessment. The results are reasonably low and declare a good conformity level between the respondents.

The category ranking test discloses three topmost factors. They include: (a) the sustainability of the building/facility; (b) the implementation of government policies; and (c) the weather condition. The lowest grades within this class are: (d) the availability of safety equipment; and (e) the quality of equipment/installation. This presents the respondents' perception that these factors, especially the lowest grades, have little influence. The topmost survey results in the overall ranking are: (a) the sustainability of the building/facility; (b) the implementation of government policies; and (c) the weather condition factors, as shown in Table 4.24.

The lowest marks within this category relate to: (d) the availability and installation of safety equipment; (e) supply performance; and (f) the quality equipment/installation characteristics. The findings reveal the sustainability of the building/facility is rated first by the respondents in the overall ranking analysis, thereby demonstrating the perceived importance of achieving sustainable building infrastructure in the company's services delivery.

4.14 Comparative analysis study between ALSCON and MPN

A comparative study was conducted between the ALSCON and MPN organisations. This was aimed at appraising the severity indices, coefficients of variation, category and the overall rankings results. Details of the results in this perspective are illustrated in Figures 4.7–4.11.

4.14.1 Severity indices analysis (SIA)

The comparison of the severity indices shows a very high correlation between the two companies, with a 60–70% interval group, as illustrated in Figure 4.7. The ratings from the ALSCON respondents show that they are not in support of three factors in this band, which are: (a) the application of building regulation part L for energy conservation in building/facility; (b) the use DEFRA standard 2007 for water resource practice; and (c) the maintain as-we-go philosophy. The indication is that these factors are either moderately or less significant in achieving sustainable building services infrastructure. The MPN respondents perceived six factors as not being very commonly practised in their company. They are: (a) the use of renewable energy sources; (b) the employment of solar panels photovoltaic technology; (c) the water recycling practice inside the building/facility; (d) the DEFRA standard 2007 for water resource practice; (e) the use of renewable energy source; and (f) the installation of energy saving devices. These perceptions could be interpreted as indicating a low level of sustainability awareness and its application within the two organisations regarding these characteristics. Furthermore, the benefits to be derived from sustainable building infrastructure services delivery may not have been fully understood by the two companies (Figure 4.7).

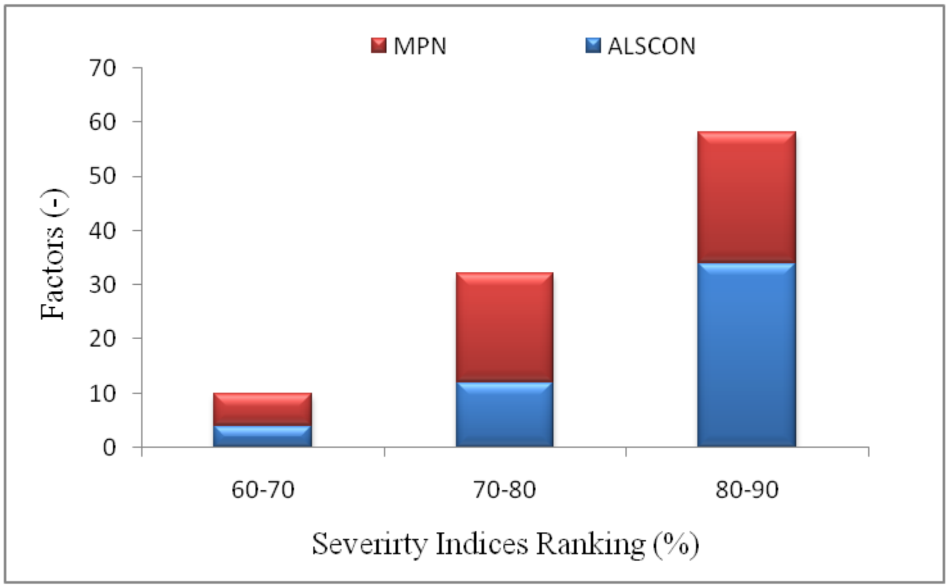


Figure 4.7: Relationship between factors and severity indices ranking

Evidently, the ALSCON and MPN respondents ranked 13 and 20 factors respectively with the severity indices ranging between 70–80%. Among the list of these characteristics in both companies are: (a) the installation of modern energy saving accessories, and (b) the use of HVAC for energy efficiency and conservation within the buildings. The inventory also consists of: (c) the installation of dual flush toilet/wireless urinals; (d) the building type; and (e) the adoption of innovative driven concepts in managing the infrastructure systems.

This outcome is consistent with high ratings from the respondents and expresses the significance of the highlighted factors concerning the infrastructure services delivery. Interestingly, the ALSCON and MPN respondents have further ranked 34 and 24 factors correspondingly with severity indices ranging between 80–90% (Figure 4.7). Some of these factors are: (a) the prevention of water wastage/losses through leakage; and (b) the installation of automatic shut-off faucets for water conservation within the facilities.

The list also includes: (c) the employment of technical/skilful expertise; (d) the design/drawing/envelope/specification; and (e) the quality of finishing among others. The result reflects the fact that the other remaining factors in this group are strongly encouraged for implementation in the quest to achieve sustainability goals. On the whole, the respondents in both companies scored more than 40 factors in the range of 70–90% benchmark. In relative terms, the ALSCON organisation is taking the lead in the severity indices appraisal. This result demonstrates a very high correlation in the respondents' views regarding the influence of these characteristics in attempting to achieve sustainable infrastructure management.

4.14.2 Coefficient of variation (COV) analysis

Information concerning the comparison of COV results is indicated in Figure 4.8. The preventive maintenance practice factor received 9% from the ALSCON respondents within the benchmark 0–10%. The ALSCON and MPN respondents rated 14 and 3 factors respectively within the COV range 10–20%. The most common characteristics within this band in both companies are: (a) the employment of technical/skilled expertise in handling maintenance challenges; (b) the variation orders/cost/interference; and (c) the sustainability of the building/facility. The other non-listed factors in this class all achieved equally lower COV.

The outcome suggests that the factors in the lower band strongly encourage the sustainability ethics in the direction of building services infrastructure delivery. In the

20–30% COV group, the ALSCON and MPN respondents scored 26 and 23 characteristics respectively. A further impression is that some of these factors from the two scenarios are: (a) the use of sensor-based lighting systems for energy/conservation in the building/facility, (b) the adoption of predictive maintenance practice, and (c) the design quality/specification characteristics. Additionally, (d) the construction method/technology; and (e) the supply performance of equipment, are strongly supported by the two scores of the respondents,

The COV analysis in Figure 4.8 also emphasises the ALSCON and MPN respondents' ratings of 9 and 24 in characteristics respectively within the band of 30–40%. The set of factors in this band are: (a) the application of building regulation part L for energy conservation; and (b) the employment of solar panel technology in the facility.

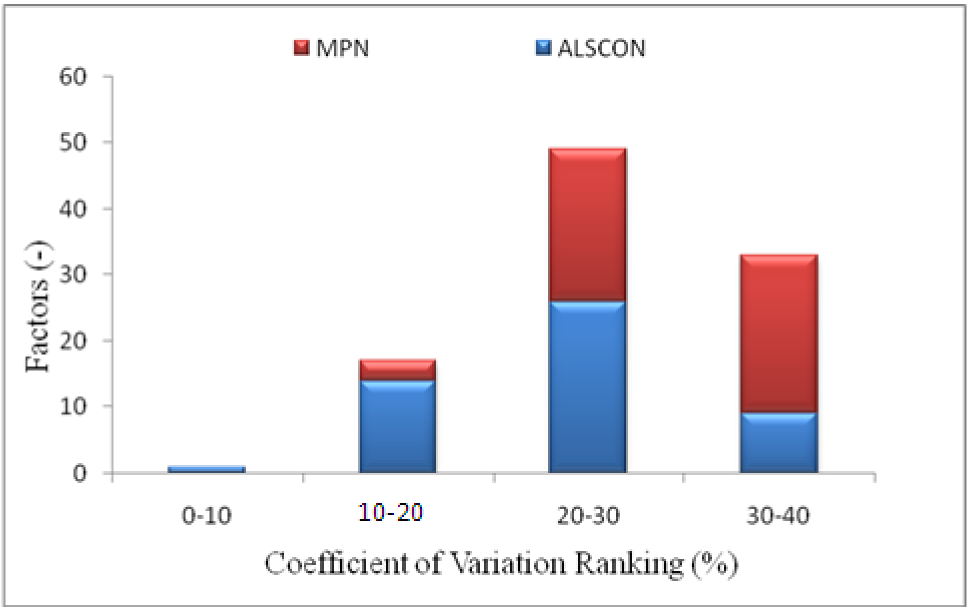


Figure 4.8: Relationship between factors and COV ranking

Moreover, the list contains: (c) the use of DEFRA standard 2007; (d) the maintain-as-we-go philosophy; and (e) the size/complexity of the building/facility among others. Apparently, the highlighted characteristics overlap in both cases' evaluations. Therefore, the lowest COV benchmark results of 10–30% give a very significant degree of correlation among the factor grouping. This outcome indicates that the ALSCON organisation is more sustainability conscious in managing its building services infrastructure systems than the MPN organisation.

4.14.3 Category ranking (CR) analysis

The category ranking examination in Figure 4.9 presents four sets of results 60–90%. In the 60% class, the ALSCON and MPN respondents' ratings are of three and seven characteristics correspondingly. These factors among others include: (a) the application of building services regulation part L for energy conservation; (b) the use of DEFRA standard 2007; (c) the maintain-as-we-go philosophy; (d) the use of energy saving fixtures; and (e) the employment of solar panel technology within the building/facility among other remaining characteristics. On the 70% benchmark are 11 and 20 factors from the ALSCON and MPN respondents' scores respectively.

The overlapping factors are: (a) the use of renewable energy concept; (b) the installation of dual flush toilet/wireless urinals; (c) the size of the building/facility area; (d) the educational awareness drive towards sustainable water usage; and (e) the employment of innovative driven concept among others. The outcome shows these factors are very significant to the aim of study as rated by the respondents and shown in Figure 4.9.

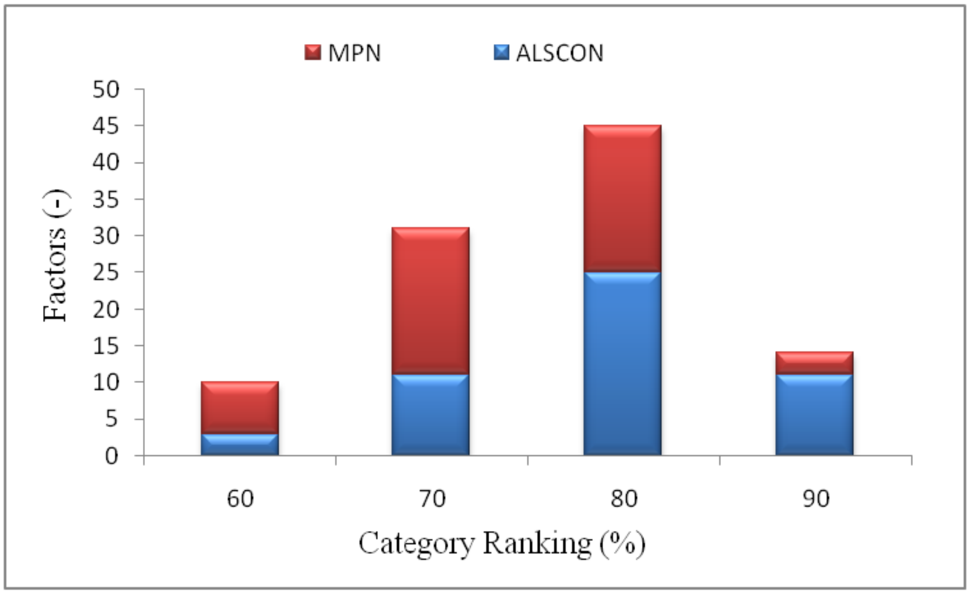


Figure 4.9: Relationship between factors and CR.

The result trend on 80% CR demonstrates that the ALSCON and MPN respondents' marks are correspondingly 25 and 20 factors. This explains the degree of significance of these characteristics. They include: (a) the feasibility of the design framework; (b) the construction method; (c) accessibility; and (d) the complexity of the building/facility. Within this band also are: (e) the users' attitude towards the building; (f) the availability of safety equipment; (g) the supply performance; and (h) the implementation of government policies, among others in this class. In the 90% group, the ALSCON and MPN respondents' grades are respectively 11 and 3 factors (Figure 4.9). The topmost characteristics in each case are: (a) the implementation of predictive maintenance culture; (b) achieving the sustainability of the building; and (c) the employment of skilful/technical expertise.

These key factors are strongly regarded by the ALSCON respondents among others in this band. Also, the MPN respondents have maintained these factors as crucial to this study indicating that they are within the most significant characteristics. They include: (a) achieving the sustainability of the building; (b) the variation orders/cost/interference; and, (c) the design quality/specification. This reveals a very strong degree of agreement between these factors in comparison. The sustainability of the building services infrastructure is considered as a very significant factor from the two scores of respondents. Therefore, this stresses the benefits of the concept of sustainability regarding improved services delivery on building services infrastructure generally.

4.14.4 Overall ranking (OR) analysis

The overall ranking test was conducted to achieve a comparison between the ALSCON and MPN companies. In this appraisal, the correlations between the top and bottom marked factors with their overall rankings are depicted in Figures 4.10 and 4.11.

4.14.5 Top marked factors

Figure 4.10 presents the top marked characteristics and the overall ranking results. The ALSCON organisation in the OR evaluation identified five top marked factors at approximately 92–98%. These factors are: (a) the implementation of suitable design /drawings/envelope/specification; (b) achieving the sustainability of the building; and

(c) the employment of technical/skilful expertise in handling building infrastructure challenges. Also, in this category are: (d) the quality of finishing; and (e) preventive maintenance practice, which are regarded as very significant within the company's policies. The MPN organisation contends that five characteristics are within the band 89–93%. The factors include: (a) the feasibility of the design framework; (b) the employment of technical/skilful expertise; (c) the design/drawings/envelope with specification; (d) the variation orders/cost/interference; and (e) the sustainability of building services infrastructure. These characteristics are crucial to the company policy thrust in projects execution (Figure 4.10).

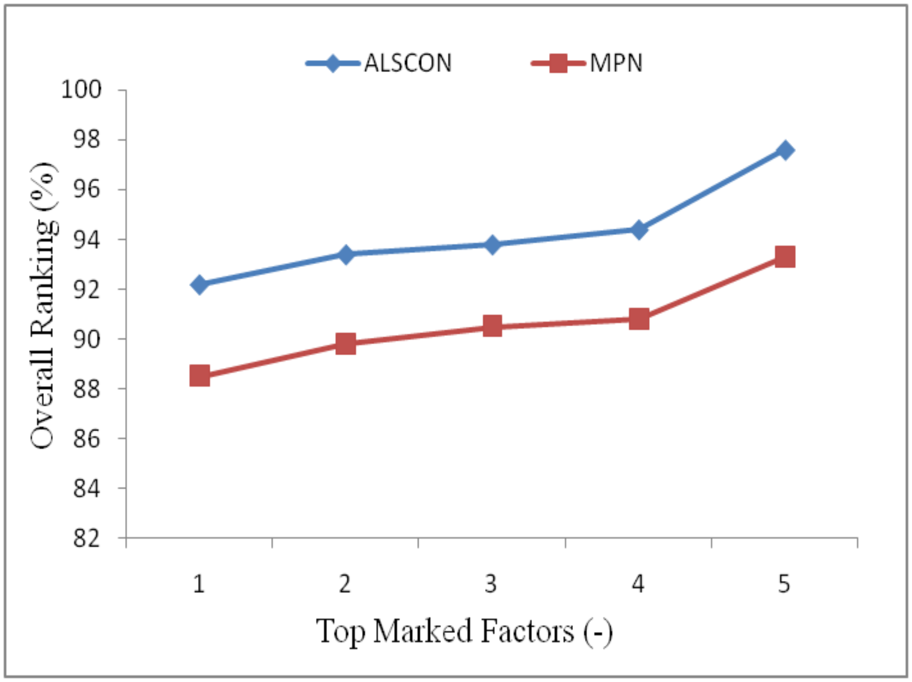


Figure 4.10: Correlation between top marked factors and OR

The ratings within these companies are completely logical. They imply that: (a) the sustainability of the building infrastructure; and (b) the employment of technical/skilful expertise play a very significant role within these companies. Also, the study has established (c) the implementation of suitable design/drawings/envelope/specification as a crucial factor in achieving improved building services infrastructure systems.

4.14.6 Bottom marked factors

The result in Figure 4.11 illustrates the bottom marked factors and the overall ranking for the study phase III–IV. In this scenario, the ALSCON organisation in the OR assessment has recognised four bottom marked factors in the range 68–70%. They include: (a) the employment of solar panels/photovoltaic technology; (b) the application of building regulation part L for energy conservation in building/facility; (c) the use of DEFRA standard 2007 for water resource management; and (d) the maintain as-we-go philosophy approach in tackling the building infrastructure problems. These characteristics are considered as unfamiliar practices with the organisation in its search for sustainability success.

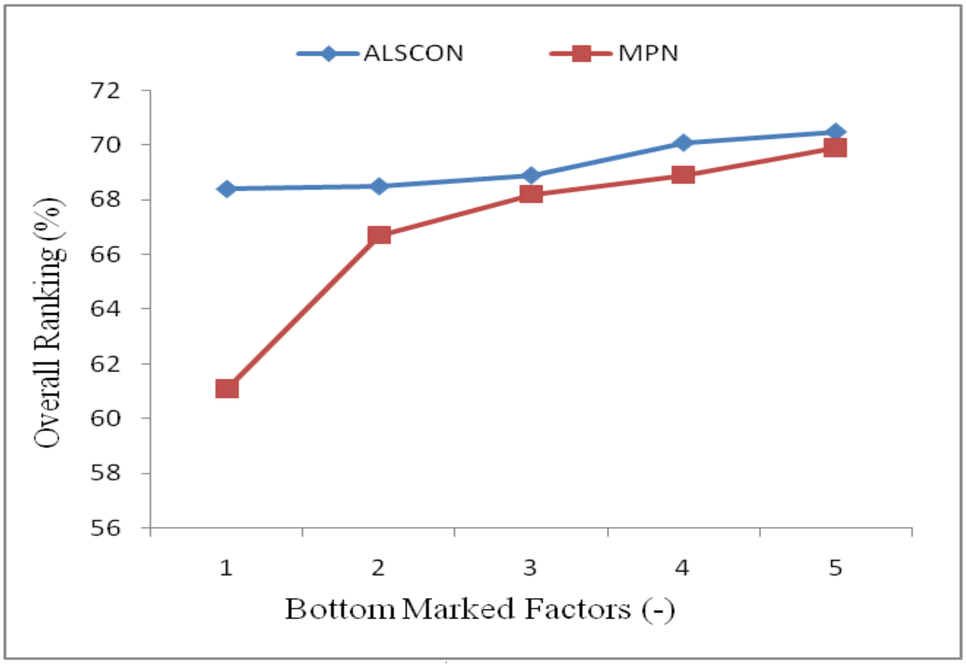


Figure 4.11: Correlation between bottom marked factors and OR

The MPN company in the OR appraisal acknowledged six bottom marked factors in the range 61–69%. They include: (a) the use of water recycling concept; (b) the use of efficient and energy saving fixtures within the building/facility; (c) the use of DEFRA standard 2007 for water resource management; (d) the employment of solar panel/photovoltaic technology within building/facility; (e) the maintain as-we-go philosophy approach; and (f) the use of the renewable energy source (Figure 4.11). However, the outcome is very reasonable in comparative terms.

This is because factors such as: (a) the maintain as-we-go philosophy; and (b) the use of DEFRA standard 2007 for water resource management are reflected in both scenarios as minor to the study. The research reveals these factors are not commonly practised within the organisations as routes to the achievement of sustainability. Nonetheless, the results are consistent across the two companies, and accordingly, it could be concluded that the research method as applied is capable of validating the two phases of study.

4.15 Constraints in phase IV

There were limiting factors affecting the data acquisition during the study. These are:

- Delays from some respondents in completing and subsequently returning the survey for data analysis and evaluation from both companies.
- Expression of lack of time in their work schedule for either holding interviews or completing the survey by the professionals, technical directors and stakeholders within these organisations.
- Administrative bureaucracies within these organisations posed difficulties in the acquisition of the envisaged data for assessment.
- Some members of staff expressing fear of divulging the company's confidential information in the process of completion of the survey.

4.16 Sustainability index (SI) matrix

This research also developed a sustainability index matrix aimed to ascertain the overall performance of the studied building services infrastructure systems within the UK and Nigeria. The sustainability index value from the probability theory is expressed as $0 \leq S_{uv} \leq 1$ for any given system. Therefore, the infrastructure systems (IS) performance could be measured based on this parameter. Table 4.25 presents the sustainability index matrix (SIM) as applied in the study.

The infrastructure performance category (IPC) contained nine categories from A to K (Table 4.25). Each IPC phase is mapped to a corresponding infrastructure system's performance status based on the sustainability index matrix domain. Then, infrastructure performance analysis (IPA) can be studied through a systematic identification of the systems parameters in a given setting.

Table 4.25: The sustainability index matrix

SI	*IPC	Remarks on IS performance status
0	K	The entire IS at total collapse stage
0.1	J	The entire IS require utmost attention before failure (downtime) occur
0.2	I	IS performance are very poor, unsustainable and needs corrective measures
0.3	H	IS performance are poor demanding for rehabilitation and *TAM culture
0.4	G	IS performance are fairly but require more scrutiny for upgrade
0.5	F	IS performance are moderate but require more critical and preventive attention
0.6	E	IS performance are good but require more preventive maintenance culture
0.7	D	IS performance are good but require preventive attention
0.8	C	IS performance are very good and reliable but need to be sustained
0.9	B	IS performance are excellent and sustainable for optimum operation
1.0	A	IS, is exceptionally outstanding but practically impossibly to attain worldwide

*IPC– Infrastructure performance category; *TAM – Turn around maintenance

The observations reported in Table 4.25 regarding building services infrastructure systems and facilities management are also well documented by other authors (see Barret, 1995; BREEAM, 2008; RICS, 2000; RICS, 2008; Grigg, 1988; Chanter and Swallow, 2000). Hence, the following processes or combinations are appraised in this context:

- Address building services infrastructure systems with the corrective measures in worst facilities state; along the sustainability index (SI) range 0 – 0.2.
- Perform crisis-related building services infrastructure systems upgrade only.
- Perform critical building services infrastructure systems analysis and employ the best management techniques and innovative models to offer solutions when related operations are scheduled.
- Apply pre-specified life cycle frameworks and strategic building services infrastructure systems management techniques.
- Perform the repair of those building infrastructure systems components with the highest risk of failure for optimum operation and sustainability success.
- Adopt a preventive maintenance culture on the building infrastructure systems as a sustainable measure to avoid downtime.

- Reduce the demand for more resources use in the building services infrastructure systems through reduce, reuse and recycle (3R) or innovative models.
- Compare the economic advantages of the building services infrastructure systems strategies in view of sustainability accomplishment at large (Table 4.25).

The highlighted procedures in managing building services infrastructure and facilities management have also been reported (ABS, 2012; Armstrong, 1987; GSGF, 2010; Shah, 2007; Cheryl, 2008; Barret, 1995; GBPC, 2010; Grigg, 1988; Sabol, 2008). Indeed, studies by Grigg (1988), and Chanter and Swallow (2000), on building and infrastructure systems management have also revealed a similar result in measuring effective performance. This system approach using the sustainability index matrix will guarantee value engineering (VE), (Smith, 2008; Muto *et al.*, 2006) related to the building services infrastructure and building construction performance in pursuit of sustainability goals. The VE is regarded as a scientific approach in analysing systems performance to determine the overall quality of services delivery achieved at the lowest cost (Smith, 2008; Parnel *et al.*, 2008; Dutil *et al.*, 2011).

4.17 Validating the two study phases using the SEI model

In this study, the SEI model was applied to ascertain the level of infrastructure management activities within the ALSCON and MPN organisations:

- From the ALSCON company evaluation, the research contributions regarding the economic, environmental and social values (in terms of system probability) yielded 5/6, 5/7 and 4/5 respectively. These outcomes present the building services infrastructure system with S_{uv} factor of 0.47 as the sustainability index result.
- From the MPN company appraisal, the study input concerning the economic, environmental and social values (in terms of system probability) offered a mix of 6/7, 2/3 and 3/4 respectively. These results yield the building services infrastructure system with S_{uv} factor of 0.43 as the sustainability index.

These sustainability indices are acceptable, given the intervening factors of interest. Based on the sustainability index results, it could be adduced that the ALSCON organisation is more inclined towards sustainable building services infrastructure systems than the MPN counterpart. More details regarding these results are indicated in subsequent sections of this thesis.

4.18 Comparison between the Nigerian and UK scenarios

The comparative analysis conducted between the Nigeria and UK settings was performed using the SEI model, and the results from the four phases of study I–IV within the two countries were compared as presented in Table 4.26.

Table 4.26: The sustainability index (SI) results

Country	Case Study	SI Results
United Kingdom	O&M	0.54
	BCC	0.70
Nigeria	ALSCON	0.47
	MPN	0.43

The SEI model concentrates on normalising sustainability within the range $0 \leq S_{uv} \leq 1$ through the application of the probability (P) theory model. This explains that the BCC has gained the highest sustainability index over the other companies. It further indicates that the BCC is more sustainability driven than the O&M sector in the UK setting. The Nigerian situation is also shown in Table 4.26.

The critical point in building services infrastructure (BSI) in this context is the operational phase of a building when the services delivery are no longer achieved as expected, thereby suggesting decommissioning (UKGBC, 2009; Zulkarnain, *et al.*, 2011; Chanter and Swallow, 2000). A further explanation could be that more resources (energy, water) are expected to be consumed and huge amounts of money anticipated to address refurbishment within a preventive maintenance culture (Shah, 2007; Barret, 1995; White, 2008). To get rid of such expenditure, a building having served for many years will depreciate in its value and the services delivery gradually declined (LCI, 2007; Langdon, 2007; Ellis, 2007).

Having identified such potential risk associated with the resources exploitation in a building, this analysis could mitigate and inform the building services and facility managers in their decision-making (RICS, 2000; Grigg, 1988; Shah, 2007; RICS, 2008; Barret, 1995). A normalised lifetime expresses the sorting of variables (data) for ease of computation (Heidi *et al.*, 2005). Figure 4.12 illustrates the curve of these results by means of a partial differential equation method given in Equation (22) to determine the BSI critical level of performance.

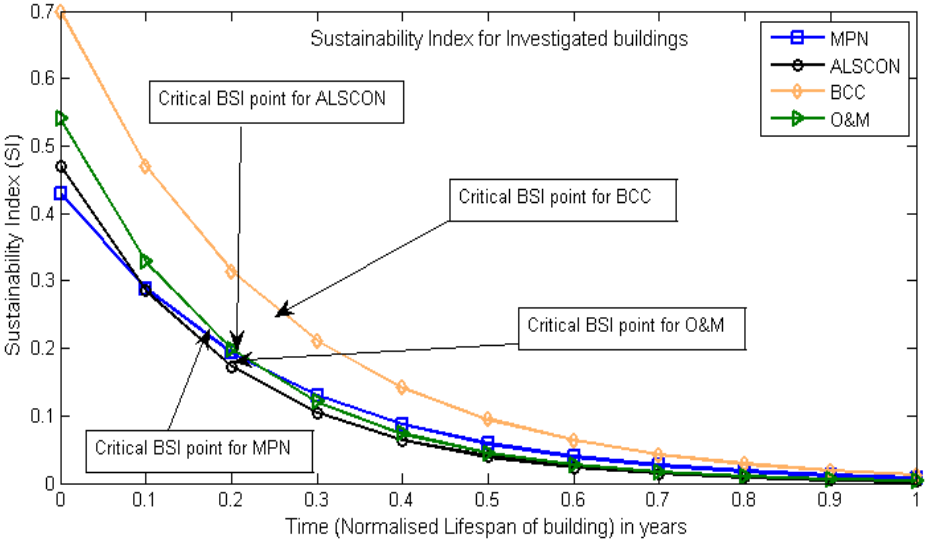


Figure 4.12: SI and time in investigated buildings at their critical level of operation

Figure 4.12 shows the BSI suitable performance attained through the application of the model expressed in Equation (36). This considers the normalised lifetime of the building in years and the sustainability index (SI) on the x and y axes respectively. Then, the BSI area of performance (A) will ultimately yield approximately:

$$A = xy \tag{32}$$

$$y = f(x) \tag{33}$$

$$SI = f(BSI) \tag{34}$$

$$A = \int_0^1 SId(BSI) \tag{35}$$

$$A = \int_{o}^{1} f(BSI)d(BSI) \tag{36}$$

The critical level of the investigated buildings (facilities) regarding the individual organisation's performance (Figure 4.12) was determined through Equation (22). The following results were obtained from the four phases of study I–IV as the buildings' critical situations. Appendix III contains the detailed analysis of this computation.

- O&M = 0.20
- BCC = 0.26
- ALSCON = 0.17
- MPN = 0.16

The interpretations of the outcomes present the relationship between the sustainability indices and the normalised lifetime within the investigated buildings at their critical level of operation. This further reveals the ranking of the studied building services infrastructure systems and their sustainability attainment. These results are very reasonable as a Matlab software technique was employed for the computation of the field data to enhance accuracy and reliability.

Certainly, these results are consistent with extant literatures as the BCC within the UK has embraced the sustainability ethics (Turner, 2006; UKSC, 2006; UKGBC, 2009; UKGSD, 2005; GSGF, 2010). As such, accurate and reliable indices of sustainability information can be qualified and quantified in real engineering cases. In the Nigerian situation, ALSCON Company is more sustainability conscious than the MPN as shown from the overall analysis (Table 4.26). On the whole, the BCC is leading in the overall appraisal. This perhaps may be because the other three organisations are more involved in the operations and maintenance of the building services infrastructure systems.

4.19 Contributions to knowledge in study phase I–IV

The study has developed the SEI model and subsequently applied it to determine the level of building services infrastructure management performance within the four phases of study under consideration. This is yet another breakthrough in measuring the indices of sustainability from the engineering perspective. As contained in Sections

4.16–4.18, the sustainability index of the examined organisations is shown through the integration of probability theory, and the SEI model into sustainability. Also, the application of the partial differential equation method has offered a great benefit in normalising the sustainable development values (indices) for the strategic management decisions in the building infrastructure systems domain.

4.20 Summary of study phase I–IV

The research outcomes have established that building services infrastructure delivery could be achieved through a suitable design, construction, operation, and maintenance culture. This drive becomes imperative due to the resources utilisation challenges facing the task of achieving optimum and sustainable benefits. Against this background, the findings revealed that the following factors are crucial across all the phases of study. They are: (a) the implementation of appropriate design/drawings/envelope/specification; (b) the availability of safety equipment/installation within the building/facility; and (c) the employment of technical/skilful expertise, all of which are seen to play very significant roles within these companies in tackling maintenance challenges.

The: (d) adoption of a team working approach; (e) the preventive maintenance culture; and (f) the sustainability of the building infrastructure, are among the list in this category. The lowest group are: (a) the maintain as-we-go philosophy approach; (b) the use of water recycling concept; and (c) the weather conditions.

Conclusions could be drawn that characteristics with higher severity indices have been assessed as having a significant influence, whereas those with lower severity indices are either less significant, or indeed completely insignificant in the drive for sustainability. It could be further stated that the formulated SEI model, and partial differential equation method, and their applications, are able to deliver the research objectives.

Chapter Five

5.0 Life cycle assessment and life cycle costs

5.1 Introduction

This phase overviews the life cycle assessment (LCA) and the economic life cycle costs (LCC) of the building services infrastructure systems in terms of performance. LCA is a generic procedure used to verify the environmental impacts of building infrastructure systems (Dutil *et al.*, 2011; Bayer *et al.*, 2010). Building infrastructure appraisal is shown for six buildings within the UK. LCC is a technique applied to establish the total costs of ownership of building services infrastructure network. Thus:

LCC in this study appraises the sum of all the costs associated with an asset or part thereof, including acquisition and installation. It also accounts for the operation (use), maintenance, refurbishment and disposal costs related to the building services infrastructure and construction projects (Sterner, 2000; Landon, 2007; Landon, 2010).

5.1.1 Presenting the study in phase V

The research evaluates sustainable infrastructure systems management within residential and office buildings. Basically, efforts in the survey were directed towards the building services infrastructure and construction sectors. This study specifically presents the LCA and LCC evaluation within six ongoing constructed buildings in the UK. Six new high-rise buildings were appraised on their services delivery and management. The owners of these buildings are four universities, a college, and one multi-occupant residential building. The evaluated buildings were of variable heights between four-to-six-storey towers and in each case, 100m^2 was considered as a functional unit for this study. The main structural frames of the buildings were made of cast-in-place concrete and steel frames (Junnila and Horvath, 2003; Blengini, 2009). The estimated building services infrastructure utilities included water, heating, energy use, maintenance and their services over the life cycle (Home *et al.*, 2009; Bayer *et al.*, 2010). Other details regarding this phase of the study inventory are shown in Table 5.1.

Table 5.1: Basic research parameters

Building Parameters	Related information
Location	United Kingdom
Lifespan	50 years
Type: Six- buildings/No.	University/4, College/1 and Residential/1 buildings
Height	Four-to-six-storey towers
Envelope	Bricks/blocks, steel frames and curtain wall combination
Operating energy and utilities	HVAC, heating, electricity, water and other resources
Life cycle analysis (LCA) phases	Construction, use/maintenance and end-of-life (EoL)
Life cycle cost (LCC)	Economic benefits analysis in each case
Functional Unit (FU)	$100m^2$
Other	Analysed factors

The data used for the entire supply chain analysed were provided by six different organisations, one for each of the building envelopes. Data from the college and universities were provided by the estate, maintenance, and facilities managers. Additionally, the site's project managers within these schools supported the study by providing more valuable information. In the residential building situation, data used for this study were supplied by the site project managers. For that reason, the bills of materials quantities (data) were later exported into a Gabi 4 software pacakge and modelled with the aim of identifying 'hot spots' and data gaps across the materials supply chain.

The supply chain in this case consists of the construction, operation (use) and maintenance, and the decommissioning-EoL phases of the building infrastructure. The life cycle inventory and life cycle impact address the global warming potential (GWP) and other environmental impacts over the lifespan in these buildings.

5.1.2 Goal and scope definition

The main goal of the research is to analyse and value the life cycle environmental impacts associated with the building services infrastructure and building construction within the UK. This study goals are tailored viz:

- To calculate and compare the life cycle environmental impacts of buildings
- To identify the 'hot spots' along the building supply chain, and
- To analyse the data and suggest possible improvements and recommendations.

5.1.3 The life cycle analysis

The LCA activities of a six-building infrastructure and their services delivery were studied from the generic stages of design/construction, operation (use) and maintenance, and the EoL phase. During this analysis, records of the lists of materials and other parameters were obtained in each case from the companies as illustrated in Buildings (A–F) for modelling and optimisation. Thus, a summary of water, energy utilities and other material flows was subsequently produced.

5.1.4 Functional unit

Typically, the main functional unit as applied in the study was 100m^2 specification of building over a 50-year lifespan. This functional unit was chosen in order to provide a common basis for appraisal and comparability within the investigated buildings (Peuportier and Herfray, 2011; Gorree *et al.,* 2002). Blengini (2009) explains that more often than not, a functional unit is the unitary internal-usable floor area, sometimes with reference to the entire building infrastructure lifespan (Borg and Erlandssona, 2003). As such, the reference unit is considered as a single flat, a living unit, or it might even pertain to the number of occupants living within the building (REGENER, 1997). Therefore, such an option is found arbitrary but for comparison purposes the standardisation might be very useful (Peuportier and Herfray, 2011). This is also relevant to the function of the building under review.

5.2 Goal and scope of the research

The overall scope of the study is seen to encompass the LCA and LCC of the projects activities related to the building services and building construction. It further overviews the pre-use phase of manufacturing, transportation of the raw materials, and their utilisation within the building construction sites (Blengini, 2009; Thompson, 2001). At the same time, this phase includes the erection, installation activities, and services delivery within the building envelope (Thompson, 2001; Zablza *et al.,* 2009; Home *et al.,* 2009). The supply chains are primarily in three distinct stages, namely: construction, operation (use) and maintenance, and EoL, as shown in Figure 5.1.

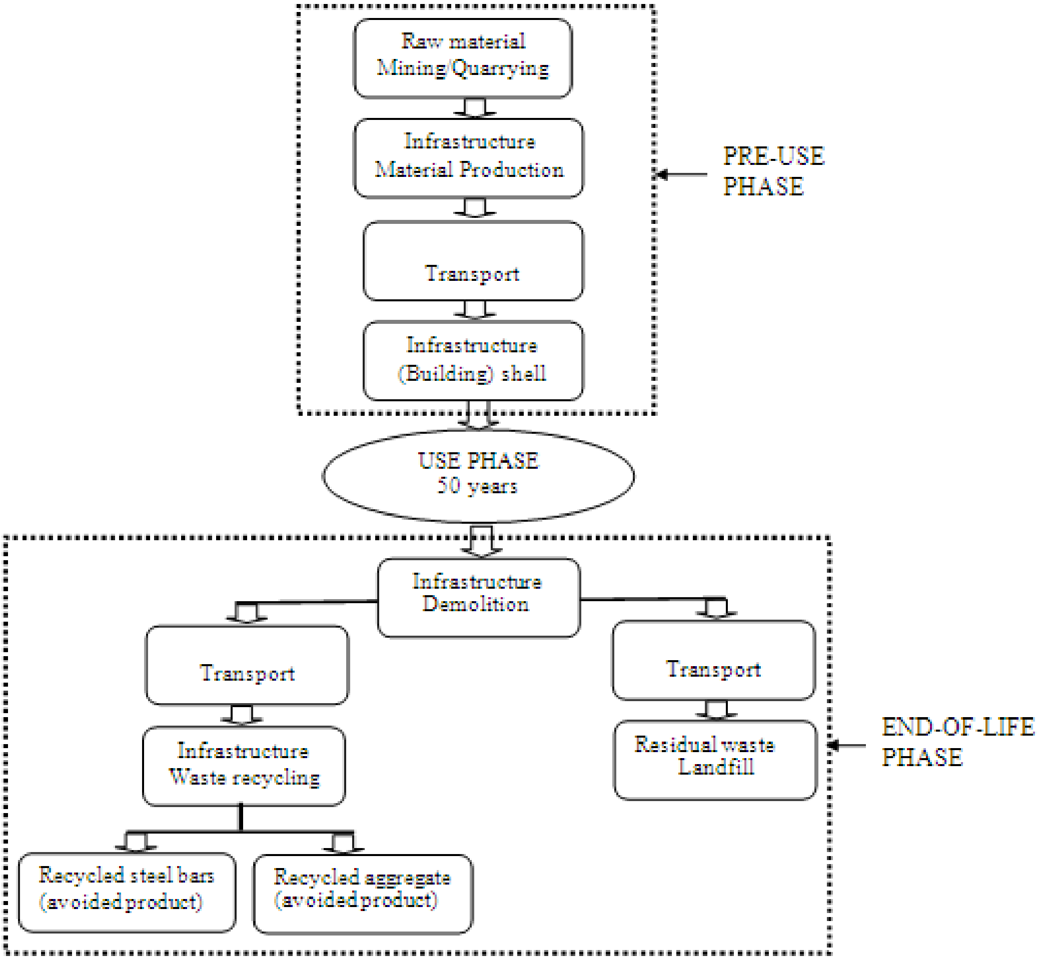


Figure 5.1: System boundaries (Blengini, 2009)

Specifically, in the building services aspect, efforts were directed towards appraising the operation/use and maintenance stages of the building services infrastructure systems in Figure 5.1. As a result, the interest focuses on the energy embodied in the materials and equipment fixtures within the buildings (Boyles, 2005; CIOB, 2011). These account for water, sanitary ware items, heat ventilation and air conditioning (HVAC) systems, radiators, and other equipment (Horner *et al.*, 1997; CIOB, 2010; Cheshire and Maunsell, 2007). This process reviews the building infrastructure when the services delivery is no longer usable and considered for demolition management (Blengini, 2009). At this stage, the building materials will either be recycled at the on-site/off-site recycling station or conveyed to landfill (Coyle and Turner, 2008; UKSC, 2006; White, 2008). This development is commonly described a ‘cradle to grave’ assessment.

The field data obtained from six different organisations was employed for the analysis. This was studied within the system boundaries of cradle to grave as shown in Figure 5.1, and the indicated supply chain was modelled for optimum results. The following energy requirements were considered in the course of this examination:

- Raw materials production;
- Raw materials transport (conveyance) to the six different construction sites;
- Transport of the waste for disposal off-site (assumed);
- Disposal of the waste to the landfill (assumed);
- Transport of waste to the recycling facilities (assumed); and,
- Waste water treatment.

5.3 Life cycle inventory

The life cycle analyses of each of the six buildings and their infrastructure services delivery were conducted from the generic stages of construction, operation /maintenance, through to the EoL. During the investigation, the lists of materials and other parameters were obtained in each case from the companies (shown as Buildings A–F) for modelling and optimisation. Therefore, the summaries of water, energy utilities, and material flows were used in the LCA phase of this research. In the LCC part, data regarding the materials quantification was supplied by two leading UK cost engineering companies. These were Jacobs Engineering Limited, and Davis Langdon (AECOM) Company, and the details are presented in tabular form in each phase of this study.

5.4 Review of data acquired for Buildings A–F

A review of the data acquired from the buildings' project and estate managers was made in each case. It became necessary to conduct a review based on the acquired data provided for the study in order to ascertain the veracity of the overall information. During this review, efforts were made to contact the buildings' project managers who supplied data for the LCC study. It was difficult to reach all of them except one of the project managers who confirmed some details regarding the data provided earlier. It was assumed that some of these managers may have changed their jobs considering the period when the survey information was sought (Appendix IV). Furthermore, it was found that some of them were no longer willing to assist in the research. Missing information in each stage of the supply chain was noticed and the following reasons were given:

- The data earlier provided were generic and for the overall buildings specification;
- Some details in these data are confidential and not for public consumption;
- It was difficult to provide accurate data since construction of these buildings was ongoing in all the investigated sites;
- The surveys were completed by these managers and later returned as feedback.

Also, from the two cost engineering companies - Jacobs Engineering Limited, and Davis Langdon - the following information was noted: Only one person from these organisations could confirm certain details about the cost estimation, which was more than two years' old, and as a result it became difficult to establish some of the details. One of the estimators could not be reached to confirm some of the statistics provided earlier. It was established that the costs evaluation in each case took cognisance of the 1.4% UK inflationary rate at the time, but due to insufficient data, several other important factors were not considered. Obviously, these indications have posed some difficulties as the achievable result does not repesent a true practical situation. Furthermore, during the costs evaluation, bills were not drawn on various sub-heads during the construction stage to include:

- Hiring of equipment to sites;
- Equipment services as provided by the operators on sites;
- Labour charges for the installation of equipment and other construction activities;
- Haulage of construction materials to sites; and,
- Contingency costs were not integrated into this computation;
- The other phases (use and maintenance) and the EoL were not properly estimated.

Given these facts, it could be stated that data provided for the LCC analysis were not comprehensive enough for computation. Therefore, it is suggested that the LCC analysis findings may not represent a true picture of the buildings investigated, and rather that the study findings are only capable of providing a platform for the future research regarding LCC use within building infrastructure management (Appendix XI).

5.5 Building A

Client: Liverpool John Moores University, (LJMU), UK.

Contractor: Wates Construction Company, UK.

5.5.1 Background of the contractor

Wates Construction Group (WCG) specialises in maximising value by finding the most intelligent and creative ways to deliver outstanding building infrastructure. The organisation has gained many years' of building experience; thereby developing a real understanding of the customers' needs with a proven track record in all core markets. These include education, prisons, local authority frameworks, heritage, commercial and mixed-use developments. As a UK-wide contractor, the WCG offers national delivery through experienced experts in well-resourced local offices. However, as part of a company with a £1 billion turnover, this represents trusted financial security and stability in turbulent economic times. The organisation is a frontline sustainability promoter and BREEAM compliant within and outside the UK.

In fact, WCG is one of the UK's biggest privately owned construction companies, receiving the Queen's Award for Enterprise in April, 2011. This accolade came in recognition of its continuous improvement in sustainable development in the past five years. Furthermore, the WCG has been awarded the contract for the construction of a landmark new six-storey academy of 10,000m^2 at the cost of £22 million pounds for the LJMU building project (WCG, A new landmark for Liverpool, 2012).

5.5.2 Type of building

The new University building is a high-rise office-type demonstrating real architectural merit and exceptional quality throughout with an outstanding exposed concrete frame and external wall cladding. This innovative technology incorporates a custom-made imported white brick and a sedum green roof concept. The building towards achieving the sustainable management of infrastructure (water, energy, heating) services delivery is integrated through suitable design of the various control measures. These include efficient energy and heating management (the use of combined heat and power) systems. This is typical of modern construction solutions and extensive experience of managing construction and design utilising input from a specialist supply chain (WCG, A new landmark for Liverpool, 2012). In this scenario, only 100m^2 of the building was considered as the functional unit.

5.5.3 Construction phase

Information gathered during the construction phase is presented in Tables 5.2 and 5.3.

Table 5.2: Materials quantity information

Materials	Quantity kg/ 100 m^2	Description of Materials	Recycling Content (%)	Cost of Materials (£)	Transportation Medium (road) km
Steel	7,500 kg	Steel frame	100	9,750.00	115
Cement	3.7 kg m-^{3}	Concrete	100	333.00	50
Bricks	15 kg	Double walls	50	15.00	35
Glass	50 kg	Window etc.	20	350.84	47
Plastics	45 kg	Vinyl flooring	10	500.00	22
Wood	80 kg	Doors/frames	80	1,552.00	30
Paints	400 (l)	Decoration	-	1,600.00	30
Total				14,100.84	

Table 5.3: Energy requirements during the construction phase, (4.2 months)

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	5,000	630.00	Sanitary use only
Diesel	1,365	8,026.00	
Electricity	1,166	2,743.37	
Total		11,399.37	

5.5.4 Operation/maintenance phases

Data obtained during the operation/maintenance phases are shown in Tables 5.4 and 5.5.

Table 5.4: Materials requirements for minor maintenance during the construction phase

Materials	Quantity kg/ 100 m^2	Description of Materials	Recycling Content (%)	Cost of Materials (£)	Transportation Medium (road) Km
Cement	1 kg m-^{3}	Floor patch up	100	90.00	30
Glass	1 kg	Broken glasses	20	7.02	30
Plastics	3 kg	Trucking fix	10	33.33	30
Wood	2 kg	Lining, doors	80	3.88	30
Paints	40 (l)	Decoration	-	160.00	30
Total				294.23	

Table 5.5: Energy requirements during the operation/maintenance phases, (50 years)

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	75,400	1,357,200.00	
Electricity	11,664	3,919,104.00	
Total		5,276,304.00	

5.5.5 End-of-Life (EoL) phase

The statistics provided during the EoL phase are given in Tables 5.6 and 5.7.

Table 5.6: Waste management phase, (within one month duration)

Materials	Quantity kg/ 100m^2	Description of Materials	Cost of Materials (£)	Waste Re-used (%)	Waste Recycled (%)	Transportation Medium (road) km
Steel	7.5 kg	Steel frame	9.75	100	100	40
Cement	37 kg m-^{3}	Rubbles	3,330.00	100	100	50
Bricks	1.5 kg	Walls	1.50	100	100	45
Glass	5 kg	Windows	35.00	100	100	40
Plastics	4.5 kg	Trucking	50.00	100	100	50
Wood	8 kg	Doors etc.	15.52	100	100	30
Total			3,441.77			

Table 5.7: Energy requirements during the EoL phase

Type of Energy Consumption	Quantity/100 m^2	Cost (£)	Remarks
Diesel	1,820	2,548.00	
Electricity	129.6	72.80	
Total		3,354 .40	

5.6 Building B

Client: University of Manchester, UK.

Contractor: GallifordTry Construction Company (GCC), UK.

5.6.1 Background of the contractor

GallifordTry is one of the leading construction companies implementing building and infrastructure works across the UK. Projects undertaken by the company spread across the public and private sectors. The group is renowned for the ability to provide whole-life solutions with capital base revenues of £1.2 billion. GCC has evolved through the decades to become one of the UK's foremost infrastructure and construction groups. Apart from the UK offices, the organisation has set up a business in Qatar focusing on infrastructure projects in private and regulated sectors of the economy. The company is recognised for high standards of project delivery approach through innovation, sustainability, and a diversity of activities as the company delivers seamless integrated and sustainable solutions.

This effort contributes towards the enhancement of the built environment. Some of the most significant milestones in the corporation's journey include the Centre Court's retractable roof at Wimbledon, and civil works at the Olympic Park in London. Also, in this list is the infrastructure work at Whitelee Wind Farm, Europe's largest onshore project of this kind (GCC, Strength in Diversity, 2012).

5.6.2 Type of building

The building in this case is a new high-end type located at the University of Manchester in UK. The gross estimated functional unit of the building in this study is $100m^2$. The constructed building is meant to house the chemical engineering department of the school upon completion. It consists of five-storey office towers with exposed steel frame, brick/block walls, green roof, and external wall cladding. The building is characterised by efficient lighting systems such as sensor-based dimmable controllers and good heating installation. The design and installation of sustainable technologies in this building enhance management performance.

5.6.3 Construction phase

The statistics obtained during the construction phase are presented in Tables 5.8 and 5.9.

Table 5.8: Materials quantity information

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Recycling Content (%)	Transportation Medium (road) km
Steel	15,000 kg	Mild steel	19,500.00	80	100
Cement	5.0 kg m^{-3}	Concrete (PFA)	450.00	100	12
Glass	200 kg	Curtain walls	1,404.00	20	50
Plastics	30 kg	Cavity tray DPM	333.00	10	10
Wood	250 kg	Doors/frames	485.00	70	20
Paints	100 (l)	Painting works	400.00	0	10
Total			22,572.00		

Table 5.9: Energy requirements during the construction phase, (4.2 months)

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	75,000	945.00	Drilling operation
Diesel	379	2,228.52	
Electricity	1,260	2,963.52	
Total		6,137.04	

5.6.4 Operation/maintenance phases

The data gathered during the operation/maintenance phases are shown in Table 5.10.

Table 5.10: Energy requirements during the operation/maintenance phases, (50 years)

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	60,000	1,080,000.00	
Electricity	12,600	4,233,600.00	
Total		5,313,600.00	

5.6.5 EoL phase

Statistics obtained during the EoL phase are illustrated in Tables 5.11 and 5.12.

Table 5.11: Waste management phase, (within 1month duration)

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Waste Re-used (%)	Waste Recycled (%)	Transportation Medium (road) km
Steel	500 kg	Steel frame	650.00	-	80	50
Cement	250 kg m^{-3}	Foundation	22,500.00	-	90	50
Bricks	500 kg	Walls	500.00	-	80	50
Wood	33.75 kg	Doors	65.48	-	100	50
Total			23,715.48			

Table 5.12: Energy requirements during the EoL phase

Type of Energy Consumption	Quantity/100 m^2	Cost (£)	Remarks
Diesel	2,000	2,800.00	
Electricity	140	78.40	
Total		2,878.40	

5.7 Building C

Client: University of Liverpool, UK.

Contractor: John Turner Construction Company, UK.

5.7.1 Background of the contractor

John Turner Construction Company (JTCC) established in 1907 is based in the North West of the UK. The organisation is a building and civil engineering contractor specialising in new build and refurbishment of commercial, cultural, education, health, industrial, and other infrastructure systems. The company expertise is seen in developments and refurbishment, joinery, manufacturing, electrical services, and many more activities. The JTCC has a reputation as one of the leading building contractors in Liverpool, Manchester, and Preston, as well as in other cities in the UK. The company is involved in the cutting-edge sustainability drive towards achieving best construction practice delivery success (JTCC, Home page, 2012).

5.7.2 Type of building

The studied building is a new laboratory facility located within the University of Liverpool. It is also a multi-storey building designed to accommodate laboratory equipment for research purposes, and some offices. Only $100m^2$ of the building is investigated as the functional unit of interest. The building consists of a structural frame and a cast-in-place concrete with brick/block walls and a long-spanned roof. The building is provided with the following infrastructure services: heat, ventilation, water supply, fire alarms, and energy management systems.

5.7.3 Construction phase

Statistics collected during the construction phase are presented in Tables 5.13 and 5.14.

Table 5.13: Materials quantity information

Materials	Quantity kg / 100 m^2	Description of Materials	Cost of Materials (£)	Recycling Content (%)	Transportation Medium (road) km
Steel	15,500 kg	Steel frames	20,150.00	10	60
Cement	12.5 kg $m-^3$	Concrete	1,125.00	12	40
Bricks	35 kg	Facing bricks	35.00	60	150
Glass	76 kg	Foundations	533.00	30	60
Plastics	55 kg	Walls/uPVC	611.00	50	30
Wood	168 kg	Windows/door	326.00	60	50
Paints	710 (l)	General painting	2,840.00	-	40
Total			25,620.00		

Table 5.14: Energy requirements during the construction phase, (4.2 months)

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	5,175	652.05	
Diesel	1,866	10,972.10	
Electricity	1,377	3,238.70	
Total		14,862.85	

5.7.4 Operation/maintenance phases

Data obtained during the operation/maintenance phases are shown in Tables 5.15– 5.16.

Table 5.15: Materials requirements for minor maintenance during the construction phase

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Recycling Content (%)	Transportation Medium (road) Km
Cement	5 kg $m-^3$	Repairs	450.00	90	50
Glass	8 kg	Replacement	56.14	80	50
Plastics	2 kg	Replacement	22.00	60	50
Wood	5 kg	Repair floor	9.70	70	30
Paints	40 (l)	Painting works	160.00	60	50
Total			697.84		

Table 5.16: Energy requirements the building operation phase, (50 years)

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	82,000	1,476,000.00	
Electricity	13,770	4,626,720.00	
Total		6,102,720.00	

5.7.5 EoL phase

The statistics gathered during the EoL phase are provided in Tables 5.17 and 5.18.

Table 5.17: Waste management phase, (within one month duration)

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Waste Re-used (%)	Waste Recycled (%)	Transportation Medium (road) km
Steel	8.5 kg	Steel frame	11.05	100	100	50
Cement	11.3 kg m-^{3}	Concrete	1,017.00	80	80	50
Bricks	4 kg	Walls	4.00	100	70	60
Glass	3 kg	Windows	21.00	90	80	30
Plastics	4 kg	uPVC	44.00	-	100	60
Wood	8 kg	-	15.52	100	100	50
Total			1,134.57			

Table 5.18: Energy requirements during the EoL phase

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Diesel	580	812.00	
Electricity	153	85.68	
Total		897.68	

5.8 Building D

Client: Manchester City Council, UK.

Contractor: Northern Group Build Limited, UK.

5.8.1 Background of the contractor

Northern Group Build Limited (NGBL) is a frontline organisation with expertise covering a diversity of infrastructure sectors ranging from education, sports, leisure and healthcare. It also undertakes residential, commercial, and recreational parks facilities amongst others. The company is deeply involved in sustainability ethics in the delivery of viable projects. In addition, the construction team has completed some of the most prestigious projects in Greater Manchester and the North West of the UK. Remarkably, infrastructure projects such as the City of Manchester Stadium, Manchester United Training Ground, the Preston Temple Complex, and a wide range of top specification residential developments are managed by this organisation.

The company's projects' expertise spans from the performance of feasibility studies to proposals for development options and investment opportunities. It also possesses know-how in a wide range of technical areas: delivering excellent design, engineering, and innovative construction. Activities such as testing, commissioning, handing over, operation, maintenance, and decommissioning of sustainable building infrastructure services are undertaken by this company. Through its self-delivery capabilities NGBL is able to deliver broad services that drive out waste and mitigate risk management. This allows for the integration of efficient and effective project resources, thereby increasing productivity. The company is keen to explore sustainable growth and infrastructure which will leave a legacy for the future generations (NGBL, New Build, 2012).

5.8.2 Type of building

The investigated building in this phase of the study is a six-storey high-rise residential (multi-occupant) type, located within the Manchester city centre. This building is constructed with steel frame, brick/block walls, and green roofing. Additionally, it is fitted with good quality and sustainable materials to include partitioning boards, HVAC, heating installation, efficient lighting systems, fire alarms and sensor-based dimmable devices. This building is designed and constructed with the integration of grey water management and sustainable technologies to provide quality services to the occupants. The functional unit of interest in this building during the research was $100m^2$.

5.8.3 Construction phase

Statistics obtained during the construction phase are displayed in Tables 5.19 and 5.20.

Table 5.19: Materials quantity information

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Recycling Content (%)	Transportation Medium (road) km
Steel	17,500 kg	Steel frame	22,750.00	80	150
Cement	14.8 kg m^{-3}	Concrete, other	1,332.00	100	50
Bricks	33 kg	Single face	33.00	90	35
Glass	80 kg	Window/Doors	561.60	20	40
Plastics	60 kg	Trucking generally	666.67	10	30
Wood	180 kg	Doors/frames	349.20	80	30
Paints	800 (l)	Painting/decorating	3,200.00	-	30
Total			28,891.87		

Table 5.20: Energy requirements during the construction phase, (4.2 months)

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	100,000	1,260.00	Sanitary use
Diesel	2,366	13,912.10	
Electricity	1,548	3,640.90	
Total		18,813.00	

5.8.4 Operation/maintenance phases

Data gathered during the operation/maintenance phases are shown in Tables 5.21 and 5.22.

Table 5.21: Materials requirements for minor maintenance during the construction phase

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Recycling Content (%)	Transportation Medium (road) km
Cement	2 kg m^{-3}	Masonry work	180.00	100	30
Glass	3 kg	Replacement	90.00	90	50
Plastics	3 kg	Broken pipes	17.70	80	40
Wood	8 kg	Wooden work	15.52	80	30
Paints	60 (l)	Decoration etc.	240.00	-	30
Total			543.22		

Table 5.22: Energy requirements during the operation/maintenance phases, (50 years)

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	86,000	1,540,000.00	
Electricity	15,480	5,201,280.00	
Total		6,741,280.00	

5.8.5 EoL phase

The information obtained during the EoL phase is illustrated in Tables 5.23 and 5.24.

Table 5.23: Energy requirements during the EoL phase (within 1month duration)

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Waste Re-used (%)	Waste Recycled	Transportation Medium (road) km
Steel	19,500 kg	Structural joists	12,250.00	-	80	30
Cement	22,202 kg m-^{3}	General works	1,998,180.00	-	80	30
Bricks	33 kg	Walls	16.50	-	90	30
Glass	83 kg	Doors, windows	2,490.00	-	100	30
Plastics	88 kg	Accessories	372.00	-	80	30
Wood	488 kg	Doors	375.00	-	100	30
Total			2,013,684.00			

Table 5.24: Energy requirements during the EoL phase

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Diesel	2,050	2,870.00	
Electricity	172	96.32	
Total		2,966.32	

5.9 Building E

Client: Royal Northern College of Music (RNCM) Manchester, UK.

Contractor: Overburry Construction Company, UK.

5.9.1 Background of the contractor

Overbury Construction Company, (OCC) UK is passionate about sustainability and focuses on three key elements of responsibility: social, environmental and economic goals. The organisational activities cover education, health and safety, through to diversity, equality, and corporate community involvement. The firm is not only committed to making a great place for all employees, but also looks after employees' general welfare. This includes clients, sub-contractors, suppliers, residents, and local communities.

OCC is dedicated to reducing the environmental impacts associated with industry activities. Indeed, it is the only construction company to have a carbon footprint calculator (CFC) developed by AMEE. This calculator allows for the establishment of the carbon impact of any refurbishment projects. It thereby improves the efficiency of an organisation through procurement and supply chain processes. As a best practice, communication and information security can not only deliver more sustainable results to a project and organisation, but can also help to reduce costs (OCC, 2012).

5.9.2 Type of building

A two-storey building was examined at the Royal Northern College of Music within a functional unit of $100m^2$. The building envelope is made of a structural frame and cast-in-place concrete, brick/block walls and external wall cladding. In addition, the building is furnished with efficient lighting systems such as sensor-based dimmable controllers, water distribution network, and good heating installation. The design and installation of sustainable technologies within this building promote better management performance of the infrastructure services delivery.

5.9.3 Construction phase

The information obtained during the construction phase in this study is depicted in Tables 5.25 and 5.26.

Table 5.25: Materials quantity information

Materials	Quantity kg/ $100\ m^2$	Description of Materials	Cost of Materials (£)	Recycling Content (%)	Transportation Medium (road) km
Steel	15,400 kg	Steel frames	20,020.00	100	80
Cement	12 kg $m\text{-}^3$	Concrete work	1,080.00	100	20
Bricks	28 kg	Old/New build	28.00	100	200
Glass	74 kg	Old/New build	519.48	100	30
Plastics	57 kg	Old/New build	336.30	10	20
Wood	172 kg	Old/New build	333.68	-	20
Paints	700 (l)	Old/New build	2,800.00	-	20
Total			25,117.46		

Table 5.26: Energy requirements for during the construction phase, (4.2 months)

Type of Energy Consumption	$Quantity/100m^2$	Cost (£)	Remarks
Diesel	1,820	10,710.60	
Water	1,910	240.66	
Electricity	1,116	2,624.83	
Total		13,576.09	

5.9.4 Operation/maintenance phases

Facts collected during the operation/maintenance phases are shown in Tables 5.27 and 5.28.

Table 5.27: Materials requirements during the operation phase, (50 years)

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Recycling Content (%)	Transportation Medium (road) km
Cement	4 kg m^{-3}	Repairs	360.00	80	50
Glass	3 kg	Broken glasses	21.06	90	30
Plastics	5 kg	Trucking use	29.50	80	20
Wood	7 kg	Repair floor	13.58	80	30
Paints	60 (l)	General painting	240.00	80	30
Total			664.14		

Table 5.28: Energy requirements during the operation/ maintenance phases

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	120,000	2,160,000.00	
Electricity	11,160	3,749,760.00	
Total		5,909,760.00	

5.9.5 EoL phase

The data gathered during the construction phase are illustrated in Tables 5.29 and 5.30.

Table 5.29: Waste management phase, (within one month duration)

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Waste Re-used (%)	Waste Recycled (%)	Transportation Medium (road) km
Steel	15.4 kg	Steel frame	20.02	0	100	30
Cement	1.2 kgm^{-3}	Concrete	108.00	100	100	40
Bricks	2.8 kg	Single skin	2.80	100	100	30
Glass	4.5 kg	Windows	31.59	90	100	30
Plastics	5.7 kg	Vinyl floor	33.63	80	100	30
Wood	17.2 kg	Hoarding	33.37	100	100	30
Total			229.41			

Table 5.30: Energy requirements during the waste management phase

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Diesel	1,752	2,452.80	
Electricity	124	64.44	
Total		2,516.24	

5.10 Building F

Client: University of Liverpool, Apex Project, UK.

Contractor: Shepherd Building Group, UK.

5.10.1 Background of the contractor

Shepherd Building Group (SBG) is one of the leading family-owned private businesses in the UK. The organisation was founded in 1890 with its head office in York. The company's operations in both national and international markets include substantial companies in the construction, engineering, sustainability, manufacturing and property development. Furthermore, the SBG services cover construction across the private and public sectors within mechanical and electrical engineering, air conditioning, and process services engineering. The company also manufactures modular building systems, park and leisure homes, integrated equipment housing, and bulk solids material handling systems. Additionally, it undertakes modular building hires, infrastructure and commercial property development. Success recorded by this company from inception has been characterised by high professional standards, innovations, and multi-disciplinary solutions to market demands (SGB, 2012).

5.10.2 Type of building

The building considered in this study is a newly constructed four-storey high-rise type located within the University of Liverpool. Basically, the functional unit of interest in this building during the research was $100m^2$. The building is made of a structural steel frame, brick/block walls and long-spanned roof. In this building, there are several installations of systems utilities to include heat, ventilation, HVAC, water supply, fire alarms, and sensor-based dimmable energy delivery among others. The provision of these infrastructure components aids in achieving sustainability within this building.

5.10.3 Construction phase

The statistics obtained relating to the construction phase are shown in Tables 5.31 and 5.32.

Table 5.31: Materials quantity information

Materials	Quantity kg/ 100m^2	Description of Materials	Cost of Materials (£)	Recycling Content (%)	Transportation Medium (road) km
Steel	10,000 kg	Structural frame	13,000.00	100	50
Cement	5 kg m-^{3}	Concrete C30	450.00	100	50
Bricks	25 kg	Double walls	25.00	100	35
Glass	60 kg	Window other	421.20	20	40
Plastics	50 kg	Trucking, doors	295.00	10	22
Wood	150 kg	Doors/frames	291.00	90	30
Paints	600 (l)	Painting works	2,400.00	-	20
Total			16,882.20		

Table 5.32: Energy requirements during the construction phase, (4.2 months)

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Water	5,000	630.00	Sanitary use
Diesel	1,051	1,471.14	
Electricity	1,818	4,275.94	
Total		6,377.08	

5.10.4 Operation/Maintenance Phases

The data gathered during the operation/maintenance phases are presented in Tables 5.33 and 5.34.

Table 5.33: Materials requirements for minor maintenance during the construction phase

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Recycling Content (%)	Transportation Medium (road) km
Cement	10 kg m-^{3}	Concrete/mortar	900.00	100	30
Glass	1 kg	Double glazing	7.02	20	40
Plastics	3 kg	Doors, trucking	1,770.00	10	22
Wood	2 kg	Doors/frames	3.88	80	30
Paints	56 (l)	Decoration matt	224.00	-	30
Total			2,904.90		

Table 5.34: Energy requirements during the operation/maintenance phases, (50 years)

Type of Energy Consumption	Quantity/100 m^2	Cost (£)	Remarks
Water	110,000	1,980,000.00	
Electricity	18,180	6,018,480.00	
Total		7,898,480.00	

5.10.5 EoL Phase

The statistics obtained during the EoL phase are given in Tables 5.35 and 5.36.

Table 5.35: Waste management phase, (within one month duration)

Materials	Quantity kg/ 100 m^2	Description of Materials	Cost of Materials (£)	Waste Re-used (%)	Waste Recycled (%)	Transportation Medium (road) km
Steel	500 kg	Steel works	650.00	-	100	50
Cement	250 kg m^{-3}	Concrete	22,500.00	-	90	50
Wood	33.8 kg	IPS Panels	65.57	-	100	50
Total			23,215.57			

Table 5.36: Energy requirements during the waste management phase

Type of Energy Consumption	Quantity/100m^2	Cost (£)	Remarks
Diesel	2,730	3,822.00	
Electricity	202	113.12	
Total		3,945.12	

Table 5.41 on page 219 provides a summary of all these costs. More information about this examination at each stage of the activities in each building unit is presented in Appendix XI.

5.11 Assumptions in the study phase V

The following assumptions have been made in this study:

- All the recyclable materials in the waste stream are returned into the same system over the life cycle;
- The cost indicated is exclusive of the labour, fixing, hiring of equipment and haulage of materials to the various construction sites;
- The recycling cost of waste materials is not included in this phase of analysis;
- The material quantities related to Buildings A–F were as provided by the estate, facilities and project managers in these construction companies, universities and college;
- The cost analysis as applied in this situation is in accordance with the current UK standard; and,
- Higher impact in terms of carbon emission is associated with the fossil fuel consumption and electricity in all cases over the life cycle.

5.12 Life cycle impact

In this research, the LCA of ten characteristics associated with the supply chain within building infrastructure using the CML (2007) impact assessment method were examined. CML is a method developed in the Centre of Environment Science of the Leiden University in Netherlands for impact analysis study. The impact evaluation was conducted to encompass both characterisation and weighting steps in accordance with the ISO 14044 standard (Szalay *et al.*, 2011; Guinea *et al.*, 2001). The achievable results show the significance of the life cycle within the investigated buildings with reference to the employable functional unit. Detailed information regarding the individual impact analysis and other methods are provided in the subsequent sections of this thesis.

The ten environmental impacts that were analysed are depicted in Figure 5.2. Thereafter, Figures 5.3–5.12 illustrate the analysed LCA impact results and provide a discussion in each case.

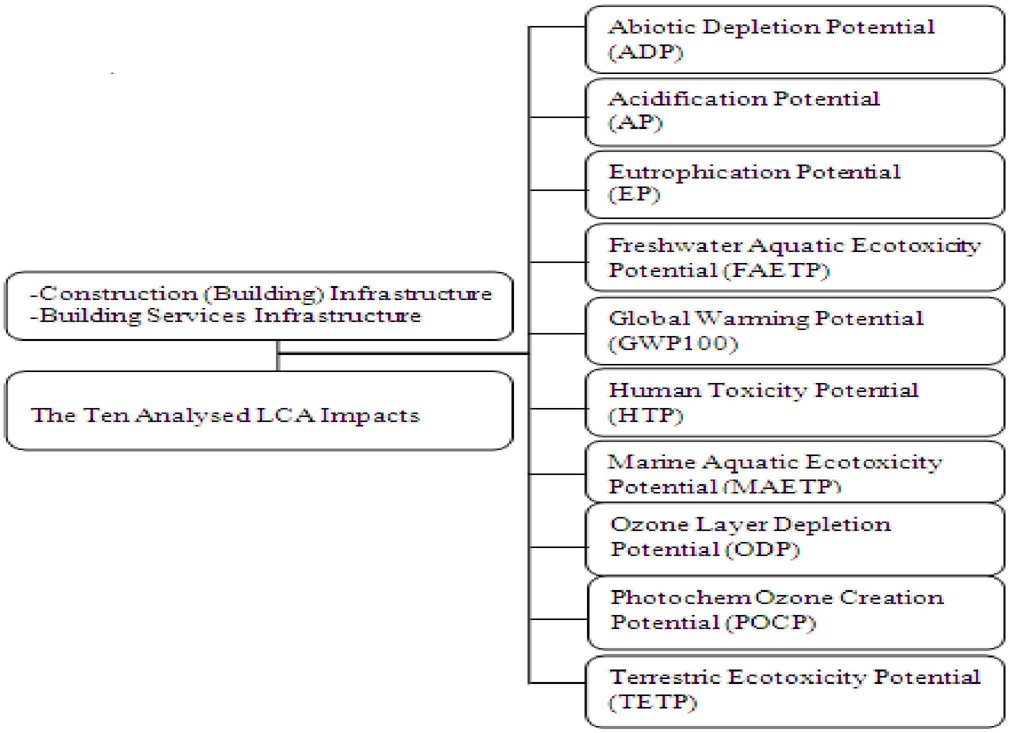


Figure 5.2: Analysed LCA environmental impacts (Guinee *et al.*, 2001)

5.12.1 Abiotic depletion potential [Sb equivalent]

The total abiotic depletion potential (ADP) impact assessment of the buildings ranges are 2,000–3,300 (Sb –eq.) per 100m^2. As shown in Figure 5.3, Building D has the highest ADP of those considered. Moreover, the total ADP of Building D 3,300 (Sb –eq.) is about 40% higher than that of Building B, which has the lowest ADP compared to all the buildings considered. The operation and maintenance stages are the major contributor to the total ADP in all the building options assessed, accounting for over 90% of the total ADP. This is mainly as a result of energy (electricity and heat) consumption in the buildings over the life cycle. Similarly, the construction stage accounts for between 3–16% of the total ADP in all the buildings considered; this contribution is mainly from the production of materials used for the construction.

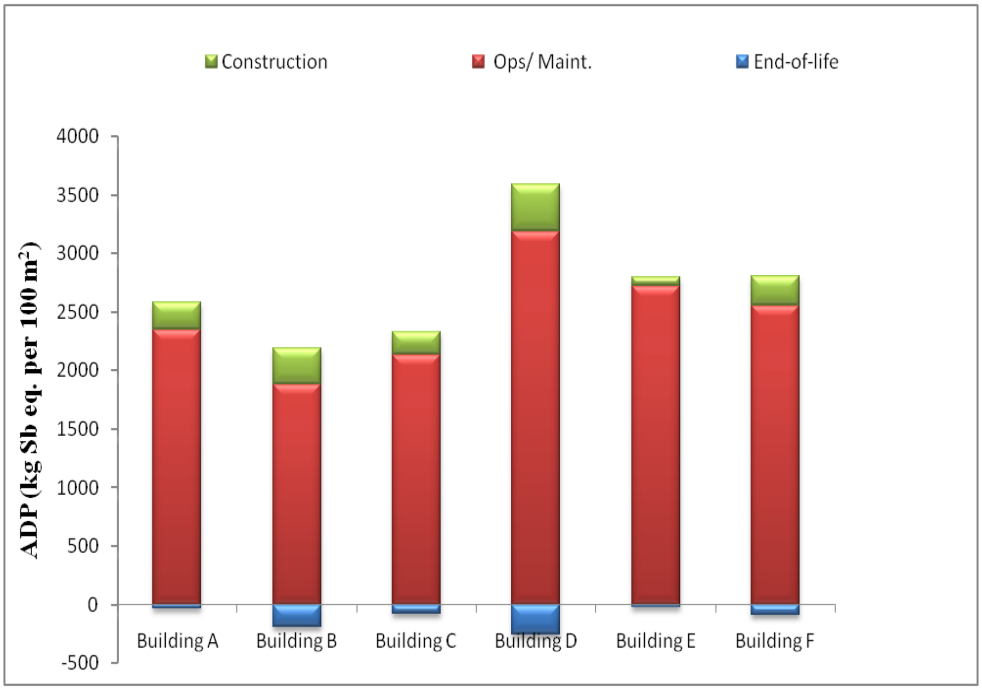


Figure 5.3: Abiotic depletion potential (ADP) life cycle impact results

However, the credits from materials recycling at the EoL reduce the total ADP by 1–9.5% as revealed in Figure 5.3. Therefore, it has been assumed in this analysis that all the construction materials used are recycled at the EoL. Typically, the total ADP of Building D is decreased by about 8% due to credits from recycling of materials at EoL stage. Thus, this highlights the importance of recycling materials at the end-of-life rather than disposing of them. The outcome of this study is valid and supports discussions in the literature (Guinee, *et al.*, 2001; Junnila and Horvath, 2003).

5.12.2 Acidification potential [SO_2 equivalent]

The impact examination went further with the acidification potentials (AP). Consequently, the six buildings were evaluated. The results noted the total AP of the buildings range is 1,200–3,300 (SO_2 –eq.) per 100m^2 of sulphur dioxide as indicated in Figure 5.4. In this analysis, Building D is leading with the AP of about 3,300 SO_2 –eq. Therefore, 64% of this (SO_2 –eq.) is achieved between Buildings D and B in contrast within this background. In the operation and maintenance stages, the research observed that over 90% of the entire AP is obtained within this phase. This outcome however explains the energy utilisation in terms of electricity and heat within these buildings over the life cycle of this study. In this situation, the result is very consistent with the literatures of Guinea *et al.* (2001), and Blengini (2009) on the energy, water and other resources management at the maintenance and operation phases of any sustainable building project.

In addition, the construction stage of these buildings account for 2–11% of the overall AP in this scenario. The indication shows the main impact provider is associated with the materials processes during the construction activities. From Figure 5.4 also, the benefits accrued at the EoL phase yield 0–0.4% AP from the materials recycling, hence reducing the related impacts. Accordingly, the results suggest virtually all the construction materials employed in this case are recycled at the EoL stage of the buildings. On the whole, the total AP of Building D is declined to about 3% in view of the gains from the recycling of materials at the EoL phase. This reveals the significance of recycling materials at the EoL stage of any sustainable infrastructure other than disposal at the landfill. Nonetheless, studies previously conducted (by Junnila and Horvath, 2003; Cabal *et al.,* 2005; Zabalza *et al.,* 2009) also confirm this result.

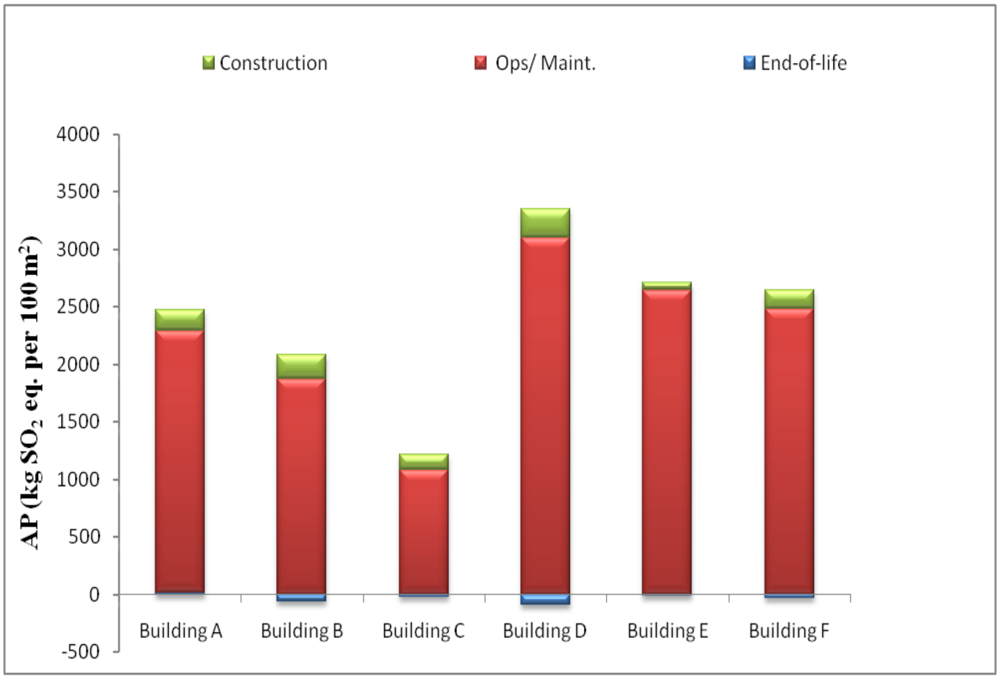


Figure 5.4: Acidification potential (AP) life cycle impact results

5.12.3 Eutrophication potential [phosphate (PO_4^-) equivalent]

The results analysis in this scenario is depicted in Figure 5.5. From the eutrophication (EP) outcome, it is revealed that Building D gained the highest hot-spots. However, the overall EP of the buildings varies from 90–200 (PO_4^- -eq.) per 100m^2 of phosphate emission in all the cases. Also, Building D is topmost with the EP above 200 PO_4^- -eq. This explains 55% (PO_4^- -eq.) in the analysis between Buildings D and C gaining the highest and lowest EP compared to other buildings in this context. At the operation and maintenance phases, the research discovered crucial project actions were involved with over 90% of the total EP. These activities are basically utilities services delivery (water, energy, heating, and wastewater) among others within the building services infrastructure life cycle.

On the other hand, the construction phase accounts for between 5–29% of the total EP in all the buildings considered in this class. This contribution is principally from the production of materials used for the construction projects.

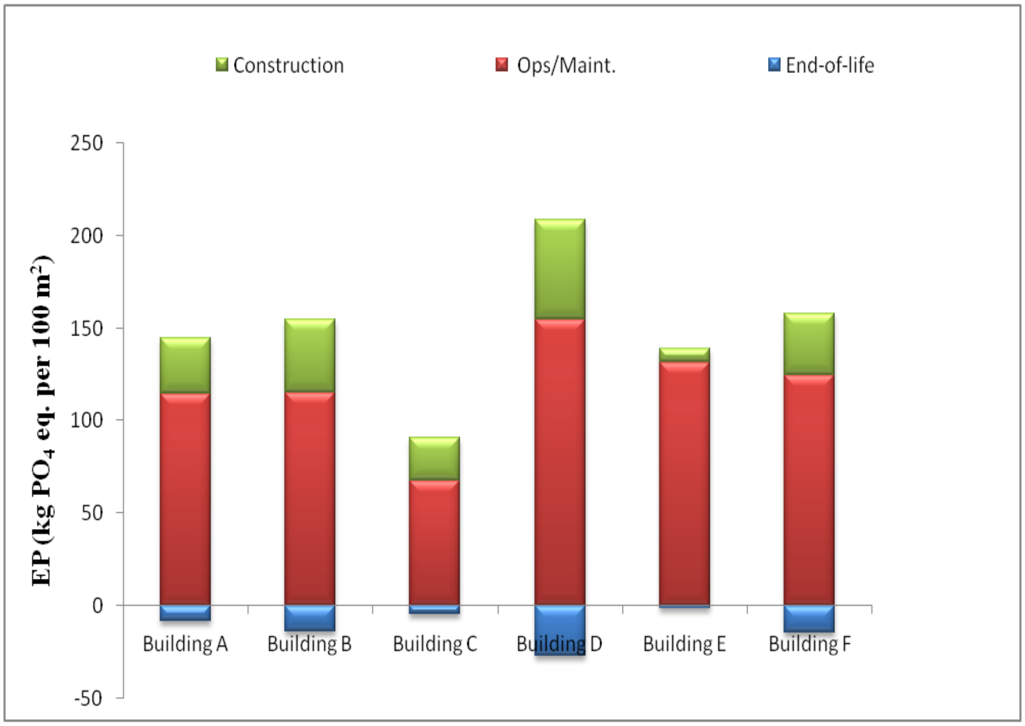


Figure 5.5: Eutrophication potential (EP) impact results

Further indications from the results are that the credits from materials recycling at the EoL reduce the total EP between 1–15% (Figure 5.5). In fact, the analysis revealed that almost all the construction materials used in this perspective are recycled at the EoL. Although, the total EP of Building D is decreased by 15% due to derivable benefits from recycling of materials at the EoL, it is nevertheless adduced that Building E is not likely to promote phosphates wastewater and other waste substances discharged into the environment comparatively during construction activities.

Generally, the waste released as a consequence, if not properly managed, can encourage environmental menace to both life and property at large. This result is consistent with the views of Junnila and Horvath (2003).

5.12.4 Freshwater aquatic ecotoxicity potential [DCB]

From Figure 5.6, the freshwater aquatic ecotoxicity potential analysis (DCB-eq.) per 100m^2 is seen. It is suggested within all the buildings, that the highest and lowest activities are 1,600–11,200 (DCB-eq.). Building D is marked with the highest impact potential in this class.

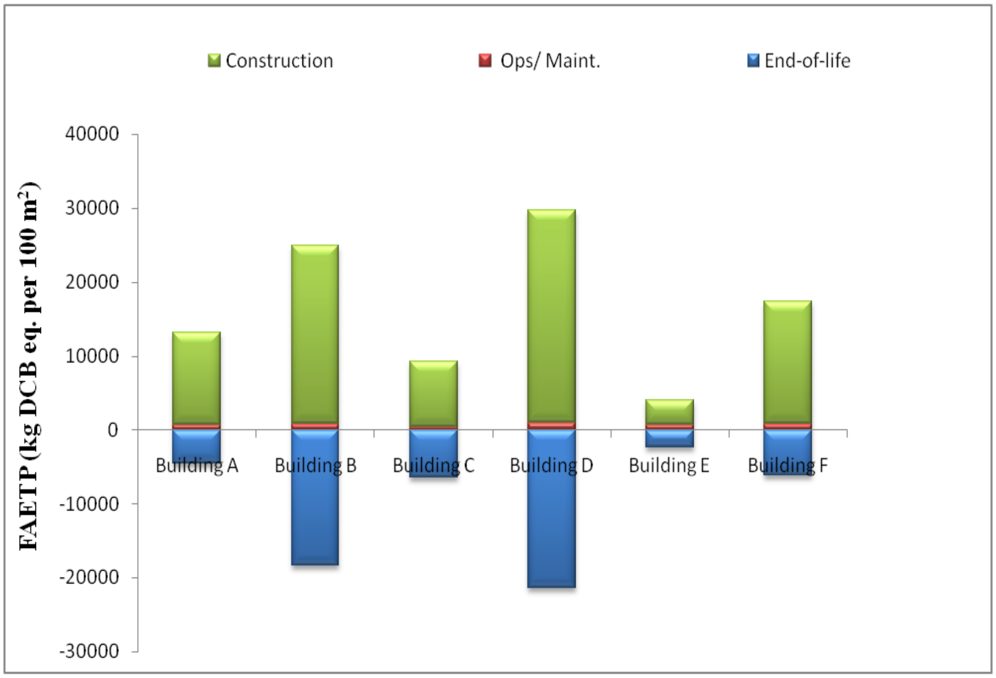


Figure 5.6: Freshwater aquatic ecotoxicity potential (FAETP) impact results

Figure 5.6 shows 86% (DCB-eq.) with Buildings D and E achieving the top and bottom DCB. The construction phase explains about 60% of the entire project activities. In fact, at the construction stage the associated building materials and water utility used are enormous, with a high recycling content. Furthermore, there is no indication of the presence of DCB potential in the entire building. This signifies that there are no contamination impact (marine, fresh-water, and ecosystem) challenges due to wastewater or water supply facilities.

At the operation and maintenance stages, between 7% and 44% credit is achieved. The EoL phase outcome shows that the entire DCB range is 54–278%. Contextually, this demonstrates that a very large quantity of the construction materials used will be recycled at the EoL stage of the infrastructure. Then, the total DCB of Building D is reduced by about 26% due to the benefits obtained from recycling of materials at this phase. This result agrees with that found in previous studies by Janssen and Hendriks (2002), and Doka (2007).

5.12.5 Global warming potential [carbondioxide equivalent]

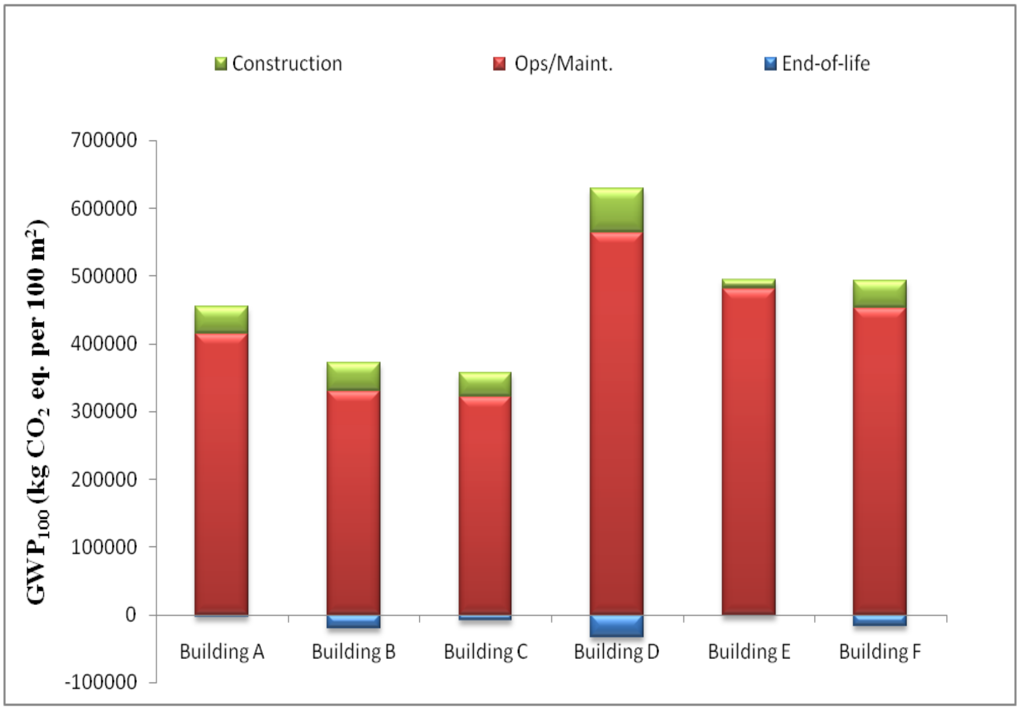


Figure 5.7: Global warming potential (GWP_{100}) impact results.

The investigated global warming potential carbondioxide (CO_2) impacts related to the buildings are (300,000–600,000 CO_2- eq.) per $100m^2$. However, the result shows 94% GWP_{100} within all the buildings. It is also revealed in this study that Building D is leading with the highest GWP_{100} above 600,000 (CO_2- eq.). Consequently, Building D is about 45% higher than Building C, which has the lowest GWP_{100} compared to all the buildings considered. Apparently, the operation and maintenance stages are the major contributors to the total GWP_{100} in all the building options assessed, accounting for over 97% of the total GWP_{100}. This is largely as a result of energy utilities (electricity and heat) consumption per $100m^2$ over the life cycle of the buildings.

The construction phase accounts for between 3–12% (CO_2- eq.) of the entire GWP_{100} within all the buildings (Figure 5.7). The GWP_{100} analysis revealed that this contribution is primarily from the production of materials used for the construction activities. In essence, the GWP_{100} from the remaining ancillary raw materials with the rest of the life cycle chain is very small in this scenario. The credits from materials recycling at the EoL stage, reduced the total GWP_{100} by 0.3–3%. Therefore, it has been suggested that all the construction materials utilised in this investigation are recycled at the EoL. In this scenario, the total GWP_{100} of Building D drops by about 0.3% due to credits from the recycling of materials at the EoL stage of the building.

This emphasises the importance of recycling materials at the EoL instead of depositing them as waste at the dump site. The result is very reliable given that the buildings will probably not promote global warming emissions. The GWP_{100} index usually occurs due to the greenhouse gases (carbon dioxide) emitted through burnt natural cooking gas, fossil fuels, chemicals and electricity supply within the buildings. This finding is in agreement with the earlier studies conducted by Guinea *et al.* (2001) and Cabal *et al.* (2005) in managing building infrastructure systems.

5.12.6 Human toxicity potential [DCB equivalent]

The human toxicity potential (HTP) impact of the entire buildings is in the range 33,000–350,000 (DCB-eq.) per $100m^2$. Building C takes the lead with the HTP (DCB-eq.) impact. The findings signify that Building C is 91% over Building E considering the highest and lowest hot spots from Figure 5.8. In this situation, the construction stage gained 10–226% (DCB-eq.) in all the buildings. This result explains the involvement of mostly virgin raw materials (aggregates) and their transportation during the construction phase of the building infrastructure. At the operation and maintenance phase, Building C achieved over 300,000 (DCB- eq.), showing a considerable difference in comparison with the other buildings. The result may also be mainly due to the energy utilities (electricity and heating) expended on the building over the life cycle. Within this category, the other remaining buildings' HTP are very low as illustrated in Figure 5.8.

Inventory analysis at the EoL phase is top marked by Building D ahead of B. Therefore, the reuse benefits from materials recycling at the EoL stage have brought the total DCB to 3–195%. The investigation revealed that in all the buildings, less than 4% of the construction materials were sent to the landfill and that over 96% were converted into recycled materials.

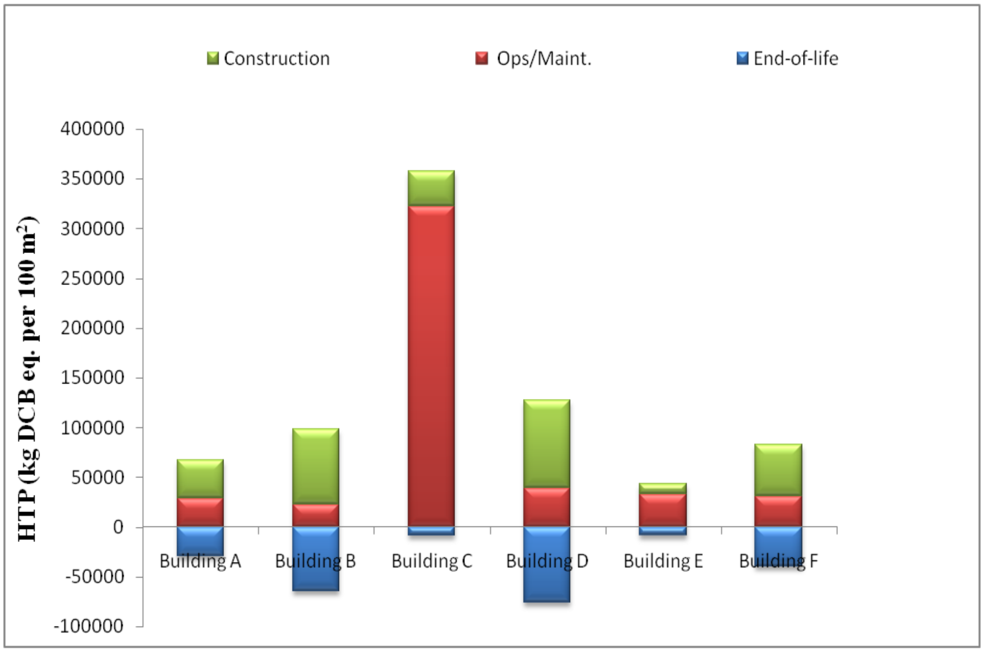


Figure 5.8: Human toxicity potential (HTP) impact results

This further stresses the significance of recycling of materials rather than final disposal as waste. Notably, the HTP impact towards infrastructure management underscores the reduction of pollution arising from human waste, physical, biological, radiological and chemical effects on the ecosystems generally. The results demonstrated that these indices are mitigated at the EoL period. This discovery is in support with the literatures of Junnila and Horvath (2003), and Blengini (2009).

5.12.7 Marine aquatic ecotoxicity potential [DCB equivalent]

The marine aquatic ecotoxicity potential (MAETP) study shows Building D to be on the top scale with over 6.00E+07 (DCB-eq.) per 100m^2. From Figure 5.9 also, the results present the total MAETP of the buildings range 16.00E+06 – 41.00E+06 yielding 61% (DCB-eq.). Within this background, therefore Building D is 61% over Building C considering the totality of top and bottom marked project activities. The construction stage constitutes a relative contribution of the usable building materials to the impacts relevant to the pre-use phase of the entire building infrastructure. As a result, it accounts for 19–127% (DCB- eq.) in all the evaluated buildings. This shows the amount of raw materials consumption and energy (transportation) associated within the buildings life cycle.

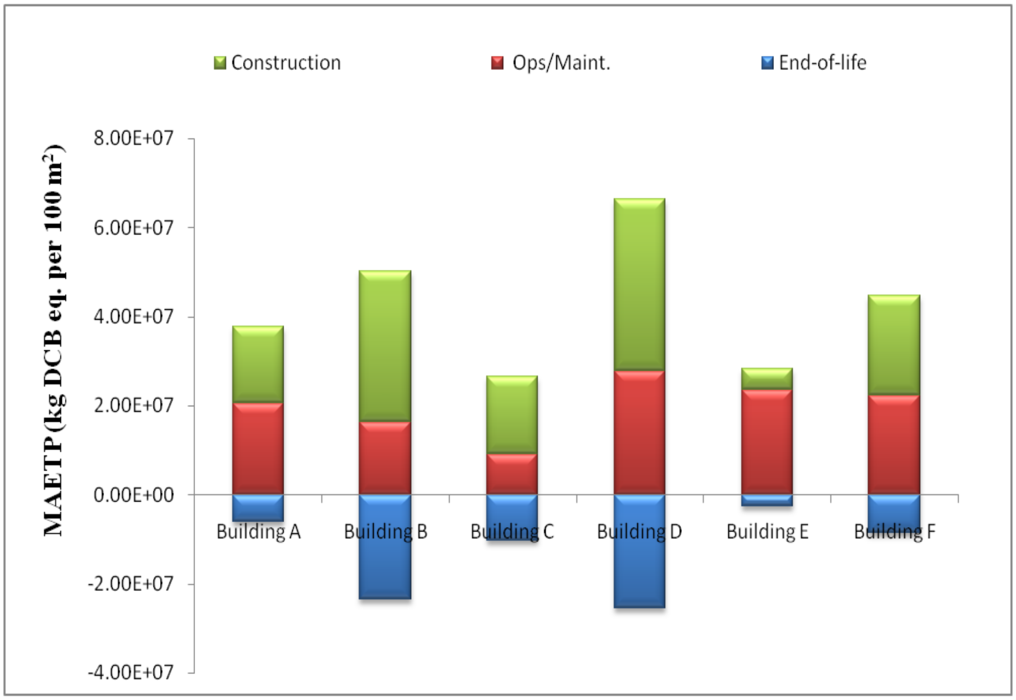


Figure 5.9: Marine aquatic ecotoxicity potential (MAETP) impact results

The operation and maintenance scenarios range is 57–92% (DCB- eq.) throughout the entire buildings. At this phase also, Building E is leading with 92% (DCB- eq.) comparatively. This becomes obvious due to the amount of credit gains at the EoL phase. The study further reveals that the EoL stage is within 10–89 % (DCB- eq.), as shown in Figure 5.9. Therefore, the outcome indicates that over 80% of the exploitable raw materials used in the infrastructure, will be recycled at the EoL stage and that very little will be deposited at the landfill. Moreover, it is suggested that the buildings impact of toxic substances emission due to MAETP and the ecosystems will be negligible. The results are in accord with those of Cabal *et al.* (2005) and D'Souza *et al.* (2011) in evaluating building infrastructure systems.

5.12.8 Ozone layer depletion potential [RII equivalent]

The analysis of the ozone layer depletion potential (ODP) was conducted. Figure 10 shows that the total ODP in all the buildings is between 0.03–0.1 (RII- eq) per $100m^2$.

With this evidence, it can be seen that 70% of (RII- eq) within Buildings D and C as the maximum and minimum hot spots in terms of project activities.

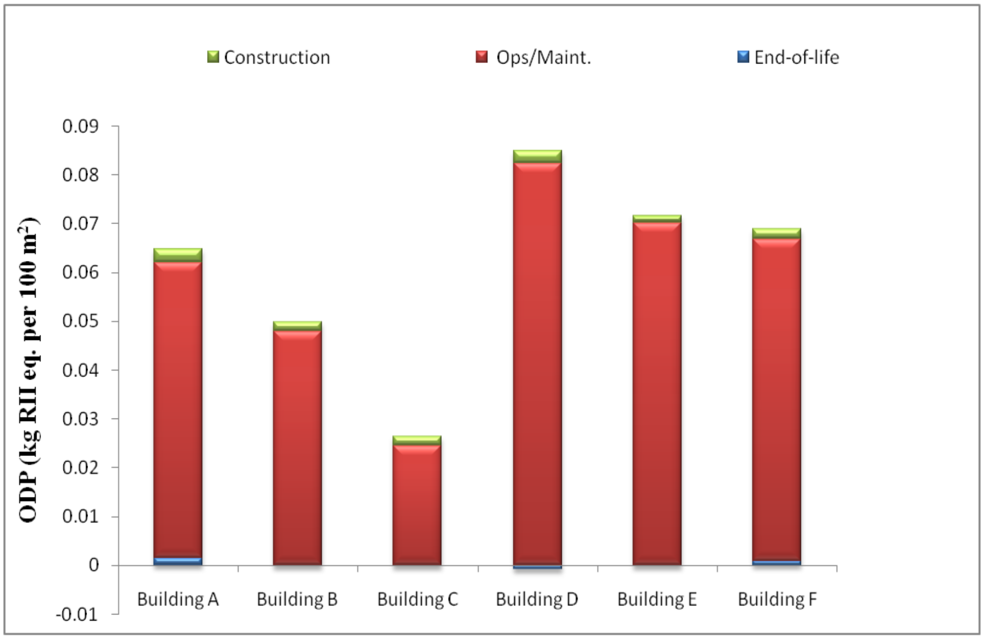


Figure 5.10: Ozone layer depletion potential (ODP) impact results

The construction stage contributes the least in building operations with only 2–7% (RII-eq). As a consequence, the research suggests many infrastructure construction materials are not applicable, thereby creating very low ODP impacts in this scenario. It is also an indication that the construction materials were recyclable. In the operation and maintenance situations, findings revealed 93–98% (RII-eq) information between Buildings C and D in all the buildings considered. The operation and maintenance stages have been responsible for over 98% of the whole activities within the infrastructure. This maintained the amount of energy and utilities usage during the buildings' life cycles (Figure 5.10).

The total credits from the materials recycling at the EoL stage are in the ODP range 0.1–2%. Hence, it is inferred by this examination that all the construction materials used in this study are recycled at the EoL phase. Specifically, the total ODP of Building D is decreased by about 1% due to credits from the recycling of materials at the EoL. In this case, the result further shows the importance of recycling of materials at the EoL rather than disposal. Similarly, the potential effects of ozone layer depletion as a consequence of these buildings will be very insignificant to both man and the environment. These findings are in agreement with the views of the CIOB (2003), and Blengini (2009) in their appraisal of buildings' sustainability (Figure 5.10).

5.12.9 Photochem ozone creation potential [C_2H_4 equivalent]

The research analysis in Figure 5.11 shows that all the buildings reach 82–192 ethylene C_2H_4-eq. per 100m^2. Also, Building D has the highest POCP of those considered. The overall POCP of Building D (192 C_2H_4 –eq.) is about 57% higher than that of Building C, which has the lowest POCP relatively to all the buildings. In the same manner, the construction stage accounts for between 4–24% of the entire POCP in all the buildings examined. Ultimately, this contribution is mainly from the production of materials used for the construction activities. This demonstrates that over 20% of these of construction materials are recyclable.

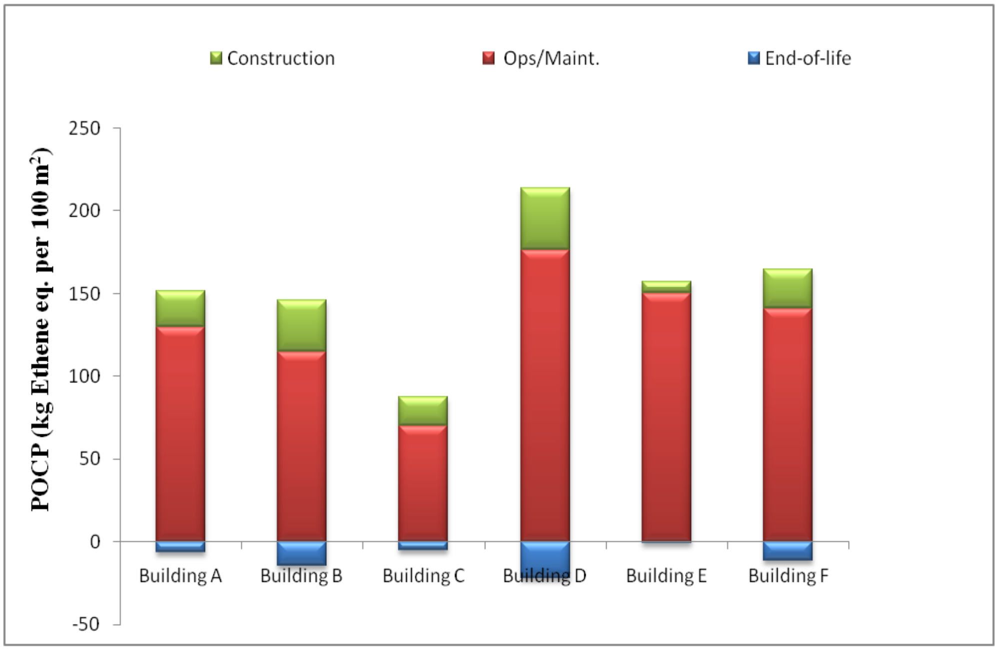


Figure 5.11: Photochem ozone creation potential (POCP) impact results

Operation and maintenance phases are the major contributor to the total POCP in all the building options assessed, accounting for over 96% of the total. This is primarily as a result of energy utilities (electricity and heat) consumption in the buildings over the life cycle. Considering the EoL history, the analysis found that the total POCP has declined between 1–11% suggesting that almost all the construction materials are potentially reusable. It is apparent that Building D has decreased by about 11% due to benefits accrued from the recycling of materials at the EoL stage (Figure 5.11). These indices underscore the economic importance of using sustainable and recyclable materials for building infrastructure systems delivery. This result is akin to that obtained by Guinea *et al.* (2001).

5.12.10 Terrestric ecotoxicity potential [DCB equivalent]

In Figure 5.12, findings of the entire buildings range are 332 –1150 Ethene –eq. per 100m^2. The category gained a TETP impact of 71% Ethene –eq. representing the total buildings highest and lowest marked activities. The construction phase describes the project operation TETP contribution as being between 82–387% of the whole TETP within this context. Further examinations of the related activities indicate that a huge volume of the construction materials was applicable during the buildings project at this stage. Hence, the raw (virgin) materials aggregates and their transportation with other construction materials are recyclable. Having obtained these high proportions of construction materials, the TETP impact at this phase is maximally controlled.

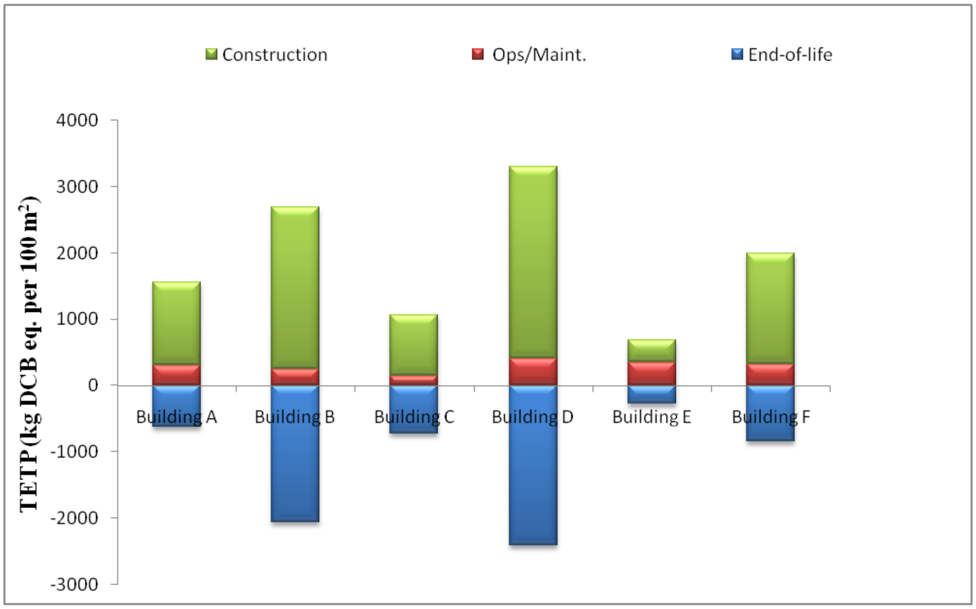


Figure 5.12: Terrestric ecotoxicity potential (TETP) impact results

Operation and maintenance stages in this study illustrate the total buildings TETP range as 28–84%. This is mainly as a result of energy utilities (electricity and heat) consumption in the buildings over the life cycle. The EoL record shows that TETP achieved less than 66–300% explaining the credits from recycling of materials at this stage. That is, approximately 1% of the materials used during the construction activities will be recovered. This indication demonstrates a good degree of the life cycle potential of the TETP at these stages of the building infrastructure (Figure 5.12). On this premise, the analysed buildings are found likely not to emit pollution of toxic substances. This result is similar to that found by the NSF (2005), and Doka (2007), in evaluating the building infrastructure.

5.12.11 Review of the building phases analysis results

A review of the ten investigated impacts at the construction, operation (use) /maintenance, and the end-of-life (EoL) phases, was undertaken. In this analysis, it is found that the most significant impact within the six buildings occurs during the construction and operation (use)/maintenance phases (BREEAM, 2008; Minx, 2008). Previous studies (see NIBS, 2006; Ding, 2008; Oritz, *et al.*, 2009; Nebel, 2006; Peuportier and Herfray, 2011) have also confirmed that construction, and operation (use) with maintenance phases of building, carry higher impact. The EoL stage in all cases, shows the economic benefits derived from recycling materials (Flapper *et al.*, 2005; GSGF, 2010). This indication further explains the gains associated with the selection of recyclable materials for construction instead of non-recyclable materials which will eventually be disposed in a landfill at the EoL stage (WRAP, 2011; Wyatt, 1994; GBPC, 2010).

5.13 Normalisation of the calculated results

This research further normalises the results as indicated in Table 5.37. Normalisation provides for the distribution of the individual impact results (Peuportier and Herfray, 2011). Szalay *et al.* (2011) and ARUP (n.d) note that normalisation is the sum of the magnitude of the category indicator results relative to reference data. Cabal *et al.* (2005)

maintained that normalisation is a more robust step aimed at identifying the relative significance and magnitude of the investigated outcomes as best practice. In this study it is necessary to determine particular impact results for comparison with the environmental benefits regarding the recyclable credits or damages analysis. For that reason, the normalisation stage addresses the characterisation pattern relative to such situation. The magnitudes of the indicator results were calculated alongside the supplied and measured field data (Appendix V). This reference information was analysed in relation to the individual buildings over a period of 50 years life cycle.

In this situation, since the measured field data were obtained within the UK, a normalisation method applicable to the European Union (EU) was chosen for the investigation (Table 5.37). Typical of the EU's normalisation method is the CML version previously used in similar studies (see Bayer *et al.,* 2010; Guinee *et al.,* 2001; Cabal *et al.,* 2005). Nonetheless, the EU factors normalisation was considered necessary for the quantification of data in this investigation. These factors are presented in the impact column against the examined buildings (BLG's).

Table 5.37: Normalisation factors

Impact	BLG A	BLG B	BLG C	BLG D	BLG E	BLG F
ADP	2.55E+03	2.00E+03	2.25E+03	3.33E+03	2.78E+03	2.71E+03
AP	2.47E+03	2.02E+03	1.20E+03	3.26E+03	2.71E+03	2.62E+03
EP	1.36E+02	1.41E+02	8.61E+01	1.81E+02	1.38E+02	1.44E+02
FAETP	8.53E+03	6.57E+03	2.84E+03	8.20E+03	1.64E+03	1.11E+04
GWP	4.51E+05	3.52E+05	3.48E+05	5.96E+05	4.94E+05	4.76E+05
HTP	3.80E+04	3.32E+04	3.47E+04	5.20E+04	3.55E+04	4.22E+04
MAETP	3.14E+02	2.66E+02	1.61E+02	4.07E+02	2.56E+02	3.59E+02
ODP	6.48E+02	4.96E+02	2.63E+02	8.42E+02	7.16E+02	6.89E+02
POCP	1.45E+02	1.32E+02	8.25E+01	1.92E+02	1.56E+02	1.53E+02
TETP	9.35E+02	6.29E+02	3.32E+02	8.85E+02	4.08E+02	1.15E+03

The impact weighting appraisal of the individual factors was conducted. That is, the normalised indicator results for each impact category were assigned numerical factors in conformity with their relative significance (Guinee *et al.,* 2001, Heidi, *et al.,* 2005). Then, these factors were subsequently multiplied and aggregated into a single score that represents the environmental performance as illustrated in Table 5.38. Therefore, the weighting factors resulting from a social panel technique were found suitable as they had been applied previously by other researchers in evaluations of related impact (see Guinee *et al.*, 2001; Bayer *et al.*, 2010; ACLCA, 2008). The outcome of this investigation was consistent in addressing the life cycle impact analysis.

Table 5.38: Impact weighting factors (Cabal *et al.*, 2005; ACLCA, 2008; ARUP, n.d)

Environmental impact indicators	Weighting factors
Abiotic depletion potential (ADP)	0.01
Acidification potential (AP)	1.3
Eutrophication potential (EP)	1.0
Fresh aquatic ecotoxicity potential(FAETP)	0.2
Global warming potential (GWP)	2.4
Human toxicity potential (HTP)	1.1
Marine aquatic ecotoxicity potential(MAETP)	0.2
Ozone depletion potential (ODP)	0.3
Photochemical oxidation potential(POCP)	0.8
Terrestrial ecotoxicity potential(TETP)	0.4

From the list of the ten investigated impacts in Tables 5.37 and 5.38, the global warming potential (GWP) is the most significant impact currently examined by numerous researchers (Heidi *et al.*, 2005; Bayer *et al.*, 2010; BREEAM, 2008; Paulsen, 2001; Borg and Erlandssona, 2003; BSI, 2006; Guinee *et al.*, 2001; CCT, 2008). Perhaps this is because global warming has a worldwide effect, and therefore, the global normalisation reference is suggested as bearing higher values (Heidi *et al.*, 2005; CCT, 2008; ARUP, n.d). It is also recommended to use the global weighting factor for the global impact (Heidi *et al.*, 2005; Bayer *et al.*, 2010). GWP is well established in connection with the greenhouse gases (CO_2) emission impact and its priority in analysis of this kind cannot be over-stressed (Darby *et al.*, 2011; CCT, 2008; BSI, 2006).

Extant literature has confirmed that due to the GWP threat, the Intergovernmental Panel on Climatic Change (IPCC) regulated by the Kyoto Protocol under the Climate Convention has developed models to address its activities (Rio Summit, 1992; Heidi *et al.*, 2005; UNFCCC, 2012). These models are revised continuously for the global warming computations in buildings (facilities) management (Klotz, *et al.*, 2007; Home, *et al.*, 2009; Elmualim *et al.*, 2012; Shah, 2007; NIBS, 2006). There is no doubt whatsoever that the GWP in both cases (Tables 5.37 and 5.38) are with the leading results. This indication is also shown in the entire analysis results.

5.14 Total environmental impacts results

In this research, an appraisal was made of six buildings within the UK. Ten impact indicators characteristics were addressed by the application of LCA, Gabi 4 software package in line with the research objectives. From Figure 5.13, the appraisal results indicate the highest impact corresponds to the GWP factor (Heidi *et al.*, 2005; Bayer *et al.*, 2010) in all the buildings and this is followed by the HTP characteristic. Within this category also, the AP and EP are found to have less significant impacts respectively. The EP impact result in this case is particularly exceptional in building C. This result however, suggests the involvement of potential greenhouse gases (GHG) emission in all the buildings (ACLCA, 2008; Heidi *et al.*, 2005).

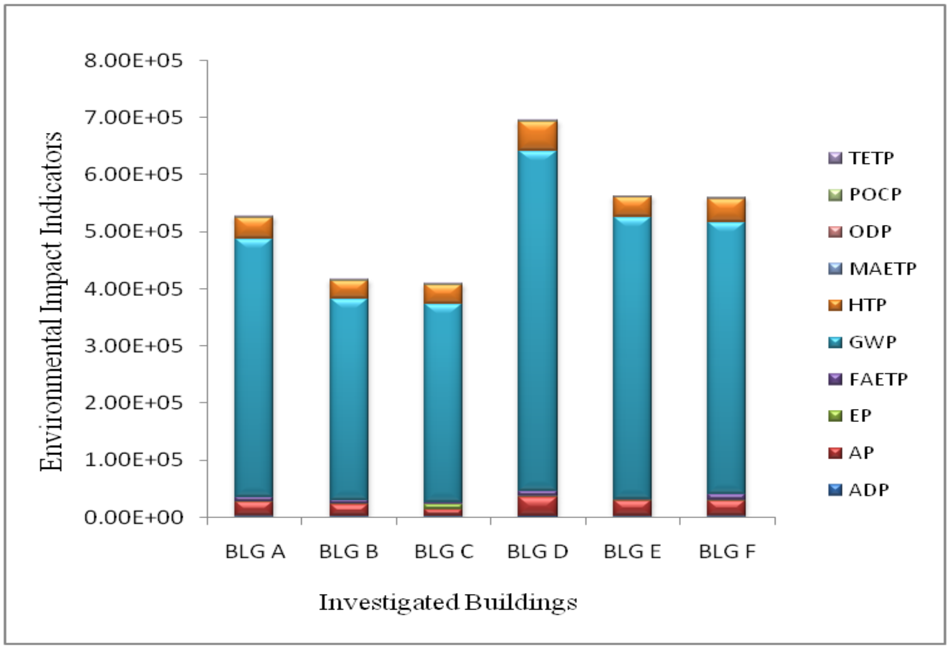


Figure 5.13: Total environmental impacts results.

Without proper mitigation, the HTP and AP impact from these buildings can influence water supply facilities and the ecosystem alike (Peuportier and Herfray, 2011; Szalay *et al.*, 2011). Actually, the AP factor within this scenario reveals much impact on Building D as this has the highest compared to other buildings (Figure 5.13). The AP impact value is, therefore, not very much in comparison to the GWP impact (Heidi *et al.*, 2005; Guinee *et al.*, 2001; Darby *et al.*, 2011). Analysing further, the EP impact is established in Building C as result of the high levels of phosphorous and nitrogen elements within the building. This suggests the other remaining factors are being over-shadowed as they exist equally in the individual analysis.

In Figure 5.13, it is seen that impact characteristics such as MAETP, ODP, TETP and FAETP, have gained lower results. This indication demonstrates that the examined buildings are not driven by the highlighted environmental impact indicators, but rather by GWP. Inclusive in the category of the least environmental impact are the ADP and POCP factors. The outcome shows their impact assessment results are not very significant comparatively with the other factors (Szalay *et al.*, 2011; Guinee *et al.*, 2001; Heidi *et al.*, 2005; Shah, 2007).

5.15 Percentages distribution analysis

Percentages distribution analysis (PDA) of the ten investigated environmental impact within Buildings A–F was studied. In this study, the enviromental impacts are separated into the 'higher' and 'lower' impact categories. The total of all the environmental impacts category is set at 100%. The aim of this analysis was to show the extent (influence) of individual impacts and their main drivers in Buildings A–F. The mathematical term in Equation (37) according to Stroud (2001) and Smith (1998) was used for this analysis and more details are found in Appendix XI.

$$\text{PDA} = \text{Component impact per building} \,/\, \text{Total no. of impacts per building} \times 100 \qquad (37)$$

The investigated buildings and the environmental impact category distribution in (%) results through the application of Equation (37) are shown in Figures 5.14 and 5.15.

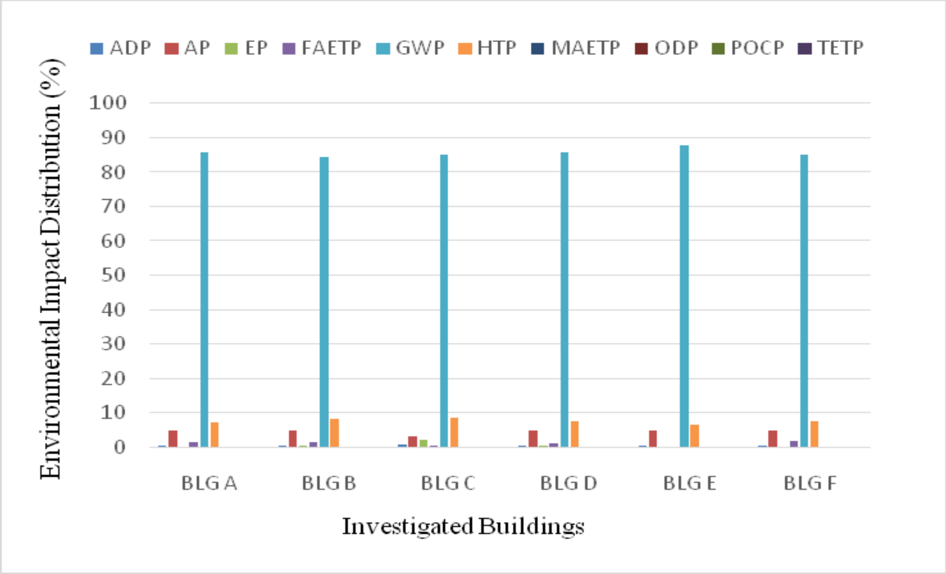


Figure 5.14: Environmental impacts distribution curve in Buildings A–F, case I.

The percentages distribution of the global warming potential (GWP) within the investigated buildings is more than 80% of the total impact as indicated in Figure 5.14. The percentages distributions of other investigated environmental impact in each case are less than 10%. This result shows the global warming potential achieved higher impact across all the buildings examined. The percentages distributions of other remaining environmental impacts are regarded as minor in this analysis (Figure 5.15).

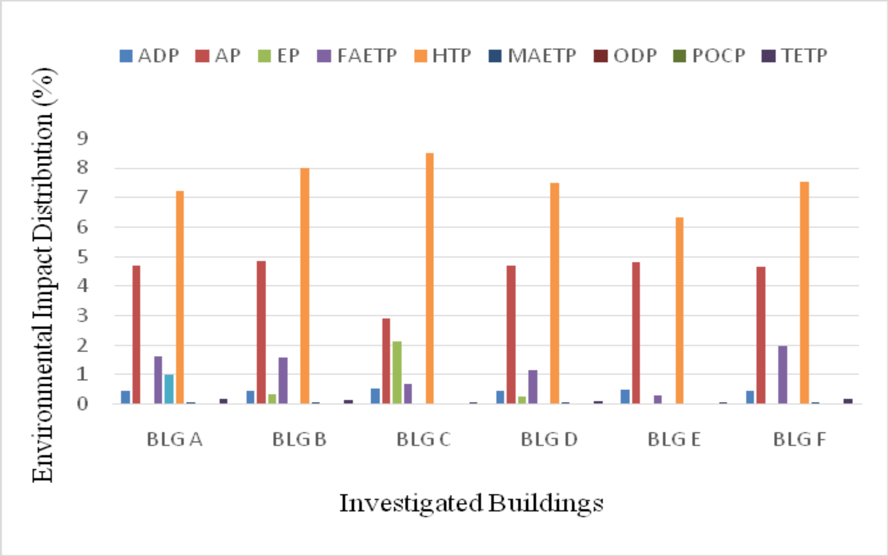


Figure 5.15: Environmental impacts distribution curve in Buildings A–F, case II.

The environmental impact distribution curve in Figure 5.15 is exclusive of the global warming potential result. In this analysis, the GWP result due to its influence in case I was later extracted from case II to show a clear picture of the remaining other environmental impacts. This impact category is considered as lower due to its lower influence within the investigated buildings. Related studies and findings from several authors (Cuellar and Adisa, 2011; Guinee, 2001; Bayer *et al.*, 2010; Heidi *et al.*, 2005) have confirmed that the GWP impact is higher since all buildings are considered over their life cycle. The GWP impact is mainly associated with the embodied and operational energy in these buildings over their life span (Guinee, 2001; Boyles, 2005; BREEAM, 2008). The other remaining impacts have low influence (Heidi *et al.*, 2005; ISO, 2000; MTP, 2009).

From Table 5.39, the main environmental impacts drivers and causes or contributing processes within the investigated buildings are seen. The findings indicate that the global warming potential is often related to the application of natural gas along with fossil fuel and this promotes carbon dioxide (CO_2) resulting in green house gas (GHG) emissions and climatic change (Lelyveld, and Woods, 2010; Eco Homes, 2003; ASHRAE, 2004; Nebel, 2006).

Table 5.39: Environmental impacts, causes or contributing processes in Buildings A–F.

S/No	Environmental impact category and their contributions	(%)	Drivers and main causes or contributing processses in buildings
1	Abiotic depletion	< 1	Natural gas and fossil fuel oil use
2	Acidification	< 5	Sulphur dioxide (SO_2) release
3	Eutrophication	>2 in building C, but, all other buildings are < 1	Emission of phosphate (PO^{4-}) and ammonia (NH_3)
4	Fresh aquatic ecotoxicity	>1	Heavy metals: mainly baruim and vanaduim existence
5	Global warming	> 80	Release of carbon dioxide (CO_2) through fuel and natural gas use
6	Human toxicity	> 8	Pollution related to sulphur dioxide (SO_2) and nitrogen oxide (NO_x)
7	Marine aquatic ecotoxicity	< 1	Scale formation and carbonate in the water supply facilities
8	Ozone depletion	< 1	Chemicals use: chlorine (Cl_2) and bromine (Br) in these buildings.
9	Photochemical oxidation	< 1	Smog: hydrocarbons and NO_x reacting under the influence of ultra

			violet (UV) light
10	Terrestrial ecotoxicity	< 1	Existence of heavy metals: especially mercury

Global warming potential and other analysed environmental impacts arising from buildings and facilities are well documented by several researchers (see Scott *et al.*, 2008; Shah, 2007; Serb, 2008). This outcome points to the fact that CO_2 is the main driver followed by SO_2 and NO_x gases within the investigated buildings. The contributions of other processses in this case have been studied earlier (see Guinee, 2001; Gorree *et al.,* 2001).

5.16 General interpretation: percentages distribution test

It is evident from Table 5.39 that the processes involved with the use of natural gas and fossil fuel emit CO_2 and contribute to the highest impact from the analysed environmental impacts category. Apart from this, only a limited number of processes are responsible for the highest contributions to most impact categories; these are the application of SO_2 and NO_x gases. Also, the utilisation of phosphate (PO^{4-}) and ammonia (NH_3) is likely to contribute to the release of these gases within the investigated buildings. This explains that excluding global warming, eutrophication has a potential impact on Building C in particular. There is no doubt whatsoever about this result because Building C is meant to accommodate a laboratory facility with some offices as noted in Section 5.7.2. Hence, the building services infrastructure delivery is explained due to its peculiar nature when compared with the other investigated buildings as shown in Figure 5.15.

The general explanation from Figure 5.15 indicates that since the primary function of this building is to accommodate laboratory equipment for academic research purposes, its overall purpose is different from that of other buildings (Yu and Mclaren, 1995; Walker *et al.,* 2007; Slater, 1995; Zalbalza, 2009). The type and purpose of a building informs its design, construction, installation of equipment, management of the building services, and appointment of facilities managers (Shah, 2007; Peuportier and Herfray, 2011; Elmualim *et al.,* 2012; Pitt, 2005; RICS, 2008; Romm, 1994; CIB, 2004). The investigation further suggests that the results from other environmental impacts with low contribution processses should be considered with care as their effects could pose problems at the EoL stage in these buildings (Blengini, 2009; Armbruster, 1990; Smith, 2009; Thompson, 2001; Petts and Eduljee, 1994; Kim and Qi, 1995; Demsey and Oppelt, 1993; Feuillade *et al.*, 2008).

5.17 Constraints in the study phase V

There were limiting factors affecting data acquisition during this study. These are:

- Delays from some respondents in completing and subsequently returning the surveys for data analysis and evaluation.
- Expression of lack of time in their work schedule for completing the questionnaire by the experts, technical directors, and stakeholders within these establishments.
- Some members of staff expressing fear of divulging the companies' confidential information in the process of completing the survey.
- Inability to acquire all the needed data in the supply chain for the LCC analysis.

5.18 Summary of study phase V

The outcomes from this research have explained the LCA evaluation of the environmental impacts within six buildings in the UK. This study also overviews water, energy (heating and electricity), with other materials consumption necessary for the success of the building infrastructure systems. The area of focus was mainly on the building services and construction activities. In this study, three key stages of impact activities construction, operation (use) and maintenance alongside the EoL phases are addressed. The Gabi 4 software CML package (Guinee *et al.,* 2001) was employed in the building infrastructure analysis. This software is the most comprehensive and detailed package increasingly undertaken for the LCA examination and it provides the benchmark for future studies in the area of building infrastructure sustainability.

The impact assessment results within the construction stage typically account for the largest impacts. This outcome suggests that large quantities of raw (virgin) aggregates materials and their transportation were involved during the construction stage of the buildings activities (Ding, 2008; Boyles, 2005; CIB, 2004). The transportation of construction materials to the various sites provides a very significant contribution to the overall life cycle impacts of the analysed buildings. This contributes to quite a considerable GWP impact (Bayer *et al.,* 2010, Darby *et al.,* 2011). The operation and maintenance phases have the largest impacts associated with energy utilities (electricity and heating) consumption in the buildings over the life cycle (BREEAM, 2008; Minx, 2008; Heidi *et al.,* 2005; RICS, 2008). Therefore, the impact is highly important in comparison to the entire life cycle stages. The EoL phase shows considerable impacts in various categories and normally credit the product system (CIOB, 2010; Borg and Erlandssona, 2003; Blengini, 2009). Given the benefits accrued from the high recycling rate of materials achieved for the entire building infrastructure systems (Flapper *et al.,* 2005).

From Figures 5.13–5.15 the overall impacts from the characteristics considered are clearly seen, and it is observed that the GWP impact achieved the highest result in the analysis. Indeed, the GWP impact value for all the six investigated buildings in comparison to the other factors is very significant. GWP impact is primarily caused by the consumption rate of fossil fuel and natural gas within the examined buildings (Heidi *et al.,* 2005; Shah, 2007). In this situation, the GWP is promoting CO_2 trace and is likely to be driven in all the appraised cases (Szalay *et al.,* 2011; Guinee *et al.,* 2001). So, the achievable result concerning this factor is very consistent and reliable over the life cycle period. HTP, AP and EP results are moderately significant in the study overall.

It is further revealed that the MAETP, ODP and TETP impacts gained the least results. Also within the lowest marks group are the FAETP, POCP and ADP environmental impacts. The results of some of the least impact factors are clearly displayed, but showed hardly any difference. It is worth mentioning that this study was reported in a consistent and transparent manner. Therefore, the findings are in agreement with studies conducted earlier (see Bayer *et al.,* 2010; Cabal *et al.,* 2005: Blengini, 2009).

5.19 The life cycle cost analysis

The economic life cycle cost appraisal of the infrastructure services delivery within Buildings A–F was conducted according to the methods outlined by Langdon (2007), and TG4 (2003). This becomes necessary in establishing the LCC for each phase of the building services infrastructure systems. The LCC examination considered the system as a closed-loop recycling process per functional unit (FU) and did not account for the inflation of materials over the life cycle. As a consequence, the percentages of waste materials recycled and re-used were calculated based on the current UK standards as depicted in Table 5.41. Basically, the analysis as contained in this table was applied at the waste stream of the EoL phase of the entire building infrastructure.

5.20 Landfill and recycling costs

The landfill and recycling costs of materials are often quantified in pounds per tonnes as demonstrated in Table 5.40. It is obvious that the landfill cost (£/tonne) of materials is quite high in comparison with the recycling costs. This is because the UK landfill tax regime per tonne of waste is put at £48-£56. However, this is in a push to reduce and divert more construction waste materials from the landfill towards recycling composting (WRAP, 2012). On this basis, the outcomes of the LCC are as presented.

Table 5.40: Landfill and recycling costs (£/tonne) of materials.

Materials	Landfill Cost £/tonne	Recycling cost £/tonne	Source
Steel	56.00(Depending on grade)	4.00 (Depending)	WRAP, 2012
Cement (concrete)	50.50	7.25	WRAP, 2012
Bricks	50.50	6.50	WRAP, 2012
Glass	56.00	8.00	WRAP, 2012
Plastics	56.00	5.50	WRAP, 2012
Wood	56.00	2.00	WRAP, 2012

The information included in Table 5.40 was extrapolated into this study at the construction, operation (use)/maintenance, and the EoL phases of the buildings activities. Particularly, the research employed the data for evaluating the percentages of the building materials recycling (waste re-used) content and landfill waste at the EoL phase. This becomes imperative since the research was conducted in building services infrastructure systems within the UK, meaning the UK proper tax regime could be applied.

5.21 Buildings A–F and the associated costs (£/FU)

The study has established the related cost (£/FU) of the investigated Buildings A–F and the correlations are presented. The data in Table 5.41 provided by the companies handling projects in Buildings A–F do not include information on the plant hiring, haulage, labour and the overhead costs. Therefore, the evaluation in each case was based on the supplied data. Also, Davis Langdon, and Jacob’s Costs Engineering companies, UK, assisted in providing the materials valuation analysis. More details regarding the LCC examination are indicated in Figures 5.19–5.24 respectively.

Table 5.41: Relationship between buildings and costs (£/FU) within the phases.

Buildings	Construction Phase-Total LCC (£/FU)	Ops/Maint. Phases-Total LCC (£/FU)	EoL Phase- Total LCC waste management (£/FU)
A	25,5001.21	5,276,598.23	6,795.17
B	28,664.04	5,313,600.00	26,593.88
C	40,482.85	6,102,720.00	2,032.25
D	47,704.87	6,741,823.22	2,016,650.32
E	38,683.55	5,910,424.14	2,745.65
F	23,259.08	7,901,384.90	27,150.69

5.21.1 Life cycle costs for Building A

The life cycle phases and the LCC (£/FU) for Building A are shown in Figure 5.16. In this figure, it is evident the materials and utilities used during the construction phase are far above £25 thousand pounds. It also appears that a great amount of the construction materials utilised are recyclable, and that the method and technology adopted for the building is effective over the life cycle (Clift, 2003; ARUP, n.d). This development will certainly encourage sustainability through the exploitation of recyclable materials rather than the use of virgin resources (Flapper *et al.*, 2005; BPC, 2010). Operation and maintenance phases over 50 years lifespan have recorded more than £6 million pounds.

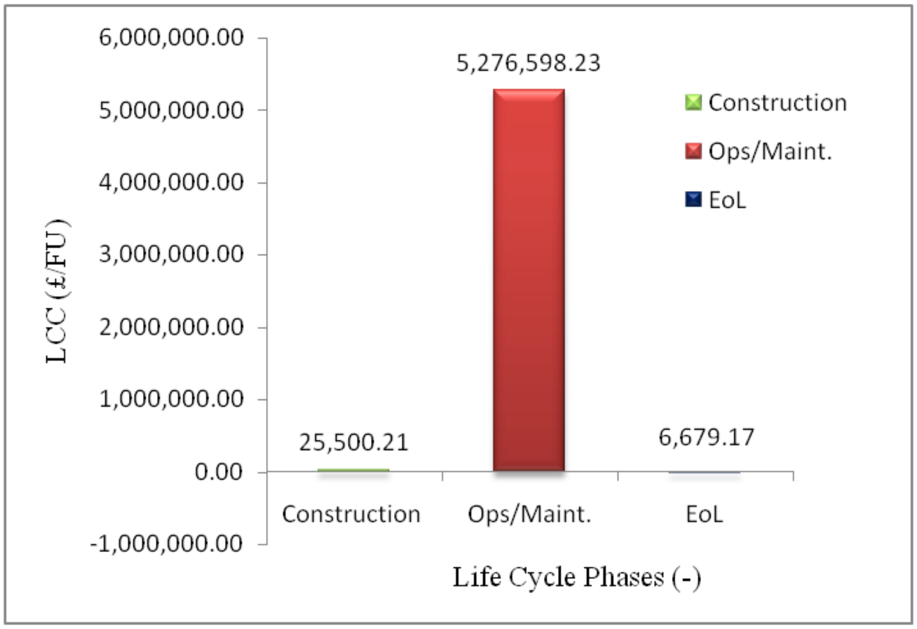


Figure 5.16: Life cycle phases and the LCC (£/FU) for Building A.

In fact, this forecast does not take into cognisance, the inflationary rate associated with the building services infrastructure utilities (energy, water, gas) and the maintenance culture within this period. The EoL phase depicts the credits from the recyclable and landfill materials over the life cycle. Also, the total LCC of over £6 thousand pounds accounts for the overall amount spent and the benefits over the life cycle as shown in Building A (Figure 5.16). The outcome from Building A shows a good pay back trend towards the concept of sustainability in managing building services infrastructure systems (Kehily and Hore, 2012; Flapper *et al.*, 2005). The findings also revealed conformity with the literature (Gulch and Baumann, 2004; Bakis, *et al.*, 2003, Langdon, 2007).

5.21.2 Life cycle costs for Building B

In Figure 5.17, it is seen that over £28 thousand pounds per FU was expended at the construction phase. This is a reflection of the huge quantity of materials and utilities consumed during that phase. Consequently, the measured field data used for this examination shows that reasonable percentages of the materials employed in the building process are recyclable (Wyatt, 1994; ASTM, 2002, Clift, 2003). Given that the materials applied are re-usable over the building's life cycle, there will be some considerable gains accrued (Flapper *et al.*, 2005; Blengini, 2009).

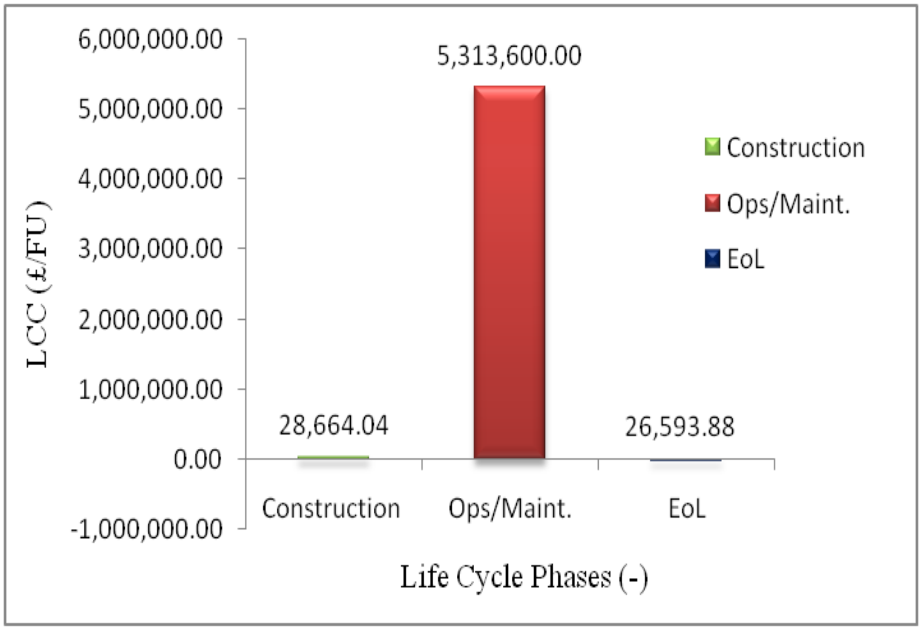


Figure 5.17: Life cycle phases and the LCC (£/FU) for Building B.

The operation and maintenance phases are very exceptional with more than £5 million pounds spending over the 50 year period. This prediction is exclusive of any tariff rises in utilities and maintenance management activities. The EoL phase basically showcases over £26 thousand benefits from the recyclable materials and landfill costs associated with the building per functional unit. From the above indication, the LCC (£/FU) of Building B is explained at different stages of activities with the cost involvement and benefits overall. Ellis (2007), Langdon (2010), and Langdon (2007), all find similar LCC values in building infrastructure system management.

5.21.3 Life cycle costs for Building C

The analysis for Building C signifies the LCC (£/FU) at the construction phase as being over £40 thousand pounds. The materials costs and the recycling contents as applied in the construction stage over its life cycle (Janssen and Henddriks, 2002, Blengini, 2009; Flapper *et al.*, 2005; Wyatt, 1995). The operation and maintenance stages have recorded over £6 million pound as shown in Figure 5.18.

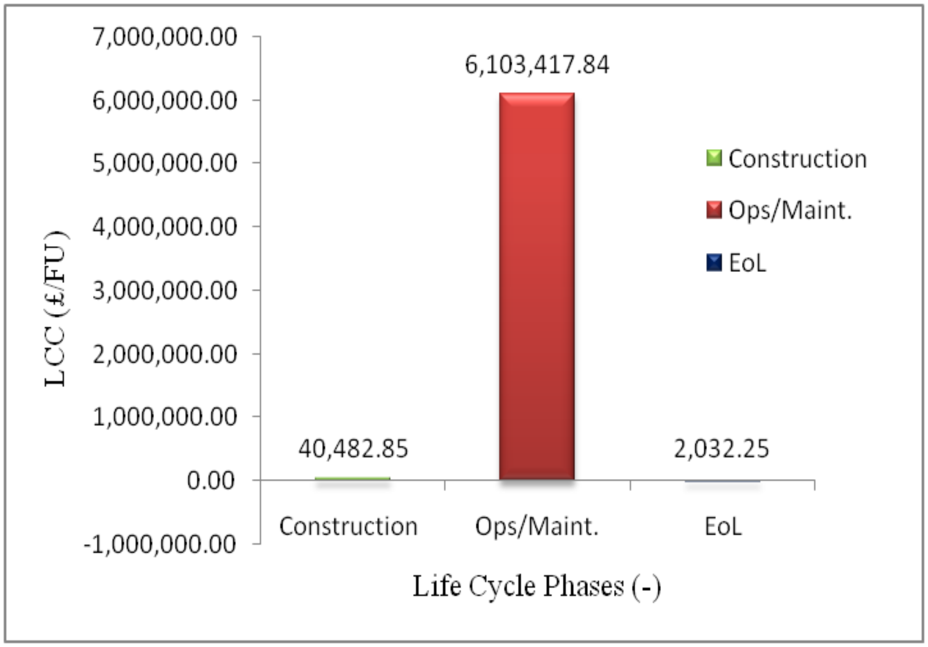


Figure 5.18: Life cycle phases and the LCC (£/FU) for Building C.

The estimate presented does not consider any increase associated with utilities and materials throughout the 50 year life span. However, the EoL phase does include the credits from the recyclable materials utilised in the building (Figure 5.18). The total LCC explains that more than £2 thousand pounds is anticipated at this phase of the infrastructure over its life cycle. Generally, the examination is consistent with the quality of materials application during the construction stage and the equipment provided within the building for services delivery. This result agrees with that found by several researchers (see Zimmermann, 2005; Parnell, 2008; Gluch and Baumann, 2004) who have appraised building infrastructure serviceability and engineering management.

5.21.4 Life cycle costs for Building D

The LCC analysis for Building D is indicated in Figure 5.19. In this investigation, the building infrastructure at the construction phase has consumed more than £47 thousand pounds. During this construction stage also, the recycling contents of materials used are reasonable over its life cycle (Sterner, 2000; Wyatt, 1994; Flapper *et al.*, 2005). The operation and maintenance stages account for over £6 million pounds.

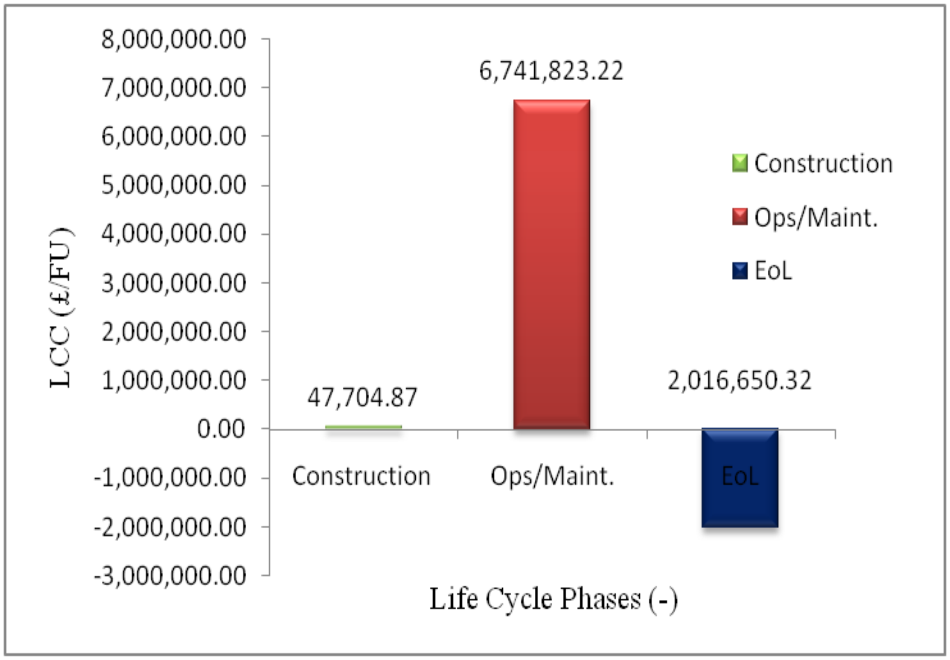


Figure 5.19: Life cycle phases and the LCC (£/FU) for Building D.

This prediction is without consideration of the price increments in the building services infrastructure (water, gas and electricity) equipment upkeep and other ancillary operations during the 50 year period. Notwithstanding, a good policy framework through suitable design for the HVAC, energy efficiency and conservation with suitable maintenance management underscored its functionality. This becomes realistic when the facility within building D is put to use.

At the EOL phase, Building D shows more than £2 million pounds accruing from the reuse of materials over its life cycle. This result is a strong indication of the vast amount of recyclable materials utilisation during the design and implementation phases of the building (Figure 5.19) (Sterner, 2000; Kehily and Hore, 2012). Obviously, this demonstrates the quality and quantity of recyclable materials consumption within the building (Flapper *et al.*, 2005; Janssen and Hendriks, 2002). Accordingly, in Building D the economic evaluation from the engineering sustainability perspective suggests the involvement of materials that are probably recyclable at the EoL phase (Blengini, 2009; Clift, 2003). In related studies, Gulch and Baumann (2004), and Ellis (2007), have made similar observations regarding engineering cost evaluation.

5.21.5 Life cycle costs for Building E

The relationship between the LCC (£/FU) and the phases of operation is presented in Figure 5.20. The construction stage accounts for more than £38 thousand pounds of the overall costs implication in Building E. At the operation and maintenance phases, the result shows that over £5 million pounds is anticipated for the entire activities over its life cycle.

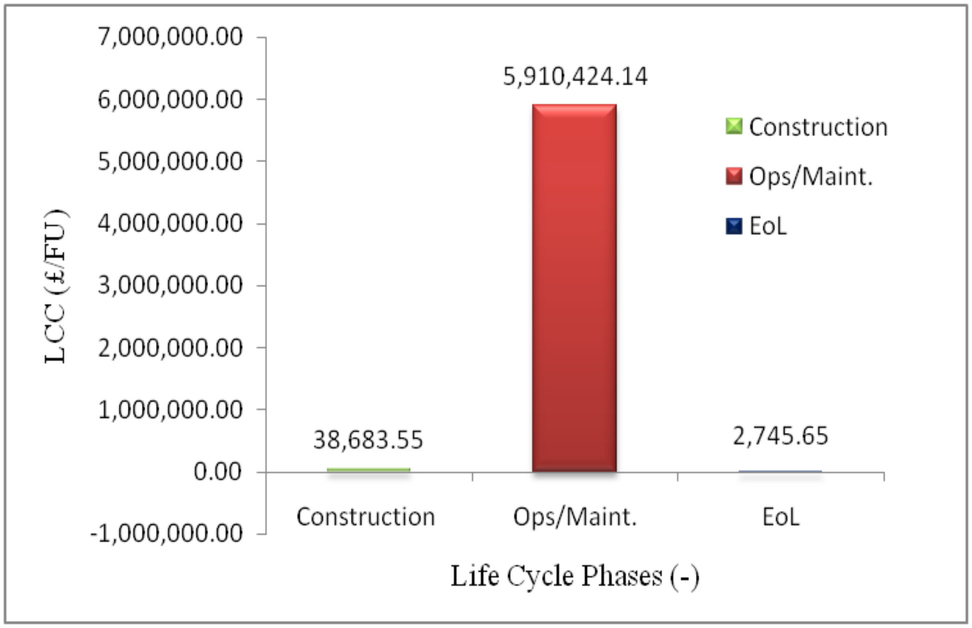


Figure 5.20: Life cycle phases and the LCC (£/FU) for Building E.

The economic evaluation is exclusive of the essential maintenance practices and utilities management within the building over the life cycle. The EoL stage financial involvement shows that the credit gains achieved from the recyclable materials (Flapper, *et al.*, 2005; Sterner, 2000) are more than £2 thousand pounds (Figure 5.20), which is a reasonable amount. This economic costs analysis is a true reflection of the associated quantity of materials, equipment quality and the services provided over the life cycle (Langdon, 2007; ASTM, 2002; Langdon, 2010), and is comparable with findings from earlier studies by Parnell (2008), and Romm (1994), of sustainable buildings management.

5.21.6 Life cycle costs for Building F

Figure 5.21 illustrates the LCC (£/FU) and the life cycle phases for Building F. In this economic costing, the construction stage is seen to cost more than £23 thousand pounds. Operation and maintenance phases account for over £7 million pounds, less the increase in tariff on utilities, maintenance, and the ancillary activities in the building infrastructure.

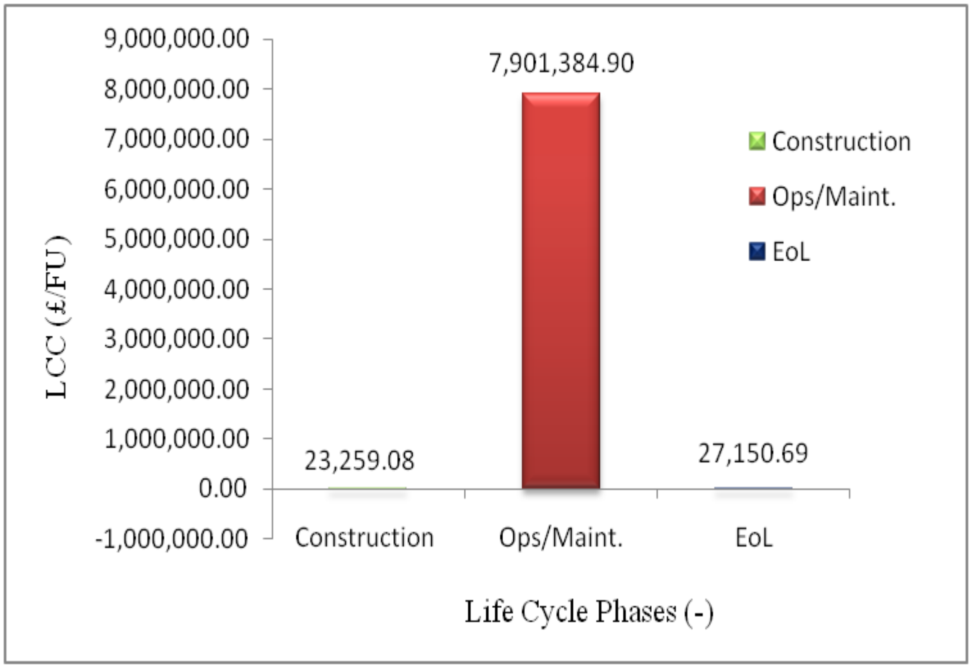


Figure 5.21: Life cycle phases and the LCC (£/FU) for Building F.

At these stages of the building, the economic analysis reveals the use of efficient energy saving fixtures and regular maintenance practices as being crucial (Horner *et al.*, 1997; CIOB, 2003). In addition, proper design through HVAC for energy efficiency and water networking within the building services infrastructure explains the economic functionality for Building F (BREEAM, 2008; CIOB, 2011; Cheshire and Maunsell, 2007).

Figure 5.21 further indicates that at the EoL phase, about £27 thousand will be achieved from the recyclable materials over the life cycle (Flapper *et al.*, 2005; Kehily and Hore, 2012; Sterner, 2000). This result discloses the economic costs benefit analysis in correlation with the materials, quality of equipment installed in the building and the services offered over the life cycle. The finding is akin to the views expressed by Hormer *et al.* (1997), and the DIN (2004) concerning the management of the economic functionality of building infrastructure systems.

5.22 General interpretation of the LCC analysis

The study has reviewed the economic estimates associated with the different life cycle stages of six Buildings A–F and their activities. LCC investigation of building infrastructure sustainability and management is an innovative technique for appraising the total cost (£/FU) of the facility possession. The method used in the LCC addresses the overall cost of acquisition, ownership and disposal within the six building infrastructure systems. Hence, it is crucial to incorporate the method when assessing alternatives so that sustainability imperatives are properly pursued.

In addition, from Figures 5.16–5.21, it is evident that the LCC method is able to present the cost appraisal at the different life cycle stages within these buildings' infrastructures. It is important to note the construction costs in this study are without various sub-heads as reported earlier in Section 5.4, page 179. At the construction phase, the estimates associated with the overall costs of building materials and design that will ensure the infrastructure services, are provided at the lowest costs. These details are as indicated in the discussion sections of this study. Similarly, at the operation and maintenance stages, the building sustainability through the incorporation of the LCC addresses the general performance. These include providing a guide and predicting a sustainable economic model and blueprint for the quality of equipment and installation in the investigated scenarios.

The LCC forecast further supplied the preventive and other mode of maintenance practices pathway in building services infrastructure, for the complete life span (Buildings A–F). These efforts will assist in selecting the best alternative, hence maximising net savings at the various phases of the building infrastructure (Langdon, 2007; Clift, 2003; Sterner, 2000; CIOB, 2003). This analysis is inclined towards guaranteeing that the entire ownership of the infrastructure performance is consistent with its quality and functionality over the life cycle (Horner, *et al.,* 1997; DIN, 2004; Parnell, 2008).

5.23 Contributions to knowledge in study phase V

The research conducted through the current best LCA and LCC practices and in accordance with the ISO 14001 standards, has established significant contributions in this field. This is occasioned by the collection and collation of quality measured field data, and their subsequent analysis. In this study, the data quality was found insufficient for the LCC analysis, but adequate for the LCA study. This study has also offered a value-added potential in the course of appraising the various stages of life cycle stages in relation to building infrastructure performance within the examined buildings. It is expected that suitable building services infrastructure systems should account for the materials recyclability and the probable impacts (Blengini, 2009; Borg and Erlandssona, 2003; Bayer *et al.,* 2010; Flapper *et al.,* 2005).

The application of the various software techniques in examining the buildings services infrastructure sustainability is yet another landmark. In particular, the combination of LCA and LCC methods in this study is new, since this approach has not been used by other researchers in their explorations of building services infrastructure.

5.24 Conclusion in study phase V

The study and findings derived from the research results will assist in the eradication of wastage of energy and utilities, and water, together with other materials usage and duplication that leads to unnecessary costs associated with the building performance. Also, the evaluation confirms the economic importance of reducing wastage at the various life cycle stages, and the impacts and contribution from doing this to the improvement of the entire life value of the building infrastructure. This analysis is able to appraise the life cycle impact and performance of building infrastructure practices in delivering the necessary results. Indeed, a fully progressive model agenda in measuring impacts associated with the buildings life cycle supply chain is contained in this study.

Building services infrastructure sustainability underscores innovative technologies characterised by efficient lighting systems to include sensor-based dimmable controllers. Good quality HVAC, heating installations, safety gadgets (fire alarms) and water supply networks among others, also promote sustainability goals. Additionally, the design and furnishing of sustainable technologies within these buildings will enhance management performance. The outcomes of this study are capable of addressing the overall objectives regarding building infrastructure management. Hence,. this result will serve as a beacon for future studies in building infrastructure systems that are examined from the sustainability and related perspectives.

Chapter Six

6.0 Energy and utilities management, study phase VI

6.1 Introduction

In this Chapter, energy and utilities consumption, waste management, and the carbon footprint were studied in the hospital and education sectors within the UK. The UK's Freedom of Information (FOI) Act 2000 was the main source of data acquisition for both sectors. This data is reliable as individual organisations certify its validity (Appendix VII). Information regarding the participating hospitals (NHS) and schools in this study is in the appendices.

This study contains three broad phases. These are the energy and utilities consumption at the operational phase, and the materials flows during the maintenance and refurbishment stages in the organisations (presented in Sections 6.5–6.6). Generally, waste management practice was also studied and is reported in Section 6.7. Carbon footprint analysis was conducted within the two environments (hospitals and education) and a partial differential equation method also applied to determine the results as shown in Sections 6.8 and 6.10. The study consists of various stages as displayed in Figure 6.1.

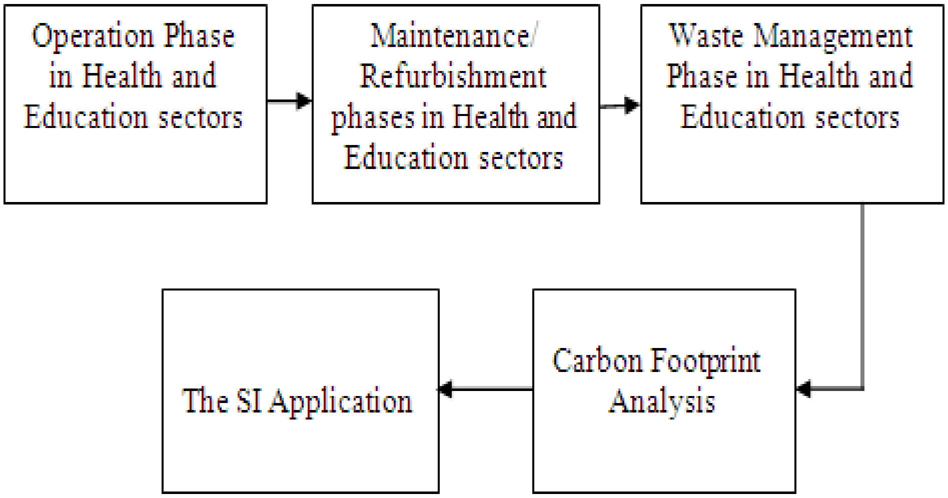


Figure 6.1: The process of study.

6.2 Presenting the study in phase VI

The study evaluates sustainable building infrastructure systems management including energy and utilities, waste, and carbon emissions, within hospitals and schools in the UK. A structured questionnaire was administered to building (facilities), operations and estate managers within hospitals (NHS) and schools across the UK. These experts were able to supply measured data from their organisations' inventory for the analysis. Operations and maintenance phases of activities were examined with a focus on energy and utilities such as water, electricity, natural gas, heating and fuel oil/lubricant consumption. The waste management list also includes segregated and non-segregated waste, recyclable, landfill, incinerated, and other waste.

6.3 Goal and scope definition

The scope of the study consists of evaluating energy and utilities, materials consumption, waste management, and the carbon footprint from the healthcare and education sectors. As indicated, the system is modelled to consider all relevant processes related to these scenarios. Accordingly, from the healthcare and education sectors a functional unit of $100m^2$ was used in conducting the analysis (Blengini, 2009; Peuportier and Herfray, 2011; Gorree *et al.*, 2002). The functional unit was chosen in order to provide a common basis for evaluation within the investigated healthcare and education organisations. This size of building is considered adequate for examining the building services infrastructure activities. The achievable results are discussed at the different phases of this investigation.

6.4 Results and discussion

The results and discussion of the investigation from these sectors are presented in the subsequent Sections 6.5.1–6.11 of this thesis. The various models developed for this study are also included. It should be noted that, the research information as contained in the thesis is the product of statistics provided by the participating NHS and schools within the UK. Hence, the questionnaire feedback in energy and utilities consumption may not demonstrate a true practical situation as observed in this analysis. Appendix VII contains this information.

6.5 Operations phase in the healthcare and education sectors

The energy infrastructure (utilities) management and other relevant information from these sectors is revealed in Tables 6.1 and 6.2 respectively. Energy and utilities consumption data from the NHS in Table 6.1 is reported in two separate perspectives, these being the totality of utilities consumption, and their percentages contribution. The aim is to show the rate of energy and utilities consumption in each case.

6.5.1 Energy and utilities consumption in the healthcare sector

Table 6.1 accounts for the energy and utilities consumption from the operational phase in the healthcare sector.

Table 6.1: Energy and utilities consumption in healthcare sector.

Energy Utilities	Units	Functional Unit	Total Consumption
Electricity	kWh	$100m^2$	10,404,963.0
Natural gas	m^3	$100m^2$	142,254,033.6
Water	Ltrs	$100m^2$	8,230,925.0
Heating	kWh	$100m^2$	7,048.2
Fuel oil/lubricant	kWh	$100m^2$	149,177.3
Total			161,046,147.1

In this analysis, natural gas accounts for 88% of the energy and utilities consumption. Research showed this huge amount of gas use as being because some NHS hospitals employ a combined heat and power station to generate electricity on site. As a consequence, a reasonable quantity of gas has been expended for the electricity generation used for the services delivery in this domain. In addition, electricity consumption from this phase of study is 6% of the overall utilities. This indicates that there is less evidence of electricity utilisation for the energy used within the hospitals than that supplied to the various sites. Although the result on electricity consumption generally shows that there is more apparent electricity usage. Water consumption in this study is 5% of the total utility data. This outcome explains the rate at which water is utilised in the healthcare organisation (Table 6.1).

Obviously, water is commonly used in this sector but the result is based on the data supplied from the respondents. Fuel oil/lubricant consumption accounts for less than 1% of the overall energy and utilities. This fuel oil/lubricant is normally used in the power station on site and equipment (machine) maintenance activities. Fuel oil/lubricant is probably used in equipment operations within this organisation generally.

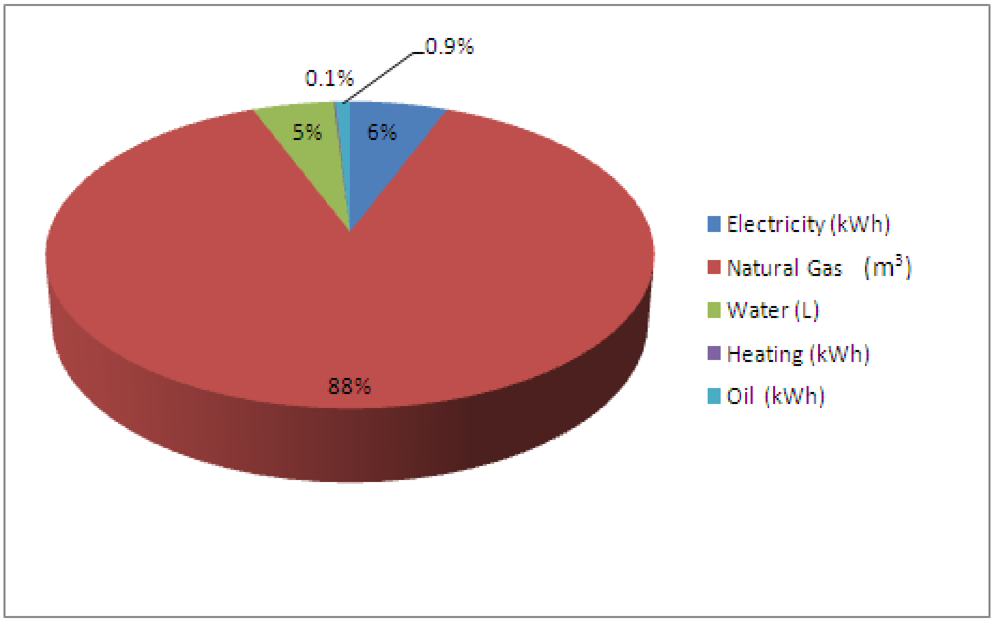


Figure 6.2: Percentages contribution on energy and utilities use, health sector.

The consumption rate of fuel oil/lubricant in this case is not large since its application is limited to few operations. Also heating energy within this sector is less than 1% of the entire investigated utilities. This is because the entire facility does not require space heating at the same time during all of the season (Figure 6.2). On this basis, heating energy utility within the hospital facilities is mainly associated with the occupant spaces and that becomes necessary especially during the winter season.

6.5.2 Energy and utilities consumption in the education sector

Table 6.2 accounts for the energy and utilities consumption from the operational phase in the education sector.

Table 6.2: Energy and utilities consumption in the education sector.

Energy Utilities	Units	Functional Unit	Total Consumption
Electricity	kWh	$100m^2$	349,911.9
Natural gas	m^3	$100m^2$	784,375.9
Water	L	$100m^2$	1,143,433.3
Heating	kWh	$100m^2$	23,852.6
Fuel oil/lubricant	kWh	$100m^2$	6,158.6
Total			2,307,732.3

The energy and utilities consumption statistics from the education sector are shown in Table 6.2. In this analysis, the report is presented in two groups. The first category is the total consumption of the individual utility and the other group is their percentage contribution in each case. Water consumption in the education sector is top marked with almost 50% of the total energy and utilities. This is attributed to the frequent use of water for sanitary services, drinking, laboratory use, cooking and other applications. In actual fact, this result is reasonable as water plays a very significant role in the school systems on a daily basis as indicated in Figure 6.3. This research noted that most of the feedback is exclusive of dormitories (students' halls) whose population is relatively high during term time regarding utilities usage.

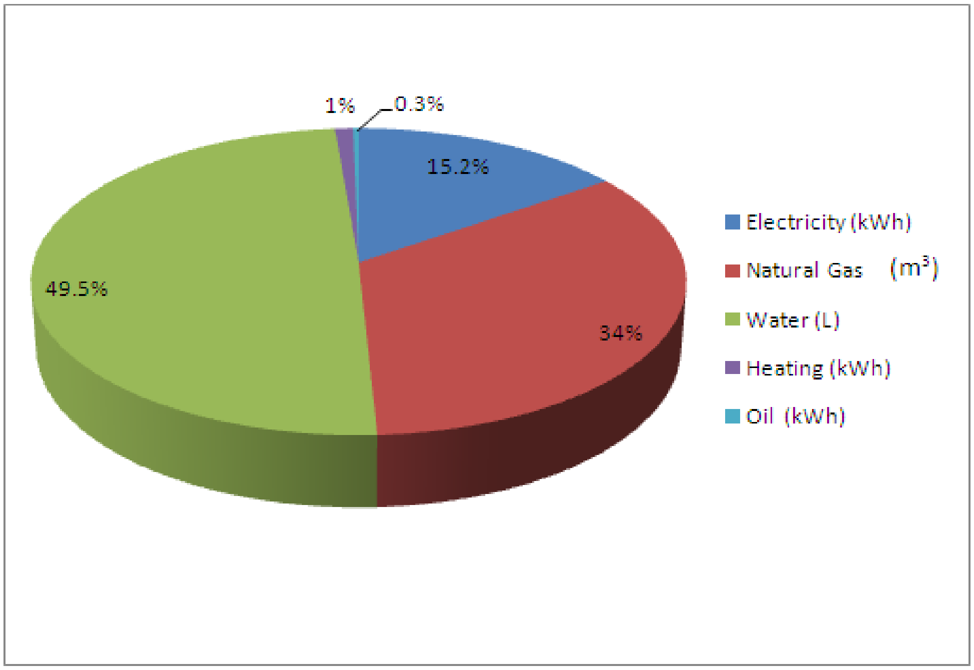


Figure 6.3: Percentages contribution on energy and utilities use in education sector.

Natural gas usage is 34% of the overall energy and utilities consumption. The main reason for the increase in use of natural gas is because some schools utilise the combined heat and power station to generate electricity on site. Therefore, this index accounts for the huge amount of gas used for the electricity generation within the education sector. Certainly, this suggests what is tenable in the other sector previously investigated. Energy consumption from the electricity supply is slightly above 15% of the total energy utilities application (Figure 6.3). The research reveals that the use of a combined heat and power station to produce electricity on site is aimed at reducing the energy bill from the electricity power supplier. The analysis clearly shows that the education sector consumes electricity based on the available data. The result is in agreement with the views of Cheshire (2007), and Cheshire and Maunsell (2007), regarding the management of sustainable building infrastructure activities.

Heating contributes only 1% in this context. It is evident that since the investigation was not targeted at the halls of residence, the result is logical. Presumably, the entire educational facility does not require space heating except where occasionally occupied. Therefore, energy emanating from heating is basically used in the schools facilities when the need arises and most especially during the winter season for cost savings. The least used energy utility is fuel oil/lubricant achieving less than 1%. Fuel oil/lubricant use, primarily in this perspective, is specifically used in equipment, power plant and other machines. The consumption rate of this energy utility is not frequently comparative to other energy and utilities use as shown in Figure 6.3. As such, the result is reasonable from the respondents' opinion and the supplied data (MTP, 2009).

6.5.3 Comparative analysis between the health and education sectors

In a comparative analysis between the two sectors, natural gas usage within the NHS is over 80% of the investigated energy and utilities. This is followed by electricity and water utilisation. The least in this category are correspondingly, heating and fuel/oil lubricant. However, in the education sector, water is leading with almost 50% of the examined energy and utilities being accounted for in this way. Natural gas utilisation is over 30% of the expended resources. Also, electricity consumption accounts for more than 15% of the energy usage. Heating energy and fuel/oil lubricant in this case are less than 2% of the total utility usage. The results from both sectors reflect similarities in percentage classifications among natural gas, electricity, and water utilities consumption. The same indication is found in both energy and utilities with heating and fuel/oil lubricant statistics. This outcome is quite realistic based on the common functional space unit measuring 100m^2 and was examined from both organisations, using information supplied by the respondents.

6.6 Maintenance phase in the health and education sectors

Table 6.3 presents the maintenance and refurbishment statistics from the two investigated sectors.

Table 6.3: Maintenance/refurbishment data in the health and education sectors.

		Health Sector- Maintenance Phase			Education Sector-Maintenance Phase		
Materials Use		Total	Recycling Contents (%)	Distance (km)	Total	*Recycling Contents (%)	*Distance (km)
Steel	kg	3,970	100	250	1,800	90	40
Cement	kg	5,500	85	240	400	100	20
Bricks	kg	41,650	85	245	1,200	100	20
Glass	m^3	2,351	90	90	700	100	30
Plastics	kg	21,430	90	70	275	100	25
Wood	kg	8,900	100	50	2,100	100	45
Water	l	6,000	-	-	-	-	-
Paints	l	6,600	-	80	160	40	55
Blocks	kg	1,280	90	230	350	80	15
Tiles	m^2	11,050	50	20	200	15	10
Vinyl	kg	20,600	100	30	-	-	-

*Distance shows the area of coverage for the delivery of materials to the building sites.

*Recycling contents signify the percentages of individual materials recyclability over the EoL stage.

The maintenance phase indicates the flow of materials and their recycling contents in each case. In the hospital (NHS) sector, the demand for construction materials such as bricks, plastics, vinyl, and tiles is very high. Also, the research information discloses that other materials including wood, paint, cement, steel and glass are among those often required for immediate use. It is also observed that the recycling contents of most of these materials are reasonable and encouraging (Williams, 1999; Holmes, 1995). This demonstrates that a greater percentage of these materials will be recycled over their life cycle and put back to use as contained in Table 6.3.

Certainly, this development will yield many benefits to the system considered as a close-loop supply chain process (Flapper *et al.,* 2005) that promotes the concept of sustainability. That covers the situation where some of these materials (demolished concrete) will be converted into a secondary aggregate and later re-used for infilling activities in construction sites. This effort will prevent the production of virgin aggregates and their transportation to the various construction sites (WW, 2005; WRAP, 2011; WMS, 2012). Then, a greater percentage of plastics, wood, bricks, steel and other materials will be totally recovered and employed for subsequent use over the life cycle. By so doing, the recovering processes through recycling will forestall the production of virgin and primary materials and their freighting issue (Williams, 1995; WRAP, 2011; WBCSD, 2000; WMS, 2012; WW, 2005).

The inventory analysis from the education sector reveals three construction materials with higher rates of supply: these are wood, bricks, and steel. In addition, their recycling contents are rather high signifying that these materials will be recycled and reused at the end-of-life (EoL) (Table 6.3). Additionally, the demands of the other remaining construction materials are moderate. Undoubtedly, with the high recycling contents associated with these materials, a reasonable amount will be recovered for further application over the life cycle (GBPC, 2010; WW, 2005; UKGSD, 2005; GSGF, 2010). This reveals the significance of recycling materials at the EoL stage of any sustainable building infrastructure rather than disposal at the landfill. Furthermore, the carbon emissions evolving in the process of producing virgin raw materials and transportation to the various construction sites will be prevented. The views of Flapper *et al.* (2005) and Baillie (2008) regarding managing closed-loop supply chains in pursuit of sustainability success are echoed in this finding.

6.7 Waste management phase - health and education sectors

6.7.1 Waste management phase in the health sector

Waste generated from the healthcare activities usually comprises a broad variety of materials ranging from used needles, syringes, to soiled dressings. The list includes body parts, diagnostic samples, blood, chemicals, pharmaceuticals, medical devices and radioactive materials (BMA, 1991; WMP, 1995). In this study, healthcare sector (NHS) waste management data is categorised into six waste streams as indicated in Table 6.4. It is apparent that some waste generated by the healthcare sector is either only suitable for high temperature incineration, or is non-recyclable in nature. Some waste is recyclable, landfill, non-burnt or regarded as general waste from a number of products (WMP, 1995; Slater, 1995).

High temperature waste accounts for 1.1% of the overall statistics within the healthcare sector. This is a small volume of waste generated compared to the other waste streams. Landfill waste from the data accounts for more than 60% in this order. The non-burnt waste contributes less than 14% of the total waste stream. Also, the incinerated waste within this category is below 16%. The recyclable waste stream is 3% of the overall waste produced by the healthcare sector.

Table 6.4: Waste management information in the healthcare sector.

Waste Type	Tonnes	Percentages Contribution (%)
High temperature waste	53.48	1.1
Landfill waste	2,986.30	60.7
Non-burnt waste	678.52	13.8
Incinerated clinical waste	773.70	15.7
Recyclable waste	102.52	3.0
General waste	279.90	5.7
Total	4,917.56	100

The general waste statistics show that almost 6% of the entire waste is produced in this phase of the study (Appendix VII). This result is a true reflection of the fact that most of the investigated hospitals are associated with disposable materials. Non-burnt and incinerated waste (equipment and tools) are within the category of waste that must be treated with extra care (Ambruster, 1990, Hall, 2008). The equipment and appliances when no longer put to use are considered as waste and are characterised with the toxic substances emission, as presented in Table 6.4. Waste generated from the healthcare sector due to poor management is capable of producing harmful effects to humans and the environment (Dempsey and Oppelt, 1993; BMA, 1991).

The NHS waste stream produces quite a reasonable amount of landfill and non-decomposable materials which are not reusable. Thus, this flow of landfill waste can potentially expose the health care workers, patients and the waste handlers to severe infections (Hall, 2008; Feuillade, 2008). Frequently, large volumes of landfill waste impacts arise from inadequate management, and enhance toxic effects, pollution to the atmosphere, and health infection (Willams, 1999; Almuneef and Memish, 2003). Recyclable waste is quite environmentally-sound as it can be recovered for further economic applications (WMS, 2012; WRAP, 2011; GSGF, 2010; Hall, 2008). Some waste obtained from the hospital equipment is probably recyclable and can be reused with effective management (WRAP, 2011; Lelyveld and Woods, 2010)(Table 6.4). General waste from the healthcare sector suggests segregated and non-segregated waste (Hall, 2008; Holmes, 1995; GSGF, 2010). Such waste, if properly separated at the source of generation, can invariably yield a reasonable payback, thus encouraging environmentally-sound solutions that contribute to sustainability goals (RCN, 2007; Willams, 1999; Hall, 2008).

The research outcome from the NHS activities is an expression of the current waste management classification and their percentage contributions from the supplied field data. In this scenario, the merits and demerits of the individual waste impacts are presented, and from this understanding it can be argued that more effort should be made within NHS sites to build more waste collection and management stations with a view to segregating waste materials (WRAP, 2011; WW, 2005). The incinerated and the non-burnt waste require expert management of the entire process (Figure 6.4). Improper handling of this waste can result in several environmental health hazards (pollution) and infection (Feuillade, 2008; RCN, 2007; Willams, 1999). But, good quality waste management ethics will guarantee safety of lives and yield more economic benefits (Ki and Qi, 1995). This result is consistent with several evaluation reports on healthcare waste management policy (see WHO, 2004 and WHO, 2007). More details relating to the waste generated in the health sector are presented graphically in Figure 6.4.

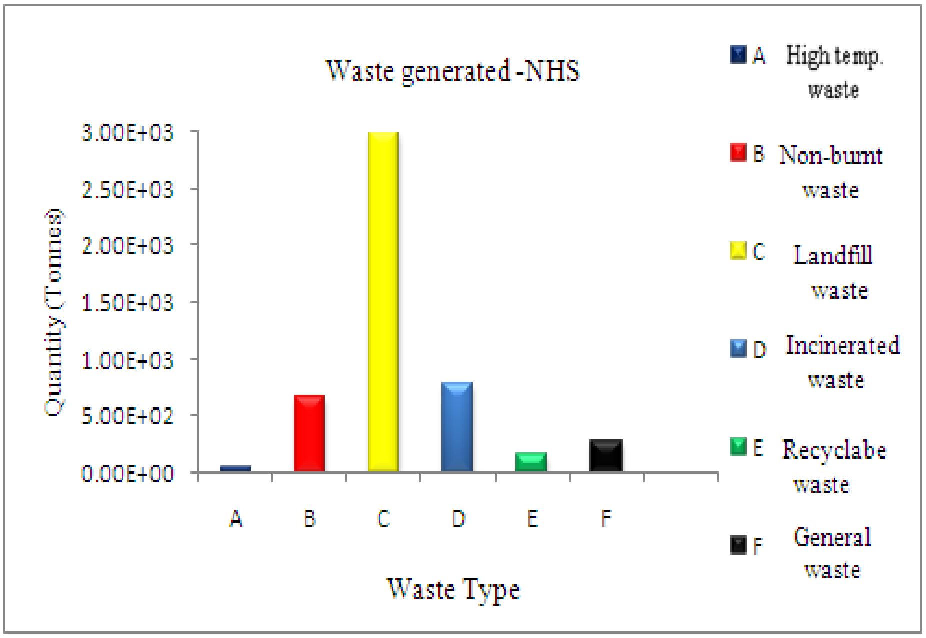


Figure 6.4: Waste generated in the healthcare sector.

The relationship between the quantity of waste produced in tonnes, and the type of waste in NHS activities, is depicted in Figure 6.4. From this plot, it is established that the high temperature waste (A) is slightly above 50 tonnes, and the non-burnt waste (B) is almost 680 tonnes. Landfill waste (C), accounts for the highest in this category with more than 2,900 tonnes of the waste generated for the NHS facilities. The incinerated waste (D) is shown as above 750 tonnes of the total waste stream in the NHS statistics. The trend shows that recyclable waste (E) is little above 100 tonnes, whilst the general waste (F) is almost 280 tonnes of the overall waste information, as shown in Figure 6.4.

Basically, this points towards the need for proper scrutiny regarding the volume of landfill waste generated from the healthcare sector. This high volume of landfill, non-burnt, and the incinerated waste streams within the healthcare sector obviously necessitate suitable appraisal in pursuit of the sustainability agenda. Related studies have also confirmed waste management activities in the healthcare sector and facilities operations (Shah, 2007; Tudor, *et al.*, 2005; Hall, 2008; Willams, 1999; Feuillade, 2008).

6.7.2 Waste management phase in the education sector

The study information regarding the waste management phase within the education sector is shown in Table 6.5.

Table 6.5: Waste management information in education sector.

Waste Type	Tonnes	Percentages Contribution (%)
Recyclable waste	9.1	58
General waste	4.8	31
Other waste	1.7	11
Total	15.6	100

The education sector waste management activities records are shown in Table 6.5. Only three classes of waste activities were identified. Waste management policy generally in this sector is tailored towards reducing, reusing, and recycling. The recyclable waste consists of glass, plastics, packaging, papers, items of furniture and toners. The list also includes chemical bottles, drinks and food cans/containers, lighting bulbs, construction and miscellaneous waste (Shah, 2007; WRAP, 2011). There is no doubt that the percentage contribution of recyclable waste is almost 60% of the total waste produced from the education sector. Interestingly, it indicates a huge volume of waste is recyclable and put back into use thereby saving the exploitation of virgin raw materials (Williams, 1995; WMS, 2012; Holmes, 1995, WRAP, 2011).

Table 6.5 also revealed that the percentage contribution of general waste is a little above 30% of the entire waste stream. Obviously, this suggests the general waste is comprised of either segregated or non-segregated materials. Considering such an amount of waste is produced by the education sector, a proper management system is desired. From this it can be appreciated that it is necessary to effectively manage the waste at the generation point as certain amounts could be made recyclable upon segregation. In essence, the other waste represents a contribution of slightly above 10%, expressing a mix between the biodegradable (grasses), compostable, and other waste substances. There is no strong indication of the existence of landfill waste from this sector based on the acquired information. Studies findings according to (WW, 2005; Coyle and Turner, 2008) are similar to this result in managing waste activities within the education sector.

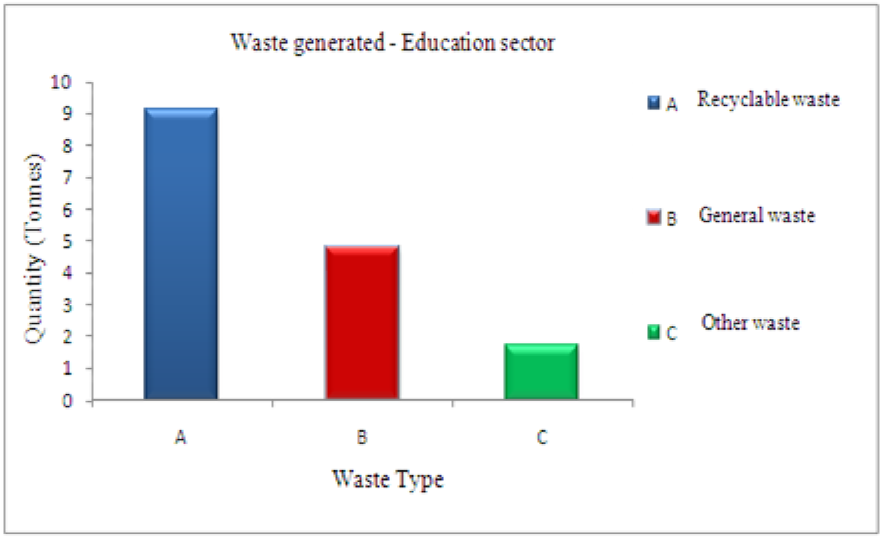


Figure 6.5: Waste generated in the education (schools) sector.

The correlation between the quantity (Tonnes) and waste type from the education sector is shown in Figure 6.5. It is evident that recyclable waste (A) is approximately 9 tonnes and general waste (B) is almost 5 tonnes. Similarly, the other form of waste stream (C) is less than 2 tonnes of the total waste generated in this category. The result sounds reasonable given the large amount of recyclable materials associated with this scenario. The outcome suggests that there is no trace of landfill waste, and hence, the existence of such may be of a very insignificant volume in this case.

In comparative terms, the two scenarios present various, and different, kinds of waste and their percentage contributions are highlighted. Generally, from the obtainable statistics in Table 6.4, the NHS sector has recorded a large volume of landfill, non-burnt and incinerated waste (Tudor *et al*., 2005). These categories of waste are often branded as being air pollutants, and as producing toxic emissions harmful to both human life and the environment (Feuillade, 2008; RCN, 2007). The volume of recycled waste is very small compared to other waste created from this sector (Serb, 2008; Yu and Mclaren, 1995). Indeed, this case requires further research on the materials and methods of waste management with the aim of reducing the volume of non-recyclable waste.

In the education sector, the research found that almost all the waste produced in this context was recyclable and, there was very little indication of non-recyclable waste, as shown in Table 6.5. This result is realistic based on the available data on good waste management practice and it conforms to the findings of other studies (see Coyle and Turner, 2008; Serb, 2008; WMS, 2012).

6.8 Carbon footprint analysis

The carbon footprint examination mainly addresses the energy and utilities consumption statistics from the NHS and education sectors as contained in Tables 6.6 and 6.7. The carbon footprint analysis explains the amount of greenhouse gas (GHG) emissions caused by a particular activity or entity from which organisations and individuals could assess their contributions to the climate change (CCT, 2008; Minx *et al.*, 2008; MTP, 2009). In this manner, the energy and utilities consumption data from these sectors were modelled to show their contributions. This was done bearing in mind the need to control such emissions for the realisation of sustainability. Carbon footprint evaluation was conducted using a carbon calculator (CCalC) software package formulated by Azapagic (2010). It should be noted that the CcalC software is made available in the public domain for application and a snap shot of this package is presented in Appendix VIII.

This analysis captures five different aspects of energy and utilities consumption in both phases of the study and their carbon footprint results are indicated. The details of the results are presented in Figures 6.6 and 6.7 respectively.

6.8.1 Carbon footprint analysis in the healthcare sector

The results show the trend that natural gas is the major driver of the GHG emissions within the healthcare organisation. That said, electricity and water are also within the higher carbon footprint band-width of the leading energy and utilities within this scenario as presented in Table 6.6.

Table 6.6: Carbon footprint appraisal in the healthcare sector.

Energy Utilities Consumption	Quantity (kWh/FU)	CO_2-equivalent (Tonnes/kWh energy)	CO_2- equivalent (Tonnes/FU)
Electricity	1.04E+07	6.25E-04	6,501.41
Natural Gas	1.42E+08	5.04E-05	7,167.04
Heating	7.05E+02	2.46E-04	1.74
Water	8.23E+06	2.60E-04	2,141.10
Fuel oil/lubricant	1.49E+05	3.29E-04	49.03
TCF			1.59E+04

*TCF denotes Total carbon footprint

The carbon footprint impact from these three utilities is considerably high and the emissions so far generated require proper scrutiny. Fuel oil/lubricant and heating energy and utilities produced quite low carbon emissions across the entire phases of the analysed building infrastructure systems. The study by Scott *et al.* (2008) within the NHS also confirms this result. More information in relation to this study is shown in Figure 6.6.

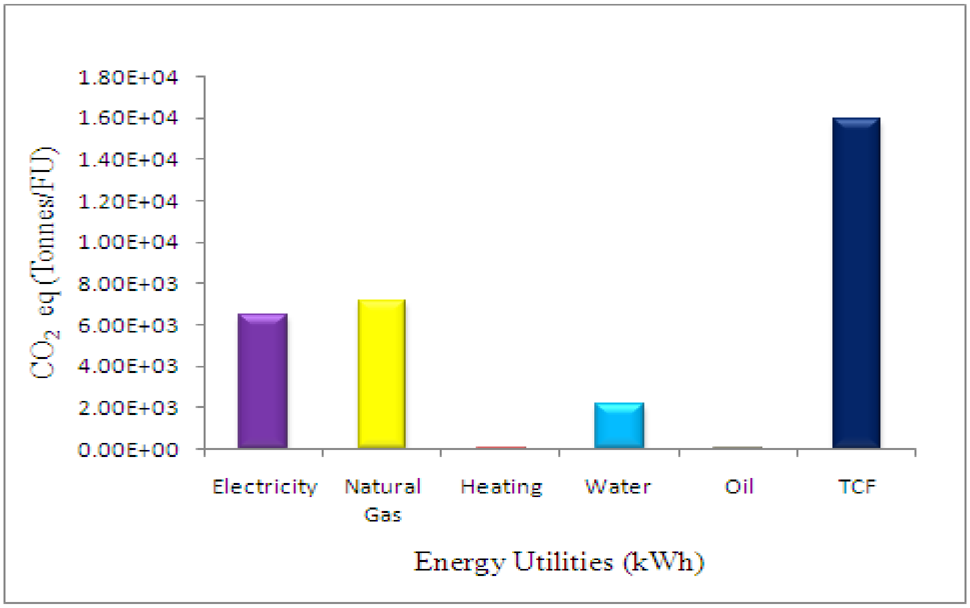


Figure 6.6: Carbon footprint result in health sector.

The graph of CO_2 eq (Tonnes/FU) and energy utilities (kWh) is shown in Figure 6.6. The results concerning the individual energy and utilities with total carbon footprint are also presented.

6.8.2 Carbon footprint analysis in the education sector

The results of the carbon footprint primarily captured the five energy and utilities impacts, with water and electricity leading the GHG emissions in the education sector as presented in Table 6.7. In this case, the other remaining energy and utilities have low carbon emission values. Table 6.7 illustrates the carbon footprint examination in the education sector.

Table 6.7: Carbon footprint appraisal in the education sector.

Energy Utilities Consumption	Quantity (kWh/FU)	CO_2-equivalent (Tonnes/kWh energy)	CO_2- equivalent (Tonnes/FU)
Electricity	3.50E+05	6.25E-04	218.64
Natural Gas	7.84E+05	5.04E-05	39.52
Heating	2.38E+04	2.46E-04	5.87
Water	1.14E+06	2.60E-04	297.53
Fuel oil/lubricant	6.16E+03	3.29E-04	2.02
TCF			5.64E+02

From Table 6.7, it can also be seen that natural gas has produced quite a reasonable emissions impact within this class of energy and utilities. Notably, fuel oil/lubricant and heating energy produced very low emissions among the other examined cases (Figure 6.7).

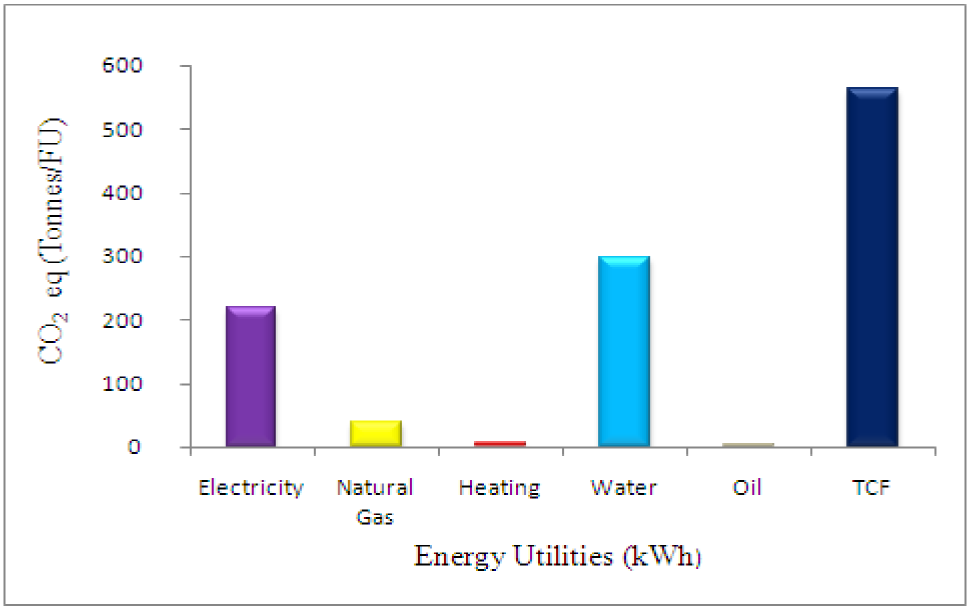


Figure 6.7: Carbon footprint result in the education sector.

The relationship between the CO_2 eq (Tonnes/FU) and the energy and utilities (kWh) is shown in Figure 6.7. As a result, the individual energy and utilities chart with the total carbon footprint is clearly presented for more information.

6.8.3 Comparative analysis between the healthcare and education sectors

This study further examines the current carbon footprint management performance between the healthcare and education sectors. The drive was to ascertain the requirements of the Kyoto protocol with the long-term reduction of carbon dioxide emissions to 80% by 2050 (CCT, 2008; UNFCCC, 2012; UNFCCC, 2009). Figure 6.8 is the correlation between the two investigated sectors and their CO_2 emission ranking.

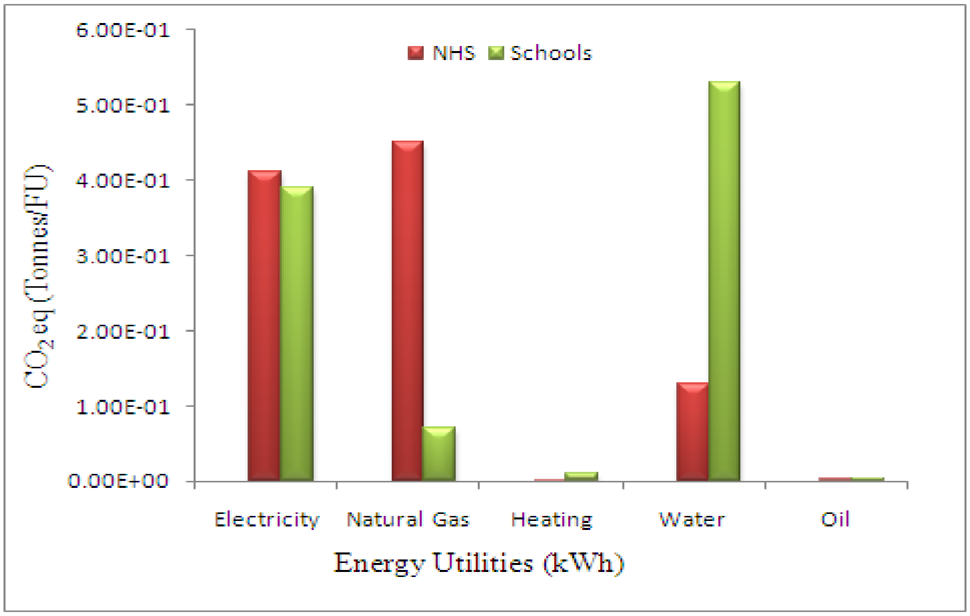


Figure 6.8: Correlation between healthcare and education sectors on CO_2 emission.

The result suggests that energy usage as a result of its demand for electricity, is slightly higher in the healthcare sector than in the education sector. This is probably because the healthcare sector operates throughout the year without any downtime or closing of its facilities, whereas the reverse is true in the education sector. Since, the education sector predominantly operates during term time, the outcome is somewhat reasonable. The natural gas utility consumption result shows that the healthcare sector is leading (Figure 6.8) in this respect. Obviously, this outcome demonstrates the fact that hospitals generally consume natural gas more than schools as they operate throughout the year. Water utility consumption is led by the education sector. This is a reflection of a huge water use especially in the schools' laboratories, hostels and offices (RICS, 2008; Shah, 2007; Hall, 2008).

Within term time, schools often consume a great volume of water and generate wastewater resources, which is not surprising given that the population density of a university is in the range 10,000–25,000 people. These figures include the members of staff, students, visitors and other users within these buildings, which are more likely to use the water facilities (Figure 6.3), and hence the result is realistic. At the same time, the outcomes regarding energy and utilities (heating and fuel oil/lubricant) are negligible demonstrating that their consumption rates are very low in both scenarios. Generally, this study revealed that both the health and education sectors are performing well in respect of the UK carbon reduction plan (CCT, 2008; OCED, 2003; OCED, 2010).

6.9 Probability analysis

Probability analyses related to the two sectors of healthcare and education were studied using Matlab software. In this case, the energy and utilities statistics from Tables 6.6 and 6.7 were exported into the Matlab software to generate data for the graphical plots and evaluation. The rationale behind this analysis was to show the forecast of aggregate carbon footprint from energy and utilities use within the investigated case study (Scott, 2008; Shah, 2007). An effort in this direction is also capable of informing the buildings (facilities) services managers about the carbon footprint activities through energy and utilities consumption (Darby, 2011; Walker, 2007; RICS, 2008; CCT, 2008). The probability analysis algorithm used in this phase of study is given as follows:

- Identify the variables for the individual case in the health and education sectors;
- Develop model equations;
- Create a relationship for the two investigated scenarios;
- Evaluate the data parameters;
- Perform a probability analysis for the carbon footprint examination;
- Plot the graph of the outcomes and verify the results.

The operational boundaries were determined by applying the concept and scope of this study as expressed in Table 6.8. Boundary conditions for both axes were given as:

Table 6.8: Analysis parameters.

Axes	Assigned boundary conditions
x- axis	(0; 297.53; 7167.04)
y- axis	l_0 = 0.75.*x.*(x - 7167.04)./(3583.52 - 7167.04)
	l_1 = 0.65.* x_1.*(x_1 - 297.53)./(149.52 - 297.53)

These boundary conditions were assigned based on the results obtained from this phase of study and to provide for modelling and evaluation in the probability analysis. The generated Matlab information during the study and the outcome of this analysis yielded a snap shot and other details of the carbon footprint plots as illustrated in Appendix VIII.

6.9.1 Probability analysis result

The probability analysis of the carbon footprint in the investigated sectors is shown in Figure 6.9. The probability analysis has delivered the most likely uncertainties associated with the energy and utilities with their carbon footprint impact in both the healthcare (NHS) and education (EDU) sectors. In addition, the energy and utilities consumption rate from the healthcare sector has covered a wider range along the carbon footprint (CO_2 eq Tonnes/FU) compared to the education sector.

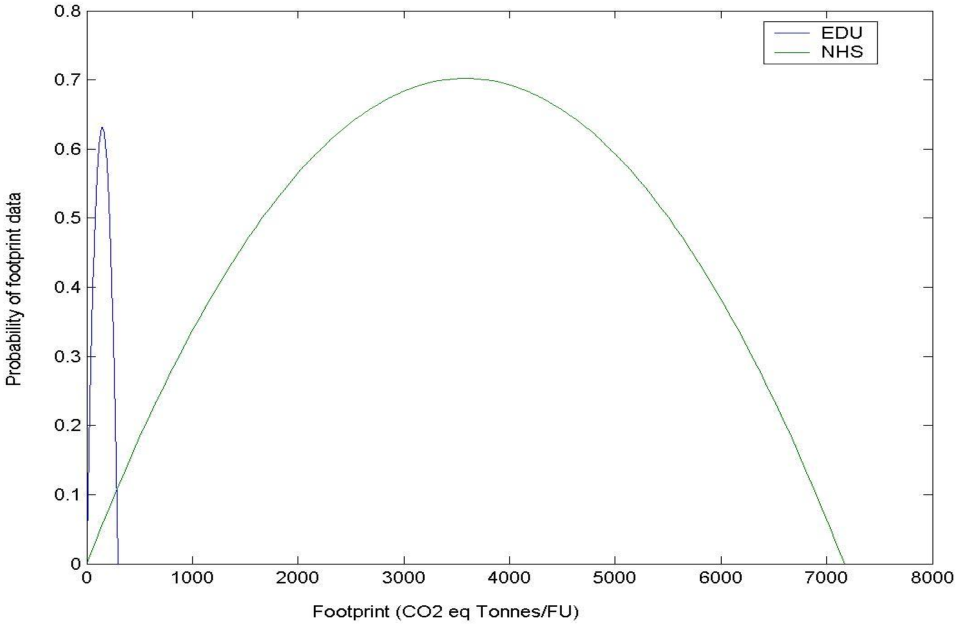


Figure 6.9: Probability result from the carbon footprint in the investigated sectors.

From the probabilistic model anaysis, the healthcare and education sectors are correspondingly estimated at 65–70% of the carbon footprint forecast. Findings also reveal that carbon footprint emissions through the energy and utilities consumption from the healthcare sector achieve higher uncertainty than the education sector. It is further suggested that the carbon footprint produced from the total energy and utilities consumed in both sectors over their life cycle GHG emissions is huge, and therefore, a proper check on these is required. The studies conducted earlier by Killip (2005), and DEFRA (2011) also confirm a related situation. However, the outcomes in this study are based on the data provided through the participatory schools and hospitals in the survey within the UK. They are consistent with several reports in the literature (CCT, 2008; Lelyveld and Woods, 2010).

6.10 Sustainability index

The sustainability index (SI) model as applied in this study aims to address and normalise the three themes of sustainability (values) associated with the carbon footprint of the energy and utilities. On this basis, accurate and reliable indices of sustainability can be qualified and quantified within the healthcare and education sectors. This study employs a combinations (*C*) and permutations function method in Equation (33) of Section 3.9.8 for the examination. Parameters and symbols were assigned to the energy and utilities in Tables 6.6 and 6.7 of this thesis. The governing equations in this investigation are stated in Section 3.9.8. It became expedient to label the energy and utilities with *x* and *y* as shown in Tables 6.9 and 6.10, to enable further analysis. From the SEI model analysis in Section 3.7.3 the mathematical expression in Equation (17) is translated into Equation (38).

$$(X_1 \cup X_2 \cup X_3) = n(X_1) + n(X_2) + n(X_3) - n(X_1 \cap X_2) - n(X_1 \cap X_3) - n(X_2 \cap X_3) + n(X_1 \cap X_2 \cap X_3) \qquad (38)$$

Table 6.9: Energy and utilities with parameters in the healthcare sector.

Energy Utilities	Consumption Rating	Symbols (Xn)	Total	SI Result
Electricity	6,501.41	X_1	15,809.55	0.74
Natural Gas	7,167.04	X_2		
Heating	1.74	X_3		
Water	2,141.10	X_4		
Fuel oil/lubricant	49.03	X_5		

Putting in all the parameters as illustrated in Table 6.9 into the combinations and permutations function application gives the mathematical term in Equation (39).

$$\begin{array}{c} [X_{1,} X_2, X_3]\ [X_{1,} X_3, X_4] \\ [X_{1,} X_4, X_5]\ [X_{2,} X_3, X_4] \\ [X_{2,} X_3, X_5]\ [X_{3,} X_4, X_5] \\ [X_{1,} X_3, X_5]\ [X_{1,} X_2, X_5] \\ [X_{2,} X_4, X_5]\ [X_{1,} X_2, X_4] \end{array} \tag{39}$$

Therefore, from the above expression; for an *N* number of energy and utilities, the sustainability index function satisfies the *NCn* number of sustainable energy and utilities indices derivations.

Taking the last function $[X_{1,} X_2, X_4]$ in the healthcare sector, these are electricity, natural gas and water as the energy and utilities Hence, the sustainability index examination implies the grouping of these energy sources and utilities from Equation (40) for comparison in both sectors;

$$(X_1 \cup X_2 \cup X_4) \tag{40}$$

Therefore:

$$SI_{\text{Healthcare Sector}} \Rightarrow (6501.41 \cup 7167.04 \cup 2141.10) = 15{,}809.55$$

Also, a similar analysis is performed in Table 6.10 for the education sector scenario to ascertain the sustainability index result.

Table 6.10: Energy and utilities with parameters in the education sector.

Energy Utilities	Consumption Rating	Symbols (Xn)	Total	SI Result
Electricity	218.64	Y_1	550.69	0.62
Natural Gas	34.52	Y_2		
Heating	5.87	Y_3		
Water	297.53	Y_4		
Fuel oil/lubricant	2.02	Y_5		

However, putting the parameters indicated in Table 6.11 into the combinations and permutations functions application yield an expression, thus;

$$\begin{array}{l} [Y_{1,} Y_2, Y_3]\ [Y_{1,} Y_3, Y_4] \\ [Y_{1,} Y_4, Y_5]\ [Y_{2,} Y_3, Y_4] \\ [Y_{2,} Y_3, Y_5]\ [Y_{3,} Y_4, Y_5] \\ [Y_{1,} Y_3, Y_5]\ [Y_{1,} Y_2, Y_5] \\ [Y_{2,} Y_4, Y_5]\ [Y_{1,} Y_2, Y_4] \end{array} \tag{41}$$

Furthermore, considering the same function $[Y_{1,}\ Y_2,\ Y_4]$ in the education sector so, electricity, natural gas and water as the energy and utilities yield;

$$SI_{\text{Education Sector}} \Rightarrow (218.64 \cup 34.52 \cup 297.53) = 550.69$$

6.11 Comparison between the healthcare and education sectors via sustainability index

This section further considers the analysis from the achieved sustainability index results in both healthcare and education sectors. This follows the sustainability index procedures as reported within previous studies evaluating the building services infrastructure (BSI) performance (Barret, 1995; UKGBC, 2009; Zulkarnain, *et al.*, 2011; Chanter and Swallow, 2000). The overall aim of adopting the sustainability index analysis method in this study was to normalise the results to unity as demonstrated in the curves shown in Figure 6.10. In this case, the buildings (facilities) at their critical level of performance are indicated. The relationship between the sustainability index results and the normalised time in the healthcare (NHS) and education (EDU) sectors is presented through the application of a partial differential equation method and Matlab analysis in Appendix VIII.

These methods have been able to determine the critical levels at which the building services infrastructure operations are not be exceeded. The plots in Figure 6.10 show clearly the outcomes of these techniques and the additional feature associated with the aforementioned analysis is also presented.

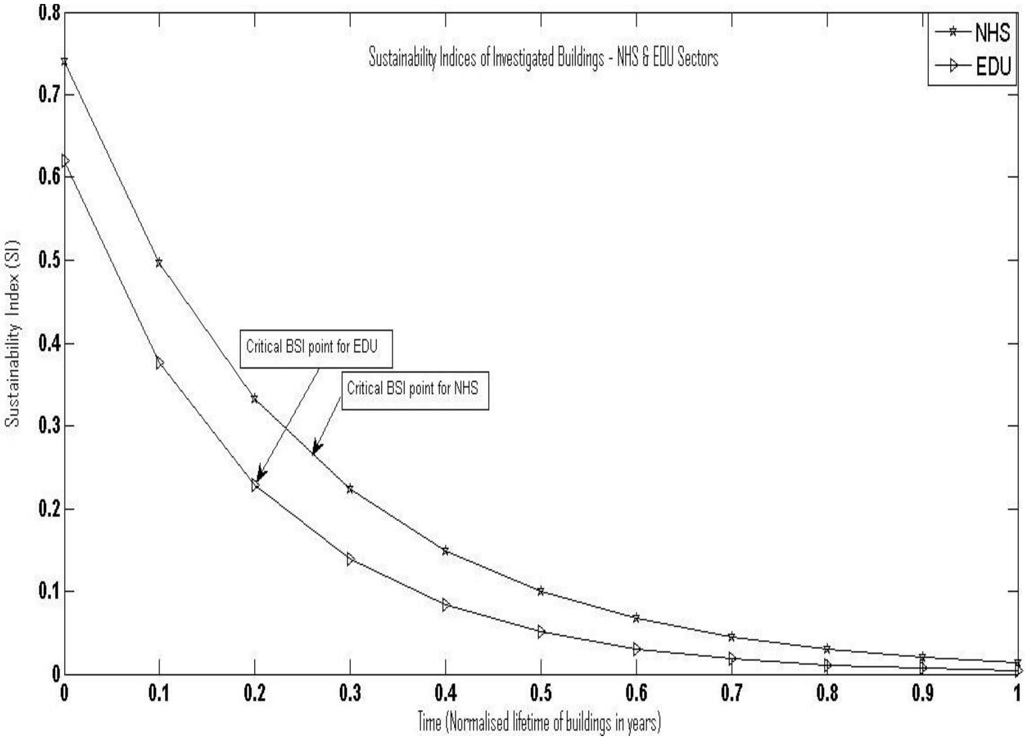


Figure 6.10: SI and time within investigated NHS and education sectors buildings.

The research results indicated in Figure 6.10 are related to the energy and utilities management from the NHS and education sectors. However, more details adduced from these results are presented:

- The analysis of the results shows that the NHS has gained 0.74 and education 0.62 as their sustainability indices respectively as contained in Figure 6.10.
- There is a marked difference between the two sectors as the sustainability index in NHS is 8% higher than the education sector (Tables 6.9 and 6.10).

- The result from this model parameter best describes the three themes of sustainable development which includes economic, social and environmental values. Hence, the combinations and permutations function adopted the same order in selecting from the list of the energy and utilities.
- The findings also indicate the application of combined heat and power (CHP) in energy utility management is explained by the selection approach as effective means of energy mix. However, the sustainability indices results in both sectors are quite good in terms of the services delivery.

These results demonstrate consistency and to further enhance accuracy in this case, a Matlab software technique was used for the computation of the measured field information as presented in Figure 6.10.

6.12 Constraints in study phase VI

The problems encountered during the data acquisition in the research were:

- Difficulties in getting information from the targeted managers in the healthcare and education sectors.
- Delays from some respondents within the investigated sectors in completing and subsequently returning the survey for data analysis.
- Administrative bureaucracies within these organisations, which posed difficulty in the acquisition of data for evaluation.
- Data disclosure and information brokering from some managers and members of staff from these organisations. As a result, they expressed fear of divulging the confidential information in the process of completing the survey.

6.13 Contributions to knowledge in study phase VI

The research outcomes from the sustainability perspective have identified three top energy types and utilities: electricity, natural gas and water. They are found to be the main drivers of the GHG emissions within the investigated sectors. Also, it became necessary to categorise these energies and utilities in order of their carbon footprint magnitude for ease of qualification, quantification, proper control, and management.

Certainly, this effort will assist in the discovery and mitigation of energy and utilities with higher GHG emissions. The application of the combinations and permutations function in addressing the sustainable index in this case is a novel concept in managing building infrastructure systems. Increasingly, the carbon footprint, probability analysis and the sustainability index appraisal approaches will offer a feasibility awareness and resources engineering. Again, a suitable framework for planning building services infrastructure activities and budgeting in the NHS and education sectors is achieved.

6.14 Summary of study phase VI

In this study, the gains of materials recyclability are emphasised. Also, the achievable results from the carbon footprints examination are capable of providing more profitable insight towards the reduction of the GHG emissions within the case study. Besides, the sustainability index result has presented a carbon footprint indicator showing the current situations and the future reduction prospects across the investigated scenarios. This development obviously is very informative not only to the healthcare and education sectors in benchmarking emission targets, but also to the facilities managers. In other words, the operators, consumers and every other facet associated within these sectors can be aware of the impact created from the energy and utilities along with emissions control strategies. Based on the adduced inference from this study, the findings have been able to address the related objectives for sustainability success.

Chapter Seven

7.0 Interviews in study phase VII

7.1 Introduction

Two professionals were interviewed as part of the research as shown in the study presentation in Section 7.2. Also in Section 7.3, the goal and scope definition of the research is stated. An excerpt from the interview session with a professional in sustainability within the building services infrastructure is highlighted in Section 7.4. Section 7.5 presents an analysis of an interview conducted with the Director of Sustainability in BDP Company about building construction projects. The results and discussion arising from the two interviews together with the constraints in this phase of study are indicated in Sections 7.6 and 7.7 respectively. And the contributions to knowledge, conclusion, and the benefits derived from all the phases of this study are presented in Sections 7.8–7.11.4 of this thesis.

7.2 Presenting the study

This chapter reports the interview sessions conducted with two sustainability professionals within the UK. They are (a) the Director of Building Services and Construction Projects Management programme at Liverpool John Moores University (LJMU), and (b) the Director of Sustainability at the BDP Company. Appendices IX and X contain the structured interview questions asked of these interviewees. The interviews were undertaken in line with the research aim and objectives.

7.3 Goal and scope definition

The goal of this study includes appraising the efforts to achieve sustainability in the integration of building services infrastructure systems, and among other areas of interest, the energy and water utilities, materials consumption, and waste management are important. Additionally, the building construction infrastructure systems were also evaluated in view of the sustainability ethics associated with thesein recent times. The scope of the study allows for the inclusion of both private and public sector enterprises within the UK, and their respective infrastructure performance. It is assumed that given the contributions made by the experts, directions for a rigorous approach in the implementation of viable engineering projects for the present and future generations, could be forthcoming.

7.4 Interview with the Director of programme LJMU

This interview was conducted by telephone with a list of structured questions being sent in advance to the interviewee (Appendix IX). The interview was held on the 17/12/09 and lasted for 45 minutes. It was focused on the research aim and objectives with a view to addressing the problems affecting sustainable infrastructure systems and sustainability ethics within the building services infrastructure. The interview analysis is as presented:

The interview began with mutual introductions, after which the interviewer introduced the research topic, "sustainable infrastructure systems management" and sustainability integration within this context.

Q1. As an academic expert in the building services and construction projects management, what are your views regarding sustainability ethics?

As sustainability ethics generally concentrates on the needs of the present without compromising the ability of future generations in every field of human endeavours, basically, the building services and construction projects management are not left out. The implication is that, building services infrastructure has much to do with the life support and security of occupants within the infrastructure systems. As a consequence, this has put much pressure on the resources use such as energy (fuel) and water to mention but just a few. Notwithstanding, from the academic perspective the global warming issues have necessitated more awareness creation and knowledge transfer approach towards this field. Against this backdrop, the requirements of sustainability must be met for any sustainable development to take place.

Q2. What are your views regarding sustainability ethics in the project management and services delivery generally?

Sustainability ethics with a view to the infrastructure projects and service delivery processes start from the philosophy of ‘good engineering’. The term good engineering is very broad but this could be found on a typical projects life cycle framework in this context. However, a good engineer should think of sustainability values in the implementation of projects and services delivery by incorporating sustainability models. On a realistic note, the sustainability focus should be perceived throughout the entire projects life cycle. This has become more imperative in the current trend towards the attainment of sustainability practices in engineering projects management.

Q3. Please, what is your opinion towards the adoption of sustainability ethics in both private/public sectors project delivery?

The outlook of sustainability theory and application into the private sector is now gaining momentum as a driving agenda for purposeful economic development. Furthermore, the public sector in the same vein cannot ignore the sustainability programme for the overall success of building infrastructure growth. Therefore, the recognition of sustainability values within the building services projects need not be overstressed. In general, both private and public sectors have acknowledged the pressure on resources depletion due to absence of sustainability practice in engineering projects. As a result, the agenda in recent times takes a centre stage in the service delivery of projects activities.

Q4. What are the effects of the above on:
(a) Building Services Infrastructure particularly?

The building services infrastructure domain has to be properly integrated into the sustainability as the projects undertaken in this sector cannot be separated from others. On that note, the total projects life cycle in this background should be considered as being fully part of the scheme. Nevertheless, the expert reiterated that there is no meaningful development contextually without the wide acceptability of the sustainability paradigm as the benefits facilitate improved services delivery.

(b) Building Construction projects management scenario?

On the building construction projects management, the idea of sustainability should involve all the factors in engineering plans and feasibility studies generally. That is, the bills of engineering measurement and evaluation (BEME) have to address cost, energy and materials utilisation. Also, the unidentified factors such as sustainable framework with regards to sustainability must be addressed. Consequently, detail analysis of the engineering progress schedule will provide for proper verification of construction work from the inception through completion stages.

Q5. What are the identifiable problems affecting the management practices within this scope?

The identifiable problems are:

(i) Sustainability education awareness: This has posed a lot of problems on the sustainability agenda. However, most people need further learning for the overall success of sustainability values. Therefore, efforts inclined towards this direction will enhance smooth transition of the notion from theory to practice.

(ii) Process identification: It involves the general ethics of the sustainability paradigm and the applications on projects. On this premise, the life cycle analysis and sustainability framework have to be established for a particular project. This will guard against unethical practices within the building services infrastructure projects delivery.

(iii) Economic shift: Explains the eco-energy and financial involvement due to the global warming danger. The experts further corroborate on the inclination towards sustainability has become very important as research reveals on the energy (fossil) fuel depletion in the near future. As a consequence, the energy (fossil) fuel diversification to other energy sources such as biomass, wind and solar becomes innovative concepts. Moreover, wastewater and the grey water resources within some building infrastructure are being recycled. This water management process (recycling) is a sustainability approach in harnessing water resources. Nevertheless, the attitudes of building infrastructure users need to be changed for the realisation of sustainability objectives.

Q6. How can the identifiable problems in Q5 be addressed?

The identifiable problems could be addressed viz:

(i) International and national conferences: This should be encouraged for the awareness creation and propagation of the sustainability values. The Rio de Janeiro earth's summit in (1992), the Kyoto and the Copenhagen conferences were aimed at disseminating information on the eco-shifts and the sustainability principles.

(ii) Academic perspective: The academic sector has a lot to deliver regarding the sustainability practices. As a result, more education awareness has to be encouraged and the curriculum structured to contain the sustainability ideology. An attempt in this direction will facilitate the practice of sustainability ethics within building services infrastructure and construction projects at large.

(iii) Collaboration: On a general note, more collaborative efforts need to be sustained nationally and internationally within the construction industry regarding sustainability. Considering the highlighted facts, the driving forces have to integrate both private and the public sectors in the quest for sustainability attainment in this perspective.

From this interview it was observable that for the building services infrastructure systems to be sustainable, efforts should be made in creating more awareness on the sustainability values. This could be achieved through conferences both nationally and internationally along with a suitable research and development (R&D) drive. Building services infrastructure and construction projects could offer improved service delivery when the users' attitudes are inclined towards sustainability goals. Collaborative efforts in this direction will engender the sustainability principles in building infrastructure systems goals.

7.5 Interview with the Director of sustainability BDP Company

Another interview was carried out with the Director of Sustainability in the BDP Company, Manchester Office, UK. In this case, the interviewer and interviewee met face to face with a list of structured questions as contained in Appendix X of this report. The interview took place on the 23/03/10 and lasted for 1 hour 12 minutes at the company's conference room in Manchester. The agenda for the interview was in line with the research aim and objectives. This interview was performed within the context of sustainability integration into the building construction industry, and it addressed both private and public sector perspectives on sustainability success within the construction sector.

As is common practice, the interview commenced with mutual introductions, and the researcher then introduced the research topic as "sustainable infrastructure systems management" and sustainability integration within the building construction sector.

Q1. As a sustainability expert in building infrastructure projects management, what are your views regarding sustainability ethics in this context?

The sustainability ideal focuses on the needs of the present without compromising the ability of the future generations. The term 'sustainability' within the construction industry generally involves the design, management and operation of the building infrastructure stages. Furthermore, from the design through operation stages, sustainability principles need to be integrated. Buildings in recent time are aimed at achieving low carbon emissions on the full life cycle. Therefore, upon successful design of a low carbon house, the management regarding set targets must be maintained and operated in accordance with the given parameters.

Q2. What are your views regarding the sustainability agenda in the current projects and services delivery?

The importance of sustainability in projects delivery is to improve the economic, environmental and social quality of life as found in the trio themes. That is, the design principles, management and operation earlier mentioned have greater impacts on the resources as a consequence of global warming. But, having integrated sustainability into building construction projects; this global warming could be addressed for improved service delivery.

Q3. What is your opinion towards the adoption of the sustainability scheme in both private/public sector projects delivery?

Observably, lots of progress has been made in these sectors. In the public sector, experiences have shown that for the past five to ten years; funding of projects is driven by: government, regulations, and policies with a focus on sustainability. On the other hand, the private sector is more conscious about public relations, business benefits and the overall interest from the clients. But, both sectors are slightly driven in different ways. However, the duo adopts sustainability-driven approach in the service delivery of projects on this background.

Q4. What are the effects of sustainability scheme on:

(a) infrastructure utilities (i) energy (ii) water management

The sustainablility of energy infrastructure (utilities) focuses on the renewable (biomass) energy schemes, energy conservation, use of solar, photovoltaic and generally for low carbon projects delivery. Consequently, as a sustainability drive, the local energy resources such as wind, sun are efficiently utilised for energy production. This sustainability technology will reduce the dependency of energy from the national grid. Moreover, the local districts can generate and distribute the energy produced locally from this innovative concept to boost the economy.

On water management setting within the building infrastructure systems, the sustainability interests underscore: the minimisation of water (reuse) and grey water technology. It also addresses the prevention of water run-off from flood menace and the efficient management of water resources. However, the application of the highlighted management methods will promote sustainability goals in pursuit of optimising the urban water infrastructure.

(b) Building construction projects management?

In light of the building construction projects, the sustainability know-how focuses on the ecological on-site practice, carbon footprint and generally the building research establishment assessment method (BREEAM). Therefore, the design of building services infrastructure must be in consonance with the guidelines of BREEAM's construction scheme, which increases the sustainability engineering scheme.

Q5. What are the identifiable problems affecting the management practices within this scope?

The identifiable problems in this case are:

- The principles of good quality engineering orientation;
- Good bills of engineering materials and evaluation (BEME) or bills of quantity (BOQ);
- More holistic views of costs associated with the construction materials;
- Knowledge barrier;
- People;
- Risk management;
- Over engineering;
- Knowledge of facilities management activities and the general management approach; and;
- Inexperience on the side of some clients.

The indicated factors from experience have hindered the overall success regarding sustainability management progress within this context.

Q6. Based on (5) above; how can these be addressed?

Consequently, the following suggestions can solve these problems:

(i) Academic awareness: The understanding of sustainability idea is very important as a medium of sensitising the populace on it goals. As a result, the realisation of sustainability principles depends on proper design, educational training, re-training and networking with the building construction industry.

(ii) Cost management: Involves either over or under estimation of cost of projects without taking cognisance of sustainability implications. This is a significant factor that requires proper scrutiny during bidding of contract processes and periodical reviews.

(iii) Improved skills: Sustainability objectives can only be achieved through collaboration; use of suitable frameworks, research and development (R&D). It encompasses technology shift among the three themes of sustainability from academic perspective to the construction industry. Therefore, efforts have to be developed to accommodate this transfer arrangement for quality services delivery.

Q7. What are the government policies regarding sustainability within this context?

Government policies (UK) regarding sustainability could be obtained in the Energy White Paper. Nevertheless, government under the carbon reduction commitment (CRC) target has placed the CO_2 energy emission target at 80% by the year 2050. That is, the industrial sectors have to agree with government energy production benchmark of 600MW as a reduction commitment. Contrary to this target attracts payment of fine to the government from such an organisation. Furthermore, these policies are formulated at the central government level; however, the local government planning authorities are meant for the implementation process. The package contains different standards for the hospitals (NHS), defence, schools and other public facilities with carbon reduction plan targets of 33% by 2020 in this background.

In addition, the performance blueprint regarding water serving management as a sustainability strategy is very rewarding. The government policies drive in this regard ensures that water have to be sustainably managed in the construction sites, homes, facilities and other building services infrastructure. As a result, the overall efforts of government aimed at preventing the menace of water over flooding the buildings or the entire city due to lack of controlling measures.

Q8.What are your views regarding the Copenhagen earth summit (2009) conference on sustainability?

The Copenhagen summit 2009 was unproductive, demonstrating irresponsibility of the leadership in the affected nations to agree on round table deliberations. However, the global warming, energy crisis and the downward eco-shifts have posed threats to the economy and sustainability principles. Therefore, it is becoming more imperative for proactive steps to be taken in addressing these anomalies. It is envisaged that the world leaders on realisation of these problems will rise to the expected challenges and sign up to common consensus. Hence, contentious issues regarding sustainability and economic development have to be addressed through a forum of this nature for the general interest and well-being of citizenry.

Q9. What is the progress made so far from the Kyoto (Japan) conference regarding the sustainability policies till date?

Basically, from the Kyoto conference agreement the United Kingdom government has been able to set some strategic targets (DEFRA, 2006). For instance, the interdisciplinary design of low carbon buildings ought to meet 10% target by 2020. Also, the industrial energy efficiency on equipment usage and the global consumer growth have equally been addressed to meet the aspiration of the forum. Notwithstanding, the endless growth towards targetting the services delivery on energy utilities (electricity, heating) bills is being reduced. On a practical note, the summit is more rewarding concerning sustainability programme on the carbon footprint in energy management.

Q10. What do think that could be achieved now from the integration of sustainability agenda into building infrastructure management generally?

The integration of sustainability into building infrastructure systems management is to improve the quality of life. It could be regarded as a common vision on the resources use, materials consumption, waste minimisation and products recycling. Fundamentally, the overall idea about sustainability in this context is rethinking on the life cycle of resources. Typically, the construction companies through this innovative concept on sustainability are becoming more conscious towards energy utilisation and waste minimisation. Therefore, the entire process of sustainability is a continuity of supply chain knowledge transfer as it cuts across the product life cycle in all facets of development.

Q11. Suggested valuable contributions during the interview session were:

The research should thoroughly investigate on the sustainability gaps and recommend positive ways of addressing the global warming crisis within this sector. More academic awareness should be tailored towards educating the masses on sustainability agenda and its benefits for the present and future generations.

7.6 Results and discussion in study phase VII

The research interviews addressed several issues regarding the sustainability incorporation from the academic and construction industry perspectives. Moreover, the two interviewed experts critically highlighted the benefits of sustainability as measures for improving the quality of life through sustainable development. Some factors were identified as major barriers viz: educational awareness, economic shifts, costs management, and knowledge barriers. The major players for the promotion of the sustainability programme are seen as educational awareness creation, and technology transfer, in respect of sustainability practices. International and national summits are also indicated as a means for policy formulation and implementation.

7.7 Constraints in study phase VII

The constraints were basically administrative bureaucracy in these organisations. It was a difficult task to arrange an interview with these directors. Initially, it was necessary for the researcher to make repeated calls and exchange mail correspondence before any personal contact was made with the director at LJMU. After securing agreement it took two more weeks before the interview was scheduled. In the case of meeting with the director of sustainability at BDP company, the situation was similar. Both interviewees mentioned that their work schedules were busy and that neither would be able to grant any form of interview during working hours except with the approval of their organisations. Generally, there were perceptions that the interviewees were afraid of divulging confidential or sensitive information on the standard of practices to outsiders.

7.8 Contributions to knowledge in study phase VII

There were many benefits deriving from the interviews conducted with these two experts, and the salient points complementing the survey information are noted as follows:

- Identification of gaps between the theory and practice of the sustainability values and mitigation,
- The current trend in respect of the sustainability programme in both building services and building construction infrastructure systems generally,
- The paradigm shift associated with the current sustainable infrastructure systems management,
- The obligatory need to promote the sustainability programme into viable engineering projects,
- The research has established a correlation between the academics and field practice in terms of integrating sustainability schemes into projects management.

7.9 Summary of study phase VII

Findings from both academic and construction industry perceptions have shown a very strong correlation on the significance of the sustainability ethics on the likelihood of sustainable growth. Additionally, the professionals observed that sustainability has become imperative in all fields of human endeavour and that its ideals must be encouraged for economic expansion. The interviewees suggested the following measures for improvement in sustainability practices:

- Educational awareness creation of sustainability ethics;
- Collaborative networking between government and the construction experts;
- Inclination on government policies;
- Cost management education between the client and the contractors;
- Technology transfer on sustainability practice; and;
- Co-operation to engender the cross-fertilisation of ideas through international and national summits.

However, the directors further reiterated the need for a positive change of attitude by the infrastructure users. That is, the resources provided within an infrastructure system have to be prudently managed for the sustainability realisation. Also, more holistic approaches regarding the available resources in this context should be the watchword for the present and future generations.

7.10 Relationship among the entire phases of study, I–VII

All the phases of this study are related in terms of the architecture, components and engineering design for services delivery. Typically, the infrastructure characteristics design in the study phases I–IV provides a holistic pattern of buildings (facilities) settings from the cradle to grave - that is, from the design, construction, operation and maintenance stages of buildings/facilities generally (Grigg, 1988; NSF, 2005). As such, the pattern provided houses all the infrastructure components assessed in the study phase V. Hence, the environmental impact from the installed equipment, energy and utilities consumption and their related costs can be evaluated to ascertain the quality of performance in buildings and facilities.

In the case of the energy and utilities appraisal in study phase VI, their activities are within buildings and facilities as elements of the infrastructure systems. The energy and utilities consumption gradually constitutes environmental impact. Hence, the resultant effects of these energy types and utilities contribute towards the global warming and climate change (PMPCB, 2010; RICS, 2008; Ellis, 2007; CCT, 2008). With the integration of a sustainability programme into building services and building construction activities as core management strategies, this situation could be appropriately addressed. This can only be achieved through suitable innovative design, construction, installation of quality equipment and standard maintenance culture practices in study phases I–V as revealed in the survey data (Horner *et al.,* 1997; Bayer *et al.,* 2010). Nevertheless, the study in phase VII is also related to the other phases of the research activity. In phase VII of this study, structured interviews were used to evaluate the perception of sustainability in the current management practices in building projects and implementation processes. The interview findings were used to corroborate the survey information. On the whole, this study has been able to address all facets of building infrastructure performance from the cradle to grave in terms of sustainability success.

7.11 Benefits derived from the entire phases of study, I–VII

So far, this study has produced many benefits and breakthroughs concerning the concept of sustainability and its integration into building infrastructure systems management in the 21st century generally. The noticeable gains from all the different phases of the study are presented in each case. Moreover, due to the nature of the research, credits from the individual phases of this study are clearly indicated in the thesis. The rationale behind this presentation is to avoid confusing the information, and to promote consistency in the study.

7.11.1 Benefits derived from the study in phases I–IV

Infrastructure characteristics study in phases I–IV have provided more insight into the determination of the impact of the various factors by the use of statistical testing. The benefit has culminated in results which could also enhance practical decisions regarding building services infrastructure management. Moreover, the study in this phase has yielded the development of a sustainable engineering infrastructure (SEI) model, sustainability index matrix, and a partial differential equation method. These techniques are capable of measuring the building infrastructure performance. This is evident as the data were qualified and quantified for sustainability valuation. Obviously, these methods have become innovative platforms for appraising the building infrastructure performance on which corporate organisations can rely when making strategic decisions. Furthermore, these models have become dependable platforms in the engineering domain regarding building management activities.

7.11.2 Benefits derived from the study in phase V

This study in phase V has delivered a generic procedure to verify the environmental impacts of the building infrastructure systems through the application of the LCA method. The LCA technique has also been applied to establish the total costs of ownership of building infrastructure network, and the outcomes with the economic benefits are reported in this thesis. This is a beneficial and interesting discovery concerning the building infrastructure systems management goals.

7.11.3 Benefits derived from the study in phase VI

In this phase of the study, many breakthroughs have emerged concerning the building infrastructure energy and utilities. Basically, measured field data in five energy utilities to include water, electricity, oil, natural gas and heating were obtained from the healthcare and education sectors within the UK. Waste management and materials flows statistics were also received from the above sectors for examination. This study has benefited through the application of the latest version of the carbon emission calculator software CcalC version formulated by Azapagic (2010) in performing the carbon footprint appraisal.

The results obtained are very interesting, providing much insight regarding the type of waste and the management strategies. Energy and utilities appraisal from the two studied sectors is performed using the partial differential equation method. A high achievement in this domain is the modelling of data using the SEI model, combinations and permutations function to obtain results on energy and utilities. Notably, the investigated sectors were examined and their sustainability indices determined through the partial differential equation method, which stands as another innovative approach in addressing sustainability in building infrastructure systems management.

7.11.4 Benefits derived from the study in phase VII

In phase VII of this overall study, the opinions of two experts, an academic, and a practitioner, have been gathered through interviews with each. Both professionals confirmed the need to embrace the sustainability ethics and to integrate these into the building infrastructure, thereby presenting a need for a paradigm shift from the current economic trend. One of the benefits from this phase of the study is the concordance in the views drawn from these experts regarding the actualisation of sustainability success. These include creating educational awareness, collaboration between government and individuals, and good quality cost engineering evaluation.

Technology transfer in sustainability practice within infrastructure systems management has been emphasised. Another gain from this study is the experts' combined belief in the need to address the sustainability challenges concerning the building infrastructure systems management through international and national conferences. This type of platform, they believe, will allow for the cross-fertilisation of ideas for the practical implementation of the sustainability ideals into building projects. Additionally, comments made by the interviewees have been able to bridge the gap between the theory and practice in pursuit of the sustainability principles. On the whole, the benefits are quite significant based on the latest discoveries in managing building infrastructure systems for improved services delivery.

Chapter Eight

8.0 Conclusions and recommendations

8.1 Introduction

This Chapter of the thesis presents the conclusions and recommendations. Section 8.1 considers the general background information regarding the research. In Sections 8.2 and 8.3, the research objectives are revisited, and the overall conclusions are presented. In Sections 8.4 and 8.5, the research contributions to knowledge and limitations are indicated. These contributions are followed by recommendations for practical implementation (Section 8.6), and for future research and policy-making respectively, in Sections 8.7 and 8.8.

Building services infrastructure systems are of great concern as the current practices have placed pressure on natural resources, and indeed crisis, due to managerial inefficiency in dealing with the available resources (Grigg, 1988; GSGF, 2010; Turner, 2006; Wood, 2006). Bearing this problem in mind, this study has produced valuable insight regarding building services infrastructure and building construction projects in the contemporary situation. Investigations in this context have identified the applications, existing challenges, and areas of weakness which could be addressed in the quest to achieve better performance (Okon *et al.*, 2010; Kintner-Meyer, 1999; ASHRAE, 2004). The existing literature in this area of consideration has pointed towards the integration of the sustainability agenda into building services infrastructure systems management as the best practice (Eco Homes, 2003; RICS, 2008; KMPG, 2008). The application of the acknowledged facts regarding building services infrastructure systems management will assist in meeting the set objectives in this research.

8.2 Discussion on the research objectives

The following research objectives on sustainable building services infrastructure systems management are now discussed successively:

- First among the list in the study objectives is the identification of the problems influencing building services infrastructure and building construction practices. Buildings (facilities) in the UK and Nigerian scenarios were appraised.

In this aspect of the study, the emphasis was on reviewing the extant literature, and on devising a questionnaire for piloting. The analysis of the related literature provided the prerequisite information regarding the building infrastructure systems management, the gaps, barriers, and the way forward. The pilot study allowed the researcher to acquire substantial feedback from experts involved in building infrastructure systems management. Using this feedback, the questionnaire was re-engineered, such that the final instrument was based on a combination of information from the related literature and pilot study results.

- The second part of the research objective centered on investigating the parameters militating against the achievement of best practices within the context of this research.

Organisations associated with building services and building construction infrastructure in Nigeria and UK were identified and asked to participate in the study. The views of experts in various organisations that were involved in this pilot study generated more insight and information on building infrastructure systems management. Essentially, this part of the study benefited from the structured survey based on the pilot study, literature analysis inputs, and experts' views. The organisations involved represented both the public private sectors, and the breadth of opinion obtained is featured in the results and discussions.

On this basis, several parameters regarding the building infrastructure systems management in the seven phases of the study were identified, and their results simulated toward achieving the best practice. Typically, in the building infrastructure characteristics study, the survey established 50 characteristics and grouped them into six different headings. These include: (a) energy resources management; (b) water resources management; (c) maintenance management practices; (d) infrastructure design characteristics; (e) infrastructure project characteristics; and (e) external factors affecting building infrastructure systems management. The Nigerian and UK standard of practice were examined on building infrastructure systems management and their outcomes presented.

- The third objective involved appraising the current standard of building services infrastructure systems management performance in both the private and public sectors.

Many building infrastructure systems within the UK and Nigeria have been studied. These include those in the Aluminium Smelting Company of Nigeria (ALSCON), Oil and Gas sectors in Nigeria, shopping malls in the UK (the Manchester Arndale Centre, and the Liverpool One Mall). In addition, organisations from the building construction sector (the Laing O' Rouke Group, Atkins Global, and MHW) provided very useful information, as did the BDP and BAM companies, which gave valuable data regarding infrastructure systems management, particularly in the UK setting.

The evaluation of the current standards of practice in building infrastructure systems management addresses the environmental impacts assessment (EIA), LCA and LCC in respect of six ongoing building services infrastructure systems in the UK. Energy and utilities (infrastructure), and carbon footprint management in the healthcare and education sectors within the UK, were assessed in terms of their ethics as seen in practice. Two interview sessions were also conducted with Directors in the BDP Company, and the LJMU, with a view to benchmarking the current standards of sustainable infrastructure management performance. This aspect of the study considered performance and practice in both academia and industry. Having involved all the organisations mentioned, the researcher analysed the data gathered by employing various methods and software packages to obtain meaningful results, which have been reported.

- The fourth objective in the study focused on the development of models and frameworks. The following were formulated and subsequently applied to test building infrastructure systems in the course of this study.

These are: (a) the sustainable engineering infrastructure (SEI) model on pages 81 and 95; (b) the partial differential equation method on page 97; (c) the sustainable index matrix; 169 and (d) the project life cycle framework on page 57.

So far, the SEI model is being applied in testing several building infrastructure systems within and outside the UK. The SEI model application contextually has been able to qualify and quantify the triple themes of sustainability values for sustainable development success. Recent refereed journal and conference publications generally on sustainability and building infrastructure systems management give credit to the SEI model as an innovative paradigm for sustainable development. It is noteworthy to mention that the SEI model is currently being used as a platform in infrastructure planning and implementation within the engineering community. Several researchers have in recent times found the SEI model very useful in the infrastructure systems management domain. The SEI model is capable of integrating the building services infrastructure systems variables analysis in the interests of achieving improved performance.

The partial differential equation method in this research is established and capable of addressing the building infrastructure challenges in the bid to achieve sustainability. The partial differential equation method application has been able to measure the building infrastructure systems performance within the area (A) for the strategic management decisions. Indeed, the partial differential equation method is a simple approach as it could also analyse various building services infrastructure systems scenarios range $0 \leq S_{uv} \leq 1$ as sustainability index. This information achieved through the partial differential equation method and application will be valuable for the proper evaluation of infrastructure systems.

In this study, the sustainability index matrix is among the developed models. This model is packaged with a catalogue consisting of a sustainable index (SI), infrastructure performance category (IPC) and the remarks on the building services infrastructure systems performance. The mapping in each case in this model indicates the level of building services infrastructure systems status and the potential expectations. Furthermore, the novelty in this model rests on probability theory as it is used in defining the sustainability index range as $0 \leq S_{uv} \leq 1$ for any given system, Table 4.25.

It is found that several studies (see Cheryl, 2008; Grigg, 1988; BREEAM, 2008; RICS, 2000; RICS, 2008) on sustainable infrastructure management have discovered similar findings in appraising services delivery levels. In the present study, building infrastructure systems from different perspectives are considered. This model is beneficial in determining the building infrastructure performance category (IPC) for possible management actions.

The project life cycle framework is also well formulated in this study. The project life cycle framework as proposed in this study addresses the infrastructure systems performance from the cradle to grave. This framework incorporates the LCA, LCC and the ISO 14001 standard to assess the building infrastructure systems services delivery. It also verified the level of building infrastructure systems performance from the construction phase through to decommissioning together with the on/off site recycling processes. Indeed, this framework has been tested on the building services infrastructure systems and also published in a refereed journal by the WCE (2010). The outlined standards are able to measure the building services infrastructure systems performance as this framework has added value to the present study.

- The last objective in this study aimed to apply the developed models and project life cycle framework to test building construction activities. This objective is also tailored towards drawing a comparative analysis and validating the entire phases of the research.

In this thesis, the developed models were applied to the study of several cases related to building services infrastructure within and outside the UK, and their results are presented. The formulated models and the project life cycle framework have hitherto been accepted for publication in several refereed journals and conferences. Remarkably, the developed models in this thesis have been used in studying different building services infrastructure systems scenarios in the UK and Nigeria. The models and framework have been tested and found reliable in evaluating building services infrastructure systems generally. Comparative analyses have been made and their outcomes in each case are presented in this thesis. On the whole, the system approaches as explained have been able to address the entire study challenges regarding building services infrastructure performance.

8.3 Overall conclusion

Seven phases of study were performed within the UK and Nigerian contexts. Basically, infrastructure systems performance has been the main focus in the study in pursuit of sustainability success. The study has presented and discussed the aim, background literature, survey administration, and methods used in conducting the analysis. The results for each phase of the study together with discussions on the results, are also presented. It is notable that the findings demonstrate variations in each case due to the aim and objectives of the different facilities considered.

Phases I–IV address the building services infrastructure characteristics generally. The study reviews different factors that militate against the proper implementation of a sustainable infrastructure management within the UK and Nigerian scenarios. The sustainability index (SI) outcomes indicate the following: O&M = 0.54, BCC = 0.70, ALSCON = 0.47 and MPN = 0.43. But, the critical level of the investigated buildings (facilities) results alternatively yields: O&M = 0.20, BCC = 0.26, ALSCON = 0.17 and MPN = 0.16 in this appraisal.

It has been established that building services infrastructure delivery could be realised through suitable design, construction, operation, and maintenance culture. This drive becomes imperative due to the resources utilisation challenges in the pursuit for optimum and sustainable benefits. On this premise, findings revealed that the following factors are crucial across the entire phases of study: (a) the implementation of suitable design/drawings/envelope/specification and; (b) the availability of safety equipment/ installation within the building/facility; (c) the employment of technical/skilled expertise; (d) the adoption of team working approach; (e) the preventive maintenance culture; and (f) the sustainability of the building services infrastructure. The least crucial are: (a) the maintain as-we-go philosophy approach, (b) the use of water recycling concept, and (c) the weather condition. The conclusion could be drawn that characteristics with higher severity indices have a significant influence within the context of the study, whereas those with lower severity indices are either less significant, or insignificant. It could be further stated the developed SEI model and its application is able to deliver the research objectives.

In phase V of this study, environmental impact and economic life cycle costs of building infrastructure are examined. Building C is leading in environmental impacts and Building D takes the lead in cost evaluation. This study will aid in the eradication of wastage associated with utilities (energy, water), materials, other usage and duplication that leads to unnecessary cost related within the building services infrastructure performance. Indeed, this evaluation confirms the economic importance at the various life cycle stages, the related impacts and their contributions to improving the entire building infrastructure value. This analysis has been able to appraise the life cycle impacts and performance of modern building infrastructure practices in delivering the necessary results. In reality, a fully progressive model agenda in measuring impacts associated with the buildings life cycle supply chain are contained in this study.

However, it is further established that building services infrastructure sustainability underscores innovative concepts characterised with technology mix. This cuts across factors viz efficient lighting systems to include sensor-based dimmable controllers. Good quality heat ventilation and air conditioning (HVAC), heating installation, safety gadgets (fire alarms), and water among others, are in this group. Also, the design and furnishing of sustainable technologies within these buildings will enhance management performance. The outcome of this study is capable of addressing the overall objectives regarding building services infrastructure management. It is hoped that this result will serve as a beacon for future studies in building services infrastructure systems examination generally and the related fields.

Study phase VI accounts for energy and utilities appraisal. Outcomes revealed that energy and utilities consumption in the healthcare sector is higher than in the education sector. The sustainability index results from the NHS and education sectors are correspondingly 0.74 and 0.62. The healthcare sector has 8% in terms of the sustainability index over the education sector based on the acquired data. Other results in this phase of study are presented.

The achievable results from the carbon footprint examinations are capable of providing more profitable insight towards the reduction of the GHG emissions within these sectors. Indeed, the sustainability index result has presented a carbon footprint indicator showing the current situations and the future reduction prospects across the investigated scenarios. This development obviously is very informative not only to the healthcare and education sectors in benchmarking emission targets, but also to the operators, consumers and every other facet associated within these sectors, since all these parties can be aware of the impact created from the energy and utilities with the emissions control strategies. Based on the inferences from this study, the findings have been able to address the related objectives.

The study in phase VII involved the interviews as a measure to validate the other cases. The results have confirmed a strong relationship between the industry and academic perspective in pursuit of the sustainability performance. This is found in the excerpts of the interviews between the researcher and the Directors of Sustainability in the BDP organization, and the LJMU. The methods as applied when examining each different phase of the entire study, are capable of justifying the results in each case.

Findings from both academia and the construction industry have shown strong corroboration on the significant influence of sustainability in pursuit sustainable development success. Also, the two professionals observed that the sustainability agenda has become imperative in all fields of human endeavour and that its principles have to be encouraged for economic expansion. The interviewees have suggested certain measures for the improvement of sustainability practices. These include raising awareness of the sustainability agenda, and collaborative networking between government and the construction experts.

Support for sustainability practices in government policies, and good quality cost management education between the client and the contractors are also suggested. At the same time, the interviewees also identified the need for technology transfer on sustainability practice, and co-operation through international and national conferences since this was believed to engender cross-fertilisation of ideas. There was certainly strong corroboration from this phase of the study for the outcomes of the other study phases I–VI.

Having considered all its findings, the study has drawn several conclusions. These are: (a) the UK Freedom of Information (FOI) Act is an effective source of acquiring quality data as applied in the healthcare and education sectors scenarios; (b) The SEI model (on pages 81 and 95) and the partial differential equation method (on page 97) can also be applied for the determination of building services infrastructure performance other than those stated in this thesis; (c) The sustainability index matrix model formulated in this study is capable of delivering high quality results in building infrastructure utilities performance, and the application of this model could be extended to other systems for critical management appraisal; (d) the sustainability ethics in pursuit of building services management could be advanced through national and international conferences since this effort will simulate the exchange of innovative ideas and best practices towards sustainable development; (e) Mutual co-operation between the industry and academic fields will promote a hybrid of knowledge and understanding in addressing the building services infrastructure challenges for sustainability accomplishment; and (f) The building services infrastructure systems experts should take the centre stage in the design and implementation of standard systems for quality services delivery.

8.4 Contributions to knowledge

In this study, efforts so far have culminated in several novel and technological breakthroughs aimed at facilitating engineering infrastructure systems management progress. This study has demonstrated a quantitative approach to the examination of sustainability-driven building services infrastructure systems, rather than a descriptive approach, and this is novel in this field. Notwithstanding, a qualitative method was also applied to corroborate the quantitative sustainability technique in this thesis. There are other several contributions to knowledge made in this study. Such advancement is established in different phases of this thesis. The study phases I–IV have developed the sustainable engineering infrastructure (SEI) model (on pages 81 and 85) together with the sustainability index matrix for the building services infrastructure management evaluation. These models have been subsequently applied to determine the level of building infrastructure management performance within the four phases of study. In effect, this is yet another discovery in measuring the indices of sustainability from the engineering perspective.

Sections 4.16–4.18 contained the sustainability index to explore the cases, developed through the integration of probability theory and the SEI model into building management for the sustainability success. Also, the application of the infrastructure management model in this study has offered a great benefit in normalising the sustainability values within limits of $0 \leq S_{uv} \leq 1$. Rationally, this development could aid in the strategic management decisions on infrastructure systems generally.

The research in phase V conducted through the current best LCA, LCC practices and in accordance with the ISO 14001 standards, has established very significant contributions in this field. This is found in the course of measured field data collection and collation and subsequent analysis. In this study, the data quality was recognised to be adequate and the application of information was valid and defensible. The study has also offered a value added potential in the course of appraising the various stages of life cycle impacts regarding building infrastructure services delivery within the examined buildings. It is expected that suitable building services infrastructure systems should account for the materials recyclability and the probable impact at large. This finding has contributed immensely to the literature regarding building services operations and management. Apart from this, the study has been able to prove the significance of analysing the life cycle of building services infrastructure delivery for sustainability goals.

On the whole, the application of the various software techniques in examining the buildings infrastructure sustainability is yet another landmark in this setting. Especially, the use of LCA, LCC with the SEI model is not commonly investigated in the context of building services infrastructure delivery, by other researchers in this field. The credits in study phase VI from the sustainability perspective have been able to identify electricity, natural gas and water as the main drivers of the GHG emissions within the investigated sectors. Also, it became necessary to categorise these energy and utilities in order of their carbon footprint magnitude for ease of qualification, quantification, proper control and management. This effort has assisted in the discovery and mitigation of carbon emissions from the energy and utilities achieving the higher GHG impact.

The application of the combinations and permutations function in the determination of the sustainability index in this case is a novel concept in managing building services infrastructure systems. Increasingly, the carbon footprint, probability analysis and the sustainability index evaluation approaches have offered feasibility awareness and resources engineering. Again, suitable frameworks for planning building services infrastructure activities and budgeting in the health and education sectors are achieved.

In phase VII of this study, many benefits are derived from the interviews conducted with the experts. The interactions between the interviewer and the interviewees have disclosed some salient information, which has added value to the study. There is the identification of gaps between the theory and practice regarding the sustainability notion and mitigation. Insight into the current trend of sustainability perception in both building services and building construction infrastructure systems generally, is provided. Other contributions to knowledge in this research are the paradigm shift associated with the current building services infrastructure management and the promotion of the sustainability programme within viable engineering projects. In any case, this study has established a correlation between the academics and field practitioners in terms of integrating the concepts of sustainability into projects management.

Among other benefits from this research, and the contributions to knowledge, is a project life cycle model formulated for building services infrastructure management success. The contributions derived from this study generally have generated a lot more payback within this area of interest. However, the studied scenarios will form the starting point to develop other proactive measures for assessing building services infrastructure systems management activities generally.

8.5 Limitations of the research

In the course of this research, certain factors have posed some limitations. Therefore, it became necessary to present such challenges for consideration in subsequent cases. These challenges are two-fold, beginning with those slightly affecting the study process. They include generally: (a) the inability to acquire data promptly from the participating organisations within the UK and Nigeria; (b) most members of staff expressed fear of divulging the company’s confidential facts in the process of completion of the survey; (c) some managers, professionals, technical directors and stakeholders in the investigated organisations expressed lack of time in their work schedule for either holding interviews or completing the survey; and (d) Lack of co-operation from some organisations (healthcare and schools) within the UK to participate in the study.

Other limitations are associated with the formulated models as applied in this thesis. These are: (a) the sustainable engineering infrastructure model and sustainable infrastructure management model can only be applied to evaluate buildings (facilities) sustainability index within the range $0 \leq S_{uv} \leq 1$. This boundary condition could be applied for other projects of interest; (b) The sustainability index matrix model formulated is used in measuring the building services infrastructure (utilities) performance in this study, but, its application could be extended to other infrastructure systems evaluation. (c) The cost analysis for energy and utilities along with materials as contained in the study phase V were provided by the buildings projects managers; (d) Inability to acquire all the needed data in the supply chain for LCC analysis study. In this case, Davis Langdon and Jacobs Costs Engineering Companies, UK, only provide the overall costs information based on the available data. Hence, the LCC analysis was conducted with this valuation information.

Also, (e) the combinations and permutations function as applied in this study phase VI only consider the selection of three arrays of energy and utilities mix from the list for analysis; (f) The entire results as presented in this study (phase VI) are based on the measured field data obtained from the various participating healthcare and schools as acknowledged; (g) All analysis was conducted within definite boundary conditions for accuracy and reliability of the results.

In phase VII of this study (interviews), the focus was on two sustainability experts; one from the academic world, and the other from industry, within the UK.

8.6 Recommendations for practical implementation

This study has made the following recommendations for practical implementation after addressing the current challenges facing building services infrastructure management goals. The practical steps suggested are:

(a) There is need to adopt innovative technologies and breakthroughs such as water recycling, energy conservation and just-in-time (JIT) management strategies.

(b) The application of economic instruments in appraising building infrastructure projects could guarantee high quality cost engineering management. Economic models to include the LCC and sustainability index matrix among others are capable of making proper forecasts.

(c) Building services experts should incorporate the use of cleaner technologies for eco building systems management design. This explains the sustainable building approach through the application of economically competitive and productive technology with the use of less materials and energy utilities. This will generate less waste, environmental damage than the alternatives as best practices.

(d) Awareness creation regarding the use of building service infrastructure utilities is of necessity based on the current economic trends. Therefore, government and corporate organisations should be actively involved in the promotion of the sustainability agenda in respect of sustainable buildings.

(f) It becomes expedient to adopt economic efficiency strategies in the design and implementation of building services infrastructure systems. This is with a view to minimising the use of resources without compromising the standard of services delivery. This study suggests that the practical implementation of this set of recommendations will support eco-efficiency within building infrastructure utilities for sustainability attainment.

8.7 Recommendations for future research

According to the results obtained in the seven phases of this study, certain recommendations are made for further research. These are offered since it will be more rewarding for future researchers to explore the current achievable results and then develop these through adding value to building services infrastructure system attainment. Hence:

(a) The formulated sustainability index matrix model and sustainability index management model could be applied in testing other projects' performance for a comparison of results.

(b) The combinations and permutations function method as used in the study analysis could be extended to assess more energy and utilities beyond the present situation.

(c) Data should be sought from other organisations to test for their sustainable index regarding the building services infrastructure performance as this approach could guide in strategic management decisions.

(d) More awareness creation through research and development (R&D) could assist in promoting the ideals of sustainability. As such, academic curriculum development should occur to incorporate the ethics and practices of sustainability in pursuit of sound building services infrastructure system.

(e) Building services and facilities management experts, engineers and other players in sustainability need adequate training and re-training to contend with the current challenges in this context.

(f) The SEI model as proposed and applied in this study should be extended to verify the sustainability indices of other systems [equation (17) on Pages 81 and 95].

(g) Due to the inability to acquire all the needed data in the supply chain for LCC analysis study, efforts should be made to acquire sufficient data within the supply chain for LCC analysis regarding building infrastructure systems management. Beyond this, no meaningful advancement could be made in managing building services infrastructure systems without the integration of innovative technologies through flexible design of systems. This is with a view to improving the services delivery associated with energy, water and waste management for eco-efficient building generally.

8.8 Recommendations for policy-makers

Policy-makers should address the following:

(a) Policy formulation through legislation and enforcement should be exercised regarding the sustainability agenda with a view to achieving best practices in the search for sustainable building services infrastructure management.

(b) Further legislative policy frameworks on the waste management activities and implementation should be developed so that waste management policies can be enforced through the use of the reduce, reuse and recycle (3R) model of waste management in building services infrastructure system. It is noted that effort in this direction will culminate in the establishment of 3R-related policies with environmentally sound recycling mechanisms for the promotion of sustainability success.

(c) Political barriers to the LCC application should be removed by policy-making in support of the implementable frameworks in the building industry. Therefore, legislative policy framework and enforcement mechanism are recommended for implementation. This will promote a situation whereby compelling obligations between the clients and contractors are met in the interests of attaining sustainable building services delivery.

(d) An enabling environment for the pursuit of sustainable buildings should be created through legislative policy formulation for the PPP model. This will assist in the technological exchange and funding of building services infrastructure projects activities.

The implementation of the highlighted strategies concerning the building services infrastructure system will encourage the best practices and add value to the effort of addressing the standard of management performance.

References

Aaronson, S. A. (2009), Business and Development, Discussion Papers on Corporate Strategy and Inadequate Governance: The Pitfalls of CSR, Paper II.

ABS, (2012), Australia Bureau of Statistics. Green Growth: Measuring the Environmental Impact of Buildings.

ACLCA, (2008). Life Cycle Assessment Definitions. Available Internet: http://www.lcacenter.org/LCA/LCAdefinitions.html. Accessed on 12/07/13.

Almuneef, M. Memish, Z. A. (2003), Effective Medical Waste Management: It can be done. American Journal of Infection Control, **31**, 3, pp 188 – 92.

Annecke, E. and Swilling, M. (2005), "Building Sustainable Communities in South Africa".

Armbruster, D. A. (1990), Hazardous Waste Disposal and the Clinical Laboratory.

Armstrong, J. H. (1987), Maintaining Building Services- A Guide to Good Practice, 3rd Edition, BSI, United Kingdom.

ARUP, (n.d) Life Cycle Assessment and Life Cycle Cost Tool for Commercial Building Developments in Hong Kong. China. Available Internet: Accessed on 20/08/13.

Ashworth, A. (1999), Cost Studies of Buildings, Third Edition, Longman, ISBN 0 582 36909 – 6.

ASHRAE, (1999), Thermal Environmental Conditions for Human Occupancy. American Society of Heating Refrigerating, and Air-conditioning Engineers, Incorporated.

ASHRAE, (2004), Thermal Environmental Conditions for Human Occupancy. Atlanta: American Society of Heating Refrigerating, and Air-conditioning Engineers, Incorporated, ANSI/ASHRAE standard 55.

ASTM, (2002), American Society for Testing Materials. Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems E 917- 02, ASTM, Philadelphia.

Atkin, B., and Wing, R. (2007), Research Methodology, Unit 1: Research Models Strategies and Methods. PhD-course literature in research methodology, Lund, Sweden.

Baillie J. (2008). Watch your Waste or Pay the Price. Health Estate. **62**, 4 pp.47–51.

Bakis, N., Kagioglou, M., Amaratunga, D., Kishk, M and Hajj, A. A. (2003), An Integrated Environment for Life Cycle Costing in Construction. Construction Informatics Digital Library.

Bardos, P., Lazar, A., and Willenbrock, N. (2009), Sustainable Remediation Forum United Kingdom. A Review of Published Sustainability Indicator Sets.

Barret, P. (1995), Facilities Management: Towards Best Practice, Oxford, Blackwell Science.

Bayer, G., Gamble, M., Gentry, R and Joshi, S. (2010), AIA Guide to Life Cycle Assessment of Buildings, United States of America.

BDP Company, Available Internet: http://www.bdp.com. Accessed on 21/01/12.

Bellandi, R. (2004), Strategic Environmental Management for Engineers, O' Brien & Gere, John Wiley & Sons, Inc., Hoboken, New Jersey, Canada.

Blengini, G. A. (2009), Life Cycle of Buildings, Demolition and Recycling Potential: A Case Study in Turin, Italy. Building and Environment, **44**, pp. 319 – 330.

Bohne, R. A., (2006), "Sustainable Infrastructure". Presentation at the First Policy Consultation Forum of the Seoul Initiative on Green Growth, Seoul, Republic of Korea.

Boyle, C. A., (2005) Sustainable buildings, Proceedings of the Institution of Civil Engineers Engineering Sustainability 158 Issue ES1, pp. 41– 48.

Broers, L. (2005), Engineering for Sustainable Development: Guiding Principles. The Royal Academy of Engineering, London, United Kingdom.

Borg, M and Erlandssona, M. (2003), Generic LCA-methodology applicable for buildings, constructions and operation services – today practice and development needs. Building and Environment, 38 pp. 919 – 938.

BREEAM, (2008), Buildings Building Research Establishment Environmental Assessment Method, United Kingdom.

BSI, (2006), British Standard Institution, "BS EN ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework".

BSI, (2008), British Standard Institution,"Publicly Available Specification PAS 2050:2008: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services".

Cabal, H., Lechón, Y. and Sáez, R. (2005), European Sustainable Electricity, EUSUSTEL; Comprehensive Analysis of Future European Demand and Generation of European Electricity and its Security of Supply.

CCT, (2008), Crown and Carbon Trust, Guide to PAS 2050, United Kingdom.

Cengel, Y. A., Turner, R. B and Cimbala D. (2008), Fundamentals of Thermal- Fluid Sciences. Third Edition with SI Units, McGraw Hill Higher Education, United States of America.

Chanter, B and Swallow, P. (2000), Building Maintenanace Management, Blackwell Science Limited.

Cheryl-Gomez, P. E. (2008), Energy & Utilities. University of Virginia, Facilities Management, (2007–2008) Annual Reports, United States of America.

Cheshire, D. (2007), Sustainability and the Property Life cycle.

Cheshire, D., and Maunsell, F. (2007), Chartered Institution of Building Services Engineers, CIBSE, Guide L: Sustainability meets ASHRAE Green Guide.

CIB, (2004), Performance Criteria of Buildings for Health and Comfort. Construction Industres Board, CIB, Task Group 42, No. 292, Findland.

CIOB, (2003), "Sustainability and Construction", Chartered Institute of Building, Berkshire, United Kingdom.

CIOB, (2010), "Sustainability and Construction", Chartered Institute of Building, Berkshire. United Kingdom.

CIOB, (2011), Building in Construction, Chartered Institute of Building. Carbon Action 2050 White papers from the Chartered Institute of Building, United Kingdom.

CIRIA, (2005), Construction Industry Research and Information Association. Easy Access, Environment Management Case Study 2. Available Internet: www.ciria.org , Accessed on 20/04/12.

Connolly, D, (2007), British Archaeological Job Resource (BAJR): Field Walking and Detecting Survey, Short Guide to Field Survey, United Kingdom.

Cooke, B., and Williams, P. (2004), Construction Planning, Programming & Control, Second Edition, Blackwell Publishing Limited, United Kingdom.

Cooper I. and Curwell S. (BEQUEST), (1997). Building Environmental Quality Evaluation for Sustainability through Time. Proceedings of the 2nd International Conference on Buildings and the Environment, CIB, 2, Paris, pp.515–523.

Coyle, L. and Turner, C. (2008), Waste and Resources Action Programme (WRAP). Materials change for better environment, United Kingdom.

Cleveland, A. B. (2013), Sustainaing Infrastructure: A Brentley White Paper, Brently's Applied Research Group.

Clift, M., and Bourke, K. (1999), Study on whole life costing, BRE Report 367, CRC.

Clift, M. (2003), Sustainable Building and Construction: Life-Cycle Costing in the Construction Sector, Centre for Whole Life Performance, Building Research Establishment, Garston, Watford, United Kingdom.

Cronbach, L. J., and Shavelson, R. J. (2004), My Current Thoughts on Coefficient Alpha and Successor Procedures. Educational and Psychological Measurement, **64**, 3, pp. 391 – 418.

Cuellar, R., and Adisa, A. (2011), Life Cycle Assessment Applied to the Residential Construction Sector: A case study of a detached house in the United Kingdom.

Darby, H., Elmualim, A. A., and Kelly, F. (2011), Case study on the whole carbon cycle in buildings. World Renewable Energy Congress, Sweden, pp. 1781–1788.

DEFRA, (2006), Department for Environment, Food and Rural Affairs, Guidance on applying the Waste Hierarchy, United Kingdom.

DEFRA, (2010), Department for Environment, Food and Rural Affairs, Guidance on applying the Waste Hierarchy, United Kingdom.

DEFRA, (2011a), Department for Environment, Food and Rural Affairs, Guidance on applying the Waste Hierarchy, United Kingdom.

DEFRA, (2011b), Department for Environment, Food and Rural Affairs, Calculations and Emission Factors, United Kingdom.

DEIS, (2010), Draft Environmental Impact Statement, SR 520 Pontoon Construction Project Economics Technical Memorandum, United States of America.

Demsey, C. R. and Oppelt, E. T. (1993). Incineration of hazardous waste: A critical review update. Air and Waste, 43, pp. 25 –73.

Devellis, R. F. (1991), Scale Development. Newbury Park, NJ: SAGE Publications, London, United Kingdom.

DIN EN, (2004), Dependability Management, Part 3 – 3: Application Guide – Life Cycle Costing (IEC 60300-3-3).

Ding, G. K. C. (2008), "Sustainable Construction- The Role of Environmental Assessment Tools". Journal of Environmental Management, **19**, 2, pp. 32 – 37.

Doka, G. (2007), "Life Cycle Inventories of Waste Treatment Service" Ecoinvent Report, No.13, Swiss Center for Life Cycle Inventories, Dubendorf, Switzerland.

Drexhage, J., and Murphy, D. (2010), International Institute for Sustainable Development (IISD). Sustainable Development: From Brundtland to Rio 2012.

D' Souza, N., and Shonfield, P. (2011), Life Cycle Assessment of Electricity Production from a vestas V112 Turbine Wind Plant Infrastructure, Final Report, Randers, Denmark.

Dusart, A., El-Deeb, H., Jaouhari, N., Ka, D., and Ruf, L. (2011), International Stainless Steel Forum. Final Report, ISSF Workshop, Paris.

Dutil, Y., Rousse, D., and Quesada, G. (2011), Sustainable Buildings: An Ever Evolving Target, 3, pp. 443 – 464.

Eaton K. J. and Amato A. A. (1998) Comparative life cycle assessment of steel and concrete framed office buildings. Journal of Construction in Steel Research, **46**, 1–3, pp. 286 –287.

Eco Homes, (2003), Sustainable Homes. A Guide to Eco Homes, an Environmental Assessment Method for Homes. Innovation and Good Practice Programme, United Kingdom.

ELC, (2006), Environmental Literacy Council, "Life Cycle Analysis." Available Internet http: //www.enviroliteracy.org/article.php/322.htm. Accessed on 25/04/2012.

Elhag, T. M. S., Boussabine, A. H. and Ballal, T. M. A. (2005), Critical determinant of construction tendering costs: Quantity surveyors' standpoint International Journal of Project Management **23**, pp.538 – 545.

Elkington, J. (1997), Cannibals with Folks: The Triple Bottom Line of 21st Century Business. Capstone, Oxford.

Ellis, B. A. (2007), Life Cycle Cost, International Conference of Maintenance Societies.

Elmualim, A., Shockley, D., Valle, R. Ludlow, G., Shah, (2010), Barriers and commitment of facilities management profession to the sustainability agenda. Building and Environment, **45**, 1, pp. 58 – 64.

Elmualim, A. A., Roberto, V., and Kwawu, W. (2012), Discerning policy and drivers for sustainable facilities management practice. International Journal of Sustainable Built Environment. 1, pp. 16 – 25.

Epstein, M. J. (1996), Measuring Corporate Environmental Performance. Chicago: Irwin Professional Publishing.

ESCAP, (2006a), Economic and Social Commission for Asia and the Pacific: Sustainable Infrastructure in Asia. Overview and Proceedings Seoul Initiative Policy Forum on Sustainable Infrastructure, Republic of Korea.

ESCAP, (2006b), Economic and Social Commission for Asia and the Pacific, Enhancing Regional Cooperation in Infrastructure Development Including that Related to Disaster Management. Poverty and Development Division. New York: United Nations.

ESCAP, (2011), Economic and Social Commission for Asia and the Pacific: A Guidebook on Public-Private Partnership in Infrastructure, Bangkok.

Fay, M. and T. Yepes, (2003), 'Investing in Infrastructure: What is Needed from 2000 to 2010?', World Bank Policy Research Working Paper 3102.

Fernandez, M. (2010) Impact of the Energy efficient Buildings PPP.

Feuillade F, Francois V, Matejka G, Skhiri N, L agier T. (2008). "Estimate of the pollution removed by leaching of standard domestic waste". Journal of Air Waste Management Association, pp.1529 –38.

Field, A. (2006), Discovering Statistics Using SPSS, Second Edition.SAGE Publication, London, United Kingdom.

Flapper, S. D. P., Van Nunen, J. A. E. E., and Wassenhove, L. N. V. (2005), Managing Closed-loop Supply Chain. Springer Berlin, Heidelberg, New York. United States of America.

Flanagan, R., Norman, G., and Robinson, G., (1989), Life Cycle Costing – Theory and Practice, BSP Professional Books.

Friesecke, F. (2006), The Increased Significance of Public Private Partnerships (PPP) for Urban Development in Germany, pp. 1 – 18.

GBPC, (2010), Introductory Guide to Best Practice in Construction, United Kingdom.

Girouard, N. (2011), Green Growth Strategy. Global Green Growth Summit Seoul, 2020, Paris.

Gorree, M., Guinée, J. B., Huppes, G and Oers, L. (2002), Environmental Life Cycle Assessment of Linoleum in Buildings. International Journal of LCA 7, pp. 158–166.

Grigg, N. S. (1988), “Infrastructure Engineering and Management.” John Wiley & Sons Incorporated, Canada.

Grigg, N. S. (1999), Infrastructure: Integrated Issue or Tower of Babel? Journal of Infrastructure Systems, pp.115 – 117.

Gulch, P. and Baumann, H. (2004), “The Life Cycle Costing Approach: A conceptual discussion of its usefulness for environmental decision-making” Building and Environment, **39**, 5, pp. 571 – 580.

GSGF, (2010), Green Skill for A Green Future, Strategies for Environmental Technologies in Building Services Engineering Sector, 13.

Guinée, J. B., Bruijn, H., Duin, R., Huijbregts, M. A. J., Lindeijer, E., Roorda, A. A. H., and Ven, L. (2001). Life Cycle Assessment. An operational guide to the ISO standards. Centre of Environmental Science, Leiden University (CML) Netherlands. Final report.

Guinée, J. B., (2001): Handbook on life cycle assessment– Operational Guide to the ISO Standards. International Journal of LCA 6, p.255.

Hacking, T and Guthrie, P. (2008) A framework for clarifying the meaning Triple Bottom-Line, Integrated, and Sustainability Assessment. Environmental Impact Assessment Review, 28, pp. 73 – 89.

Halfawy, M. R. (2008), Integration of Municipal Infrastructure Asset Management Processes: Challenges and Solutions. Journal of Civil Engineering, **22,** 3, pp. 216 – 229.

Hall, A. G. (2008), Greening Healthcare: 21st Century and Beyond. Front Health Service Manage. **25**, 1, pp. 37– 43.

Hansen, N. R. (2005), Probability theory and Statistics, University of Copenhagen, Denmark.

Heidi, K. Stranddorf, H. K., Hoffmann, L and Schmidt, A. (2005), Impact categories, normalisation and weighting in LCA Environmental news, No. 78.

Hill, R. C and Bowen, P. A. (1997). "Sustainable Construction: Principles and Framework for Attainment." Journal of Construction management and Economics, **15** pp. 223 – 239.

Hill, R. C., Bergman, J. C and Bowen, P. A. (1994), A framework for the attainment of sustainable construction. In Proceedings of First International Conference of CIB TG 16 on Sustainable Construction, Tampa, Florida, pp.13 – 25.

Holmes, J. (1995). The UK Waste Management Industry. Institute of Waste Management, Northampton, United Kingdom

Home, R., Grant, T., and Varghese, K. (2009), Life Cycle Assessment, Principles, Practice and Prospect. CSIRO Publishing, Australia.

Horner, R. M. W., Haram, M. A., and Munns, A. K. (1997), "Building Maintenance Strategy: a New Management approach" Journal of Quality in Maintenance Engineering, **3**, 4, pp. 273.

InfraGuide, (2003), Investment Parameters for Municipal Infrastructure. National Guide to Sustainable Municipal Infrastructure, Ottawa, ON, Canada.

IPMVP, (2002), International Performance Measurement and Verification Protocol, United States Department of Energy Office of Scientific and Technical Information.

ISO, (1997), International Organisation for Standardisation 14001 Environmental Management - Life cycle assessment - Principles and Framework.

ISO, (2000), International Organisation for Standardisation, 14040: Environmental management – Life cycle assessment: International Organisation for Standardisation, Geneva.

ISO, (2002), International Organisation for Standardisation, 14001: The basics: and environmental management systems for busy Managers, Available Internet: www.iso.ch/iso/en/iso 9000-14000.html Accessed on 21/06/12.

Janssen, G. M. T., and Hendriks, C. H. (2002), "Sustainable Use of Recycled Materials in Building Construction" in Advances in Building Technology, pp. 1399 – 1406.

Junnila, S. and Horvath, A. (2003), Life-Cycle Environmental Effects of an Office Building. Journal of Infrastructure Systems, **9**, 4, pp. 157 – 166.

Kehily, D., Hore, A. (2012), Life Cycle Cost Analysis Under Ireland's Capital Works Management Framework. Proceedings of the Joint CIB, International Conference on Facilities Management, Procurement Systems and Public Private Partnership. Delivering Value to the Community Department of Construction Economics and Management. Cape Town, South Africa.

Keller, F., (2009) Triple Bottom Line Report on Cascade Engineering Fiscal Year. Cascade's LEED-EB Platinum certified building, The Learning Community in Grand Rapids, Michigan, United States of America.

Killip, G. (2005), Emission Factors and the Future of Fuel. Background Material M, 40% House Project, United Kingdom.

Kim, B. J and Qi, S. (1995). Hazardrous Waste Management, McGraw-Hill, New York, United States of America.

Kintner-Meyer, M. (1999), Utility/Energy Management and Controls System (EMCS) Communication Protocol Requirements. ASHRAE Research Project.

Klotz, L., Horman, M. and Bodenschatz, M. (2007), A Lean Modeling Protocol for Evaluating Green Project Delivery. Lean Construction Journal, **3**, 1.

Knoepfel, I. (2001), "Dow Jones Sustainability Group Index: A Global Benchmark for Corporate Sustainability", Corporate Environment Strategy, **8**, 1, pp. 6 – 15.

Korkmaz, S., and Mrozowski, T. (2008), Proposal for the Development of a Decision Making Framework for Minimising the Life Cycle Impacts of Buildings at Michigan State University White Paper.

Koskela, L. (2009), Lean Construction for Sustainable Business Joint CIEF and CPN seminar held at the Centre for Construction Innovation, CUBE, pp.113 – 115, United Kingdom.

KPMG, (2008), International Survey of Corporate Responsibility Reporting, Amstelveen.

Kumar, R. (1999), Research Methodology: A step-by-step guide for beginners. London, United Kingdom: SAGE Publication Limited.

Kvale, S. (1996), An Introduction to Quantitative Research-Interviewing. London, United Kingdom, Sage Publication Limited.

Laing O'Rourke, (2012), Construct and Manufacture Available Internet:/www.lianggorourke.com/about/index.htm Accessed on 21/01/12.

Landman, M. (1999), "Breaking through the Barriers to Sustainable Building: Insights from professional on government initiatives to promote environmentally sound practices."

Langdon, D. (2007), Final Guidance: Life Cycle Costing (LCC) as a Contribution to Sustainable Construction, Davis Langdon Management Consulting, United Kingdom.

Langdon, D. (2010), Final Report: Development of a Promotional Campaign for Life Cycle Costing in Construction, United Kingdom.

Last, J. M. (2003), A Dictionary of Epidemiology, Oxford University Press, New York.

Launch, T. (2005), Connecting East Asia: A New Framework for Infrastructure Asian Development Bank and Japan Bank for International Cooperation World Bank.

Lazarus, N. (2005), Potential for Reducing the Environmental Impact of Construction Materials. Bio Regional Development Group, United Kingdom.

LCI, (2007), Life Cycle Initiative. Life Cycle Management: A Business Guide to Sustainability, United Nations Environment Programme.

Lelyveld, T., and Woods, P. (2010), Carbon Compliance: Setting an appropriate limit for zero carbon new homes United Kingdom.

Lee, W. L and Burnett, J. (2008), Benchmarking energy use assessment of HK-BEAM, BREEAM and LEE, Building and Environment 43 pp.1882–1891.

Lewis, M. K., and Grimsey, D. (2002), Evaluating the Risk of Public Private Partnerships for Infrastructure Projects. International Journal of Project Management, 20, pp.107 – 118.

Lippiatt, B. C. (1999), Selecting cost-effective green building products: BEES approach. Journal of Construction Engineering and Management, pp. 448 – 455.

Liverpool One, Liverpool. Available internet: http://www.qype.co.uk/place/356822-Liverpool-One-Liverpool. Accessed on 22/01/12.

Loosemore, M., Phua, F., (2011), Responsibility Corporate Strategy in Construction and Engineering: Doing the Right Thing? Spon Press, Abingdon, United Kingdom.

Lorenz, D. (2008), Sustainable Property Investment and Management. Key Issues and Major Challenges.

Lundan, S. M. (Ed.) (2004), Multinationals Environment and Global Competition. Elsevier, London.

Manchester Arndale, the centre of the city. Available internet: http://www.manchester arndale.com. Accessed on 21/01/12.

MTP, (2009), BNXS01, Market Transformation Programme: Carbon Dioxide Emission Factors for United Kingdom, Energy Use.

Maxwell, J. A. (1996), Qualitative Research Design: An Interactive Approach, Applied Social Research Methods Series, **41**, SAGE Publications, Thousand Oaks, CA.

McCracken, G. (1988), The Long Interview, Thousand Oaks, CA.

Merriam, S. B. (1988), Case Study Research in Education: A Qualitative Approach. San Francisco, CA: Jossey-Bass Publishers.

Miles, J., and Shevlin, M. (2001), Applying Regression and Correlation: A guide for students and researchers, London. Sage.

Minx, J. Scott, K. Peters, G., and Barrett, J. (2008), An Analysis of Sweden’s Carbon Footprint.

Miyatake, Y. (1994), Sustainable Construction. Keynote address to First International Conference of CIB TG 16 on Sustainable Construction, Tampa.

Moir, L. (2001), What do we Mean by Corporate Social Responsibility? Corporate Governance, **1**, 2, pp. 16 – 22.

Montgomery, D. C., Runger, G. C and Hubele, N. F. (1998). Engineering Statistics, John Wiley and Sons Incorporated, United States of America.

Muto, A. H. S., Petrosjan, L. A., and Raghavan, T. E. (2006), Advances in Dynamic Games Applications to Economics, Management Science, Engineering, and Environmental Management. Boston, MA: Birkhäuser Boston.

MWH, (2012), Building a Better World. Available internet: http://www.mwhglobal.com Accessed on 22/01/12.

NIBS, (2006), National Institute of Building Sciences. The Whole Building Design Guide. Available Internet: http://www.wbdg.org/index.php. Accessed on 25/04/12.

Nebel, B. (2006), White Paper – Life Cycle Assessment and the building and construction industry. Prepared for Beacon Pathway Limited.

Norris, G. (2001), Integrating Life Cycle Cost Analysis and Life Cycle Assessment. International Journal of LCA, **6**, 2, pp.118 – 121.

NSA, (1991), Pay Now or Pay Later: Controlling Cost of Ownership from Design Throughout the Service Life of Public Buildings, The National Academy of Sciences, National Academy Press, Washington, D.C. Available Internet: http://www.nap.edu/openbook/0309044812/html/R1.html.Accessed on 24/04/12.

NSF, (2005) Project Workshop, Rutgers University, "Life-Cycle Assessment of Building Infrastructure". Towards Self-Sustainaing High rise Buildings. United States of America.

OECD, (2003), Organisation for Economic Co-operation and Development: Environmentally Sustainable Buildings – Challenges and Policies, Publications, Paris.

OECD, (2009a), Organisation for Economic Co-operation and Development. The Economics of Climate Change Mitigation: Policies and Options for Global Action beyond 2012, OECD, Paris.

OECD, (2009b), Organisation for Economic Co-operation and Development: Green Growth Strategy – Beyond the Crisis: Discussion Paper for the Consultation with the OECD Liaison Committee, Paris.

OECD, (2010), Organisation for Economic Co-operation and Development: Green Growth Strategy Interim Report: Implementing our Commitment for a Sustainable Future, Paris.

Okon, B. B., Ekpo, S., and Elhag, T. S. (2010), A Sustainable Engineering Infrastructure (SEI) Model for the 21st Century. Journal of Lecture Notes in Engineering and Computer Science, 1, **2184**, pp. 1101 – 1105.

Okon, B. B., and Elhag, T. S. (2011), Sustainability Index: An Application into Sustainable Engineering Infrastructure Management and Assessment. Journal of Mechanics Engineering and Automation 1, **1**, pp.18 – 31.

Okon, B. B., and Elhag, T. M. S. (2011) Infrastructure Assessment: A Case Study of Aluminium Smelting Plant, Nigeria. Journal: Lecture Notes in Engineering and Computer Science, **2192**, pp. 2052 – 2056.

Okon, B. B. and Elhag, T. M. S., (2011), Sustainable Engineering and Innovative Technology in Managing Infrastructure Systems, 10th International Research Conference on Quality, Innovation & knowledge Management, Malaysia.

Okon, B. B. and Elhag, T. M. S., (2011), The Role of Education for Sustainable Engineering and Technology in Construction Infrastructure. Proceedings of the Engineering Sustainability (ES) Conference, University of Pittsburgh, United States of America.

Okon, B. B. and Elhag, T. M. S., (2012), The Sustainable Infrastructure Management Model (SIMM): International Conference on Systems Engineering and Engineering Management. World Congress on Engineering and Computer Science (WCECS), San Francisco, United States of America.

O'Leary, Z. (2004), The Essential Guide to doing Research. SAGE Publications, London. United Kingdom.

Ortiz, O., Castells, F., and Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. Construction and Building Materials, **23**, pp.28 – 39.

Park, C. S., and Tippett, D. D. (1999), "Engineering Economics and Project Management" Mechanical Engineering Handbook, Ed. Frank Kreith Boca Raton: CRC Press LLC.

Parnell, G. S., Driscoll, P. J., and Handerson, D. L. (2008), Decision Making in Systems Engineering and Management, Hoboken.

Patrick, H., Barbara L., Bare, C. Jane, C., and Rushing, A. S. (2002). BEES User Preferences for Life-Cycle Decision Support Tools: Evaluation of a Survey of BEES Users, NISTIR 6874 (Gaithersburg, MD): National Institute of Standards and Technology.

Paulsen, J. (2001), Life Cycle Assessment for Buildings Products: The significance of the usage phase, Doctoral thesis, Sweden.

Pedersen, E. R. (2006), Making Corporate Social Responsibility (CSR) Operable: How Companies Translate Stakeholder Dialogue into Practice. Business and Society Review **111**, 2, pp. 137–163.

Petrovic- Lazarevic, S. (2006), ISO 14001 Improving the Construction Industry’s Competitiveness, Working Paper 44.

Petts, J. and Eduljee, G. (1994). Environmental Impact Assessment for Waste Treatment and Disposal Facilities. Wiley Chichester, United Kingdom.

Peuportier, B and Herfray, G. (2011), Low resource consumption within buildings and constructions by use of LCA in design and decision making. Deliverable D3.1 Building LCA good practice report, Armines.

Pitt, M. (2005), Trend in Shopping Centre Waste Management. Facilities 23, 11/12. pp. 522 – 533.

PMPCB, (2010), Performance Measurement Protocol for Commercial Buildings, Spatial Systems Associates, United States of America.

Pope, J. Annandale, D., and Morrison-Saunders, A. (2004). Conceptualising Sustainability Assessment. Environmental Impact Assessment Review, 24, pp. 595 – 616.

Price, A. and Newsome, E. (2003), Strategic Management: Considerations of Paradoxes, Process and Associated concepts as Applied to Construction. Journal of Management in Engineering, **19**, 4, pp.183 – 192.

Prudhomme, R. (2004), Infrastructure and Development, Paper prepared for the (Annual Bank Conference on Development Economics, ABCDE). The World Bank and Oxford University Press, pp.153 –181.

RCN, (2007). Royal College of Nursing “Safe Management of Healthcare Waste” RCN Guidance. pp. 1–17.

REGENER, (1997), Application of the Life Cycle Analysis to buildings European methodology for the evaluation of environmental impact of buildings. Detailed description and review, United Kingdom.

Revelle, W., and Zinbarg, R. E. (2008), Coefficients Alpha, Beta, Omega and the GLB: Comments on Sijtsma 11. The Psychometrika.

Richard, W. (1996), Corporate Environmental Management Systems and strategies second edition, Earthscan.

RICS, (2000), Royal Institution of Chartered Surveyors, Building Maintenance: strategy, planning & procurement, RICS, Business Services Limited, United Kingdom.

RICS, (2008), Royal Institution of Chartered Surveyors, Building Maintenance: strategy, planning & procurement, RICS, Business Services Limited, United Kingdom.

Rio Summit, (1992), Rio Declaration on Environment and Development. Institute for Global Communications, http://habitat.igc.org/agenda21/rio-dec.htm.

Romm, J. J. (1994), Sustainable Building Technical Manual Lean and Clean Management.

Royal BAM Group, (2012). Available Internet: www.bamgroup.com. Accessed on 10/01/12.

Sabol, L. (2008), Measuring Sustainability for Existing Buildings. The power of process in the built environment. IFMA, World Workplace.

Sattertherwaite, D. (2001). “In The Earthscan Reader in sustainable Cities”.

Scott, K., Minx, J., and Barrett, J. (2008), NHS England Carbon Emissions Carbon Foot printing Report, Sustainable Development Unit.

Serb, C. (2008), Think Green. Hospital Health Network; **82**, 8, pp. 22 – 6, United Kingdom.

Shah, S., (2007), Practice for Facilities Manager. Blackwell Publishing, Oxford, United Kingdom.

Shen, Y., and Spainhour, L. (2001), "IT: A Potential Solution for Managing the Infrastructure Life Cycle," Journal of Computing in Civil Engineering, **15**, 1, pp.1– 2.

Sioshani, F. (2011), Energy, Sustainability and the Environment: Technology, Incentives, Behaviour. Butterworth Heinemann, Oxford.

Slater, D. (1995), Integrated Pollution Control and Waste Minimisation. The Royal Society of Chemistry, Cambridge, United Kingdom.

Smith, J. K. (1998), The Nature of Mathematics, Eight Edition, Brooks/Cole Publishing Company, England, United Kingdom.

Smith, N. J. (2008), Engineering Project Management, Third Edition, Blackwell Publishing Limited, Oxford, United Kingdom.

Smith, K. (2009), "Climate Change and Radical Energy Innovation: The Policy Issues", TIK Working Papers on Innovation Studies, No. 20090101, Centre for Technology, Innovation and Culture, University of Oslo, Unites States of America.

Sterner, E. (2000), Life-Cycle Costing and its Use in the Swedish Building Sector, Building Research & Information, **28**, 5/6, pp. 387 – 393.

Stroud, K. A. (2001), Engineering Mathematics, Fifth Edition. Industrial Press Incorporated, New York. United States of America.

Sunesh, R. H., and Egbu, C. O. (2004). "Knowledge Management: Issues, Challenges and benefits for a sustainable urban environment."

Szalay, Z., Budavari, Z., Brown, N., Malmqvist, T., Peuportier, B., Zabalza, I., Krigsvoll, G., Wetzel, C., Cai, X., Staller, H and Tritthart, W. (2011), Low resource consumption buildings and constructions by use of LCA in design and decision making. Indicators and weighting systems, including normalisation of environmental profiles.

Tetrevova, (2006), Theoretical and practical aspects of PPP projects. Vadyba/ Management, pp. 105 – 110.

TG, (2003), Task Group, Life Cycle in Construction, Final Report, United Kingdom.

Thompson, L. L. (2001), PATH Final Report on Life Cycle Assessment Tools to Measure Environmental Impacts: Assessing Their Applicability to the Home Building Industry. Available Internet: www.pathnet.org, Accessed on 10/02/12.

Tudor, T. L., Noonan, C .L, Jenkin, L. E. T. (2005). “Healthcare Waste Management a case study from the national health service in Cornwall NHS, United Kingdom”. Waste Management, **25**, pp. 606 – 615.

Turner, R. K. (2006), Sustainability Auditing and Assessment Challenges. Building Research and Information, **34**, 3, pp.197 – 200.

UKGBC, (2009), United Kingdom Green Building Council: Code for Sustainable Buildings, Campaign for a Sustainable Environment.

UKGSD, (2005), United Kingdom Sustainable Construction Government and Sustainable Development HM Government, Securing the Future – The UK Government Sustainable Development Strategy.

UKSC, (2006), United Kingdom Sustainable Construction Review. Available Internet: http:// www.berr.gov.uk/files/file34979.pdf, Accessed on 27/02/12.

UM, (2002), University of Michigan, Sustainability Assessment Report. United States of America.

UN, (2003), United Nations, ‘‘World Urbanisation Project: the 2002 revision’’, New York: The United Nations Population Division.

UNCTAD, (2003), United Nations Conference on Trade and Development, A Manual for the Prepares and Users of Eco-Efficiency Indicators.

UNFCCC, (2009), The United Nations Framework Convention on Climate Change, ‘‘the draft of the Copenhagen Climate Change Treaty’’, pp. 3 – 181.

UNFCCC, (2012), The United Nations Framework Convention on Climate Change. Available internet: http://unfccc.int/meetings/copenhagen_dec_2009/ meeting/62 95. php Accessed on 22/02/12.

Varun, B. I. K. and Prakash, R. (2008), LCA of renewable energy for electricity generation systems-A review on Renew Sustain Energy.

Walker, D., Pitt, M., Thakur, U. J. (2007). Environmental management systems: information management and corporate responsibility. Journal of Facilities Management **5**, 1, pp. 49 – 61.

WB, (2004), World Bank Infrastructure Services in Developing Countries: Access, Quality, Costs and Policy Reform. Policy Research Working Paper 3468.

WB, (2010), "About Us." The World Bank. Available Internet: http://web.worldbank.org/WBSITE/EXTERNAL/EXTABOUTUS/0,, contentMDK: 20040565~menu PK: 1696892~page PK: 51123644~piPK: 329829~theSitePK: 29708, 00.html. Accessed on 22/04/12.

WBCSD, (2000) World Business Council for Sustainable Development Eco-Efficiency: Available Internet: Creating More Value with Less Impact,

WCED, (1987), World Commission on Environment and Development- Our Common Future, 42, 427 World Commission on Environment and Development, United Nations.

Welford, R. (2003), Corporate Environment Governance Programme, Project Report 5. Corporate Social Responsible in Europe and Asia: Critical Elements and Best Practice.

White, B. (2008), Rethinking Standards in Construction: BSI Constructing Excellence in the Built Environment, United Kingdom.

WHO, (2004), World Health Organisation, Healthcare waste management. Fact sheet, No. 281.

WHO, (2007), Waste from Healthcare Activities, Fact Sheet No. 253.

Williams, P. T. (1999) Waste Treatment and Disposal. John Wiley & Sons Incorporated, United Kingdom.

Winther B. N. and Hestnes A. G. (1999) Solar versus green: the analysis of a Norwegian row house. Solar Energy, **66**, 6, pp. 387 – 393.

WMP, (1995), Waste Management Planning: Principles and Practice. Department of Environment, London, United Kingdom.

WMS, (2012) Waste Management Strategy. City University London, United Kingdom.

Wood, B., (2006). The role of existing buildings in the sustainability agenda. Facilities **24**, (1/2), pp. 61 – 67.

WRAP, (2011), Waste and Resources Action Programme, United Kingdom.

WW, (2005), Waste Watch, Resource Management in the Education Sector, United Kingdom.

Wyatt, D. P. (1994), Recycling and Serviceability: The Twin Approach to Securing Sustainable Construction. In Proceedings of First International Conference of CIB TG 16 on Sustainable Construction, Tampa, pp. 69 – 78.

Yin, R. K. (1984), Case study research: Design and Methods, Newbury Park, CA: Sage. Publications, Incorporated.

Yin, R. K. (2003), Case study research: Design and methods. Thousand Oaks (Ca): Sage Publications, Incorporated.

Young, J. W. S. (1997), A framework for the ultimate Environment index-putting atmospheric change into context with sustainability. Environmental Monitoring and Assessment, 46, pp. 135 – 149.

Yu, C.C and Mclaren, V. (1995), A Comparison of Two Waste Stream Quantification and Characterisation Methodologies. Waste Management and Research, 13, pp. 343–361.

Yudelson, J. (2008), European Green Building Technologies: A Report on Research Conducted for the Mechanical Contractors Education and Research Foundation, United Kingdom.

Zabalza, I., Aranda, A. Scarpellini, S., and Diaz, S. (2009), Life Cycle Assessment in Building Sectors: State of the Art and Assessment of Environmental Impact for Building Materials. Ist International Energy, Life Cycle Assessment and Sustainability Workshop and Symposium (ELCAS) NISYROS, Greece.

Zimmermann, M. (2005), Life Cycle Cost. Norderstedt.

Zulkernain, S. H., Zawawi, E. M. A., Rahman, M.Y. A and Mustafa, N. K. F. (2011), A Review of Critical Success Factor in Building Maintenance Management Practice for University Sector. World Academy of Science, Engineering and Technology 53.

Appendices

The content of the appendices are as follows:

Appendix I contains the manuscript of survey used in studying the infrastructure characteristics in phase I – IV.

Appendix II provides some worked examples for the severity index and coefficient of variation analysis within building infrastructuctre characteristics study, phases I – IV.

Appendix III holds the building services infrastructure characteristics analysis in Chapter Four.

Appendix IV is the enclosure of questionnaire regarding the building infrastructure material flows. The data were analysed for the environmental impacts and life cycle cost evaluation in the study phase V.

Appendix V provides the normalisation and weighting factors analysis information in Chapter Five.

Appendix VI presents the questionnaire information for the healthcare and education sectors in the study phase VI.

Appendix VII gives statistics as feedback regarding the participating UK hospitals and schools for the energy utilities (infrastructure) assessment in the study phase VI.

Appendix VIII shows the carbon footprint analysis from the healthcare and education sectors in the study phase VI.

Appendix IX accounts for the structured interview questions during interview session with the Director of programmes, LJMU, UK in the study phase VII.

Appendix X contains for the structured interview questions during interview session with the Director of sustainability, BDP, company, UK in the study phase VII.