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MULTI-CRITERIA ASSESSMENT FOR ENVIRONMENTAL SUSTAINABILITY OF BUILDINGS

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Thesis submitted in partial fulfilment of the requirements for the degree Doctor of Philosophy

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SRMSR CHANDRATILAKE

A thesis submitted in partial fulfilment of the requirements of the University of Moratuwa for the degree of Doctor of Philosophy

DECEMBER2015

DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any materials previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where acknowledgement is made in the text.

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ABSTRACT

In the last couple of decades there has arisen a crowded toolbox of quantitative methods used to assess construction sustainability. The evolution of the assessment systems shows the interest in quantifying sustainability with a range of very specific indicators. The majority of the existing sustainability assessment methods for buildings evaluate performance of buildings for a selected set of domains, with a lot of commonality.

This study focuses on the building sector and as the first step relevant domains were identified though comprehensive analysis of available assessment systems. Site, energy efficiency, water efficiency, material, indoor environmental quality and waste and pollution are the identified domain for the study. Secondly, aspects of (criteria for) the selected domains were identified and the relative importance of the domains and aspects was established by an expert survey. Thirdly the overall domain weights were compared with those assigned by other rating systems, originating from different countries to find the correlation which can demonstrate the influence of national contexts for relative weights in rating systems.

The fourth step is to analyse the applicability of continuous functions to assess the sustainability in contrast to step functions to facilitate 'assessment' rather 'rating' of buildings. Fourth aspect of this research is to establish the dependencies and influences between indicator scores within domains. The matrix representation was used to handle these direct and indirect influences. Finally the research focused on optimisation techniques that can be used to handle tradeoffs between indicator scores and to arrive at acceptable indicator combinations with optimised environmental sustainable scores for a given building.

It was found that in the building hierarchy the "system" level is the most important, having over fifty percent of overall weight. In the building lifecycle, the "operation" stage is the most important phase. There is also strong coupling between the operation stage and system level. Good correlation was found between national statistics and the weights, demonstrating that national contexts influence the relative weights in rating systems. The outcome of the dependency evaluation shows that there are considerable dependencies between indicator scores. It was found that the proposed optimisation technique is truly useful to arrive at planning strategies that yield high environmental sustainability scores for buildings while accounting for negative dependencies.

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ABBREVIATIONS

AHP	Analytic Hierarchy Process
CCM	Common Carbon Metric
CED	Cumulative Energy Demand
LEED	Leadership in Energy and Environmental Design
EPD	Environmental Product Declarations
ERA	Environmental Risk Assessment
GBC	Green Building Council
GHG	Green House Gas
IOA	Input Output Analysis
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LC-ZEB	Life Cycle Zero Energy Buildings
MFA	Material Flow Accounting
SDI	Sustainable Development Indicators
TQA	Total Quality Assessment
ZEB	Zero Energy Buildings

PUBLICATIONS

Journal Publications

- Chandratilake, S. R. and Dias, W. P. S. (2014). Ratio based indicators and continuous score functions for better assessment of building sustainability. *Energy*, 83, 137-143

- Chandratilake, S. R. and Dias, W.P.S. (2013). Sustainability rating systems for buildings: Comparisons and correlations, *Energy*, 59, 22-28.

Conference Papers

- Chandratilake, S. R, Dias, W. P. S.(2012). *Relative importance of lifecycle and hierarchy stages for sustainability of buildings.* Paper presented at the ICSECM Conference, (135-143), Peradeniya, Sri Lanka. December 2012.

- Chandratilake, S. R, Dias, W. P. S. (2009). *Object oriented model for sustainability of buildings*. Paper presented at the IABSE Symposium, (178-182), Bangkok,August 2009.

Chapter One

Introduction

1.1 Background to the Research

Buildings are substantial CO_2 emitters and contribute substantially to climate change (Reed and Wilkinson, 2008; Wilkinson et al., 2008). This argument is based on the large environmental footprint of buildings; especially when considering the high consumption of resources due to an increased reliance on air conditioning and heating. In addition buildings consume more than 40% of materials and resources that are produced in the world. More than 35% of the total water demand is used by the operational requirements of buildings. At the same time it has been demonstrated that the value of a building can be linked to the building's perceived level of sustainability (Myers et al., 2008), where the stakeholders include building owners, tenants, and property appraisers or valuers. The problem therefore lies with how to characterize the level of sustainability in a building, which will facilitate a direct comparison among buildings. This is where sustainability rating tools can potentially play a major role.

Many countries, including Sri Lanka, have introduced new rating tools over the past few years in order to improve the knowledge about the level of sustainability in each country's building stock. On the one hand, it can be argued that the individual characteristics of each country, such as the climate and type of building stock, necessitate an individual sustainability rating tool for that country. However, to varying degrees the rating tools for different countries are constructed broadly on similar principles. This in turn has created acceptance for stakeholders, including property investors, who purchase buildings in different countries; an understanding of some contextual differences between each market has been uncomplicated to understand (Dixon et al., 2008).

While it is accepted that there are no matching parcels of land in the world (Australian Property Institute, 2007), in a similar manner every country is also unique. However, there are common approaches to appraising buildings and analyzing their sustainability values in each country, and it appears that rating tools have followed this commonality to a great degree; although at first sight they are relatively complex and inconsistent.

While it is possible to directly compare the value of an office building in Colombo city, Berlin, London or Melbourne using a ten-year discounted cash flow approach (after allowing for exchange rate variations), making a similar direct comparison of the sustainable features and rating of the same building is quite complex. It can be noted that most countries with existing or emerging rating tools have fairly developed economies and most often there is also a property market where information is readily available. The diverse range of countries and associated conditions cannot be commonly observed. This has created a barrier for developing countries to have their own rating tools.

Many of these rating tools measure sustainability of the building product and have been developed to determine the grade such as certified, silver, gold and platinum (LEED, 2013) or in 'star' ratings (Green Star, 2014). But such assessments are not capable of capturing the possibilities for optimisation. 'Indicators' are also an important part of the range of tools available and relate readily only to aspects that can be directly measured; many of the aspects are assigned scores based on observer judgement, which challenges the credibility of assessment objectivity. It is important to identify the key aspects for the assessment, and appropriate indicators used for to reflect those aspects. In general, there should be an attempt to: provide a genuine measure of a building's effect on the environment; and through this to encourage continuous improvement to optimize building performance and minimize environmental impact.

1.2 Problem Identification and Rationale

Contemporary sustainability assessment systems are based on the sector and domain framework, where transportation, building, infrastructure etc are identified as different sectors and water, energy, materials etc identified as domains within the selected sector (Chandratilake and Dias 2014). Further those domains are divided into aspects. These aspects can also be referred to as criteria for the domains, but in this thesis we will always use the term 'aspects'. The majority of the existing sustainability assessment methods for buildings evaluate performance of buildings for a selected set of domains, with a lot of commonality. The interest of practitioners to check the application of sustainability in the building lifecycle is also appealing. There is some literature on lifecycle quantitative assessments with regard to some of the common aspects like energy and carbon emissions, but with respect to overall aspects it is largely absent. Similarly there is very little literature on the influence of the

building hierarchy stages on sustainability; this may be equally important for decision making. Therefore this research intends to cater to those gaps and evaluate critical phases of the lifecycle and stages of the hierarchy in terms of environmental sustainability

Almost all the rating tools are having weights assigned for domains and aspects. But there are only a few cases (Ali and Al Nsairat, 2008) where the basis of arriving at those weights is explained. It is clear that many of those systems relied on expert surveys to arrive at weights. Any approach to arrive at weights for domains and aspects should face the inherent issue of subjectivity. One way in which the subjectivity of weights can be assessed is to study the extent to which they are inter-subjective – i.e. the degree to which there is agreement (among group of professionals) regarding the allocation of weights to aspects and domains. So it requires a survey to obtain the local weights for selected building sustainability domains and aspects.

The differences for domain weights in different rating systems can also be seen as embodying subjectivity. However, these systems have arisen from differing national contexts, e.g. LEED (2013) from the U.S. and BREEAM (2013) from the U.K. There is no literature to date that systematically explains such differences in domain weights, for examples as reflecting national concerns. This too will be explored in this research (Chandratilake and Dias, 2013).

Another feature of most rating systems is the allocation of marks by evaluators, which can be subjective to an extent. So there should be an attempt to define a quantity that reflects the given aspect of sustainability being assessed. In other words aspects should be assessed quantitatively to minimise the subjectivity. The quantified aspects need to be converted into normalised values (ratios) for the purpose of adding them together to arrive at an overall score for environmental sustainability. This work proposes such an approach.

The main difficulty when arriving at normalised values is the lack of local benchmarks for those indicators. Since most of the available benchmarks are not specific to the local context, it is doubtful that they are relevant to the assessment. Therefore this study plans to collect those benchmarks by using case studies for the generation of benchmark values. Even though the assessment is heavily dependent on the accuracy of those values, the overall assessment method proposed in the study can accommodate changes to the benchmark values so that they can be improved as and when more accurate data is accumulated.

One of the features of current rating systems however is that certain minimum requirements have to be met for each aspect before getting any credit for that aspect; a building with an aspect that is judged as being just below this threshold does not get any credit to its overall score from this aspect. This may be alright for buildings that seek to get 'star' ratings, but is inappropriate when comparing the overall sustainability indices of buildings or design alternatives. Therefore this study focuses on evaluating the appropriateness of continuous indicator score functions for the environmental sustainability assessment.

Most rating systems and tools use simple marking systems to arrive at their respective ratings. Initially aspects are assessed based on assigned marks the summing of which gives the domain marks. Then the domain marks are added to arrive at the total sustainability score, based on which the rating is determined.. This study focuses on different combination methods, which accentuate the effects of aspects that are especially important to decision making.

Because of the nature of the aspects, a given aspect can influence others, while itself being influenced by others too. For example a good score for land use (i.e. preserving free plot space) will tend to increase the score for landscape design too; while a high score for housing density will tend to reduce that for land use. Available rating tools are not capable of capturing such dependency and essentially assume aspect independence. But these dependencies can significantly influence any attempt to optimise the overall sustainability score. Exploring those dependencies and accounting for that would help to arrive at more sustainable planning strategies, especially where inverse dependency is present.

Table 1.1 gives a summary of the above discussion and helps to convert the above issues, which can be also treated as research questions, into objectives for this study. The above issues or research questions can be seen as arising from research gaps in the literature and critiques of current rating/assessment tools.

Table 1.1: From issues to objectives

	Issues / Research Questions	Objectives
1	Aspects are classified into domains but are there other ways of distributing?	Consider hierarchy and lifecycle classifications
2	Are there significant differences among individual perspectives of sustainability?	Conduct Questionnaire survey
3	Why are there differences in national rating schemes?	Relate differences to country statistics
4	There can be subjectivity of scores in the assessment	Convert aspects to ratios, to make the assessment more objective
5	There is a lack of local benchmarks	Use green building applications to arrive at these benchmarks
6	Use of step functions does not reward sustainability contents below the benchmarks	Explore different types of continuous functions to generate scores
7	There is the possibility of dependency among aspects	Assess the dependency of the aspect indicators
8	Can there be multiple combinations of strategies to optimize the overall sustainability score?	Explore the combinations using a formal optimization scheme accounting for aspect dependencies.

1.3 Objectives of the Study

1. To explore alternative methods of classifying environmental sustainability aspects of buildings.

   The aim of this objective is to identify the alternative methods of classifying aspects that could be practically useful to analyse the influences of aspects in different perspectives (in addition to classifying aspects only into domains).

2. To arrive at a weighting scheme for various domains and aspects corresponding to the building sector for a particular local context – in this case Sri Lanka; and to assess the degree of agreement across professionals on the resulting weights for domains and aspects.

3. To compare the domain weights arrived at with schemes developed in other national contexts; and to explain differences in the weights for some domains by correlations with appropriate national statistics for the countries that have developed those schemes.

4. To propose methods to overcome subjectivity in the assessment of building environmental sustainability.
   The aim of this objective is to propose a quantitative indicator for each aspect. It is proposed that the score be based on the ratio between a well defined quantity and the benchmark for that aspect.

5. To establish local benchmarks to assess the building environmental sustainability.
   The aim of this objective is to establish local benchmarks for the selected indicators to make the baseline of the assessment. Literature will be used to establish global benchmarks; while case studies will be used to generate local benchmarks.

6. To analyse the applicability of continuous indicator score functions to overcome the weakness in step functions used in current rating schemes.
   The aim of this objective is to analyse the applicability of continuous function to assess the sustainability; so that even scores below minimum requirements will receive some credit.

7. To assess the dependency between indicators of building environmental sustainability.
   The aim of this objective is to assess the aspects which are influencing others and those which are getting influenced by others.

8. To evaluate the multiple combinations of strategies to optimize the building environmental sustainability score
   The aim of this objective is to analyse the tradeoffs arising with inverse dependencies between aspects and establish optimal sustainability score combinations.

1.4 Scope and Limitations of the Study

The scope of this study is limited to environmental sustainability of buildings. Social and economic aspects are not considered; but the concept of overall assessment criteria proposed in this study can be extended to capture those aspects too.

Although this study has generated reasonable amount of data through a survey of professionals and case studies of Sri Lankan green building assessments, more emphasis is given to the development of new methodologies as opposed to the collection of new data. This does not negate the importance of the data presented here, particularly the case study data, because there are only a few buildings rated by the Green SL (2013) rating tool to date and this study has captured all of them to date.

The above lack of case studies has resulted in only 10 green buildings and 2 non green buildings being studied. However consistency in the patterns that emerged (including a comparison with the tried and tested LEED rating system) has given us some confidence in the reliability of the findings. The case studies available were also only those of office buildings.

Where the environmental sustainability optimisation was concerned, although it is commended as a tool for planning decisions, real life planning will inevitably be concerned with economic considerations as well; these had to be ignored in this study.

1.5 Thesis Outline

The main aim of this research is to develop a multi-criteria assessment framework for environmental sustainability of buildings. This was achieved with the eight objectives mentioned above.

Chapter One outlines the background to the research together with problem identification, aim and objectives and research approach. This chapter also presents the scope and limitations of the research and the thesis outline.

Chapter Two contains the literature review which identifies sustainability indicator initiatives and the background to sustainability frameworks. This shows that most of the rating tools used at present are sector and domain based frameworks. This research is also

based on that framework and the building sector is considered with domains identified from the literature.

Chapter Three identifies the relevant domains and aspects of environmental sustainability of buildings inclusive of a literature survey pertaining to it. Weights for the identified domains and aspects are obtained through a questionnaire survey. The conducting and analysis of the survey are described. The weights arrived at are analysed for consistency, compared with other rating tools, and differences explained. This chapter focuses on weights.

Chapter Four explores alternative methods of classifying building environmental sustainability aspects. There are two alternative classifications discussed under this chapter based on building hierarchy and lifecycle stage. This chapter also describes alternative methods of assigning scores, so that the overall score is made more relevant than in current rating schemes. This chapter focuses on indicators. Twelve green building assessments are used to generate the required data.

Chapter Five discuss the dependency between indicator scores. Possible causations for the dependencies are identified and compared with the correlations obtained from the green building assessments. A matrix based technique was used to identify the overall dependency between indicator scores (accounting for both direct and indirect influences).

Chapter Six discusses optimal combinations of strategies where possible likely optimal combinations are identified, while avoiding unlikely combinations through a constraint based approach. This was implemented through a java script with binary number simulation.

Chapter Seven presents the key research outcomes. It presents the conclusions derived from the overall research and gives some recommendations. It also identifies important areas for further research.

1.6 Methodology of the Research

As explained in Section 1.5, this thesis contains seven chapters. There is no separate chapter for methodology as each chapter from Chapters 3 to 6 stand alone and are self explanatory

regarding the content and methodology. Even though Chapter two contains the main literature review of the thesis each chapter contains references to literature over and above the content of the literature review.

A 'methodology map' that also gives connections between chapters is presented finally in Figure 7.1

1.7 Originality of the Research

This study involves generation of both data and novel concepts and methodologies. It has concentrated on the generation of two main data sets and three main concepts.

Where data is concerned, Sri Lankan professionals' input regarding arriving at weights for domains and aspects to determine the environmental sustainability of buildings for Sri Lanka is given in Chapter 3. This is the first survey of this nature in Sri Lanka and those weights were used in developing the Green SL rating tool.

Secondly, the sustainability scores achievable for Sri Lankan buildings were established through case studies and given in Chapter 4. Again this was absent for the Sri Lankan context and this data would be useful in decision making and regulation making purposes. It is also suggested in this chapter that these sustainability scores be used to arrive at indicator benchmarks for the local Sri Lankan context.

Where concepts are concerned, establishing the quantitative correlation between domain weights in various rating systems and the national needs and priorities of the countries in which those systems have been developed (Chapter 3) is a novel concept not found in the literature before.

The second major concept presented in this study is alternative methods of arriving at environmental sustainability scores. The study evaluated the applicability of a continuous function approach over the conventional step-function approaches and argues that this is a better way to assess sustainability content in buildings.(Chapter 4).

The third concept explored in the study was the demonstrated dependency between aspect scores. This methodology captures the causality of such dependency and considers the implications of such dependency, especially in seeking design strategies for optimizing sustainability overall scores (Chapters 5 and 6).

Chapter Two

Literature Review

2.1 Introduction

After some introductory remarks regarding sustainable development and construction (Sections 2.2 and 2.3), this literature survey focuses on four aspects. First it identifies the available sustainability frameworks that conceptualize the main dimensions of sustainability. They help in grouping the issues with appropriate justification. This will be discussed in Section 2.4.

Secondly, within the selected framework there are a few key assessment systems, namely, total quality assessment, lifecycle assessment and cumulative energy demand assessment. These systems use one or more aspects for the assessment based on the intended use or application. This will be discussed in Section 2.5.

There are many sustainability rating tools available based on the above assessment systems. This forms the third main aspect of the literature survey. These tools show similar and varying characteristics. Sections 2.6 to 2.8 discuss their characteristics along with present trends in such assessment tools for building sustainability assessment.

The fourth aspect is the building sustainability indicators and benchmarks, which are used in different assessment systems for quantification of different aspects of sustainability for decision making and comparison. This will be discussed in detail under Section 2.9.

This flow of the literature survey was chosen with the logic that it:

- shows the top down conceptual approach of quantifying building sustainability
- shows where the building sustainability fits in with overall sustainable development
- shows how the objectives of the research fit into the holistic concept of sustainability

The diagrammatic form of the literature survey flow is shown in figure 2.1

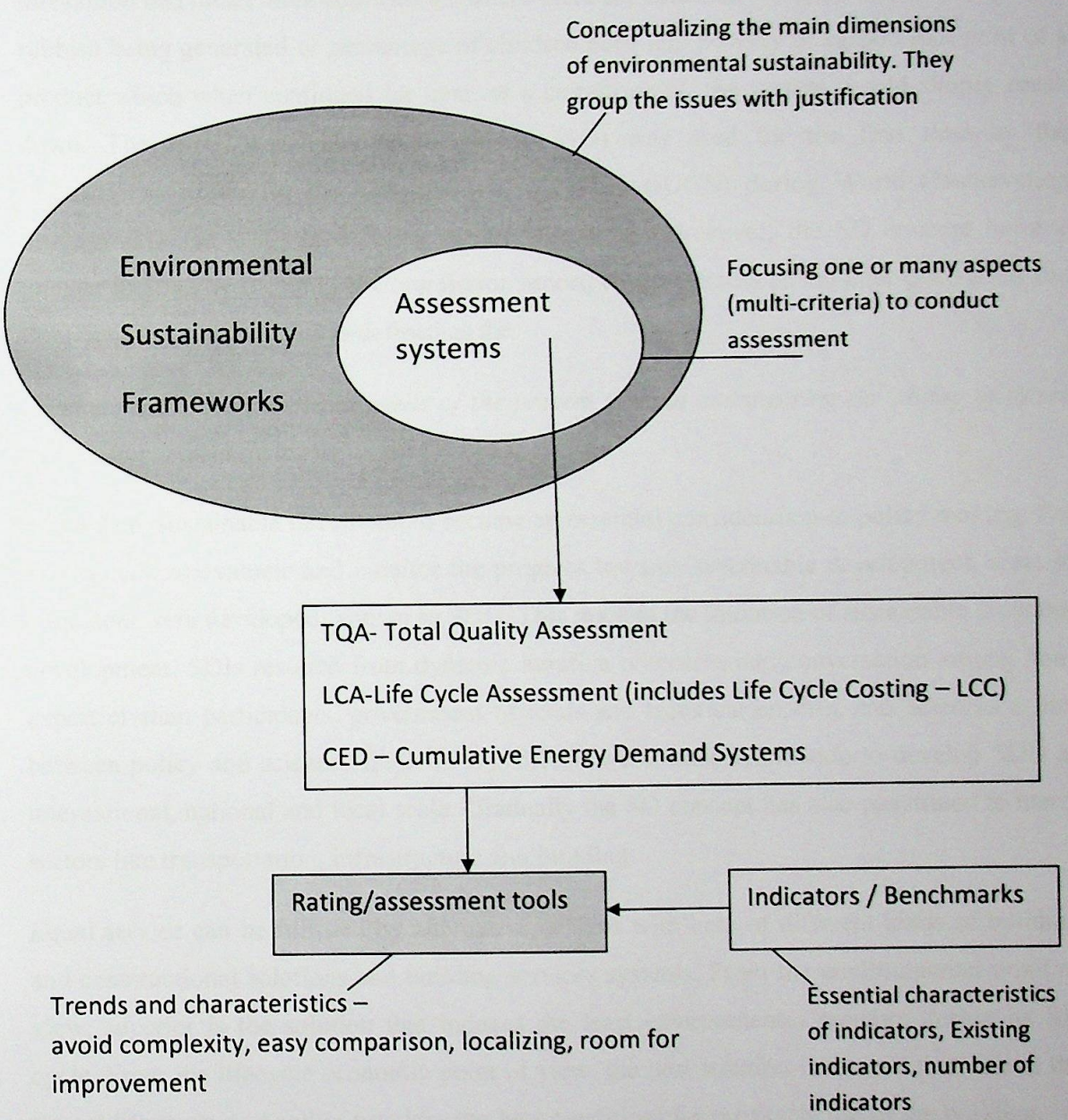

Figure 2.1: Literature synthesis of the thesis

2.2 Sustainable Development

The word 'sustainable' was primarily used in the context of the public using resources, since overusing of resources cannot continue for a long term (Sustainable Seattle, 2004). Slowly, this notion had much more applications where there are confines to expansion, like amount of rubbish being generated or percentage of children born into poverty or carbon foot print of a product which when continued for ever, at a certain point, the system would simply break down. The term 'sustainable development' (SD) was used for the first time by the International Union for the Conservation of Nature (IUCN) during World Conservation Strategy (IUCN, 1980) in defining equity in ecology. However, the SD concept became popular in 1987 by Brundtland Commission report, which introduced the inter-generation and intra-generation equity. SD is defined as the

development which meets the needs of the present without endangering the ability of future generation to meet their own needs (WECD, 1987).

Since then, sustainable development became an essential consideration in policy making. For any system, to evaluate and monitor the progress towards sustainable development, a set of indicators were developed, known as SDIs. This marked the initiation of sustainable indicator development. SDIs resulted from dynamic iterative processes and conversation among non-expert civilian participants, government officials and technical experts, and acted as a link between policy and science (IISD, 2005). Efforts were made worldwide to develop SDIs at international, national and local scale. Gradually the SD concept has also penetrated to many sectors like transportation, infrastructure and building.

Equal service can be fulfilled by alternative designs with help of different kinds of building and constructional solutions and building services systems. From the environmental point of view, superior is the solution that induces the least environmental pressure during its life cycle. From the lifecycle economic point of view, the best solution is the one that causes the lowest life cycle cost and/or provides the best conditions for profitable use of the building.

2.3. Sustainable Construction

The construction industry is a complex system that is under the influence of different external and internal factors. Construction, like any other business activity, experiences periods of rising and recession. Such processes could also be observed in Sri Lanka. Some time ago construction works floundered, but now many enterprises have scheduled their activities for years ahead. However, problems have emerged that did not exist before, for example, emigration of workers to developed countries and increasing prices for construction materials and structures. Till now construction enterprises mostly cared about quality of services and products and also strove to meet the needs of customers. However it is recognized that this approach is too narrow. More and more construction enterprises' managers realize that is not enough to reflect all the attention just to production processes and final results. The attitudes towards environment, employees and the local community started to change. Many business enterprises implement international quality and environment management standards. Sustainable construction is not a novelty, as many organizations and scientists in the world work in this field. There is a need to summarize this research and also to identify very clearly what sustainable construction is and to answer the question as to what the content of sustainable construction is. There is a need to estimate the state of the current situation and to assess the sustainability of the construction industry. There is also a need to measure how construction sustainability is changing over time and to identify which measures can be taken in order to make the current state better.

The concept of sustainability in building and construction has evolved over many years. The initial focus was on how to deal with the issue of limited resources, especially energy, and on how to reduce impacts on the natural environment. Emphasis was placed on technical issues such as materials, building components, construction technologies and energy related design concepts. More recently, an appreciation of the significance of nontechnical issues has grown. It is now recognised that economic and social sustainability are important, as are the cultural heritage aspects of the built environment. The definition of sustainable construction has various interpretations. For instance, according to the United Nations (UNEP, 2006) "Sustainable construction is a way for the building industry to move towards achieving sustainable development, taking into account environmental, socioeconomic and cultural issues. Specifically, it involves issues such as design and management of buildings, materials and building performance, energy and resource consumption within the larger scope of urban

development and management". Sustainable construction is defined as "the creation and responsible management of a healthy built environment based on resource efficient and ecological principles" (Kibert, 1994; Šaparauskas, 2001). Sustainable construction is seen as a way for the building industry to respond to achieve sustainable development (Bourdeau, 1999).

The application of sustainable development to the construction industry is sustainable construction: best described as a subset of sustainable development in the construction industry. It encompasses issues such as whole life cycle, procurement, site planning and organisation, material selection, re-use, recycle, waste and energy minimisation (UNEP, 2006)

Sustainable construction covers a wide range of issues, including: energy efficiency, respect for the workforce, health and safety, diversity in the workforce, building regulation and construction in developing countries (RICS, 2006). Summarizing different information sources one can state that sustainable construction covers a very broad list of issues: from creation of sustainable building and its environment to solution of socio-economical problems. There cannot be only one right approach.

2.4 Sustainability Frameworks

Frameworks are the logical structures over which the indicators are developed. They promote interpretation and integration and make the indicators understandable to non-experts. They help to clarify and focus what to measure, what to expect from measurements and which derived data (indicators) to use (IISD, 2005). Without a framework, indicators always remain ad hoc and incomplete and biased to the specific expertise and research interest of the authors, overly dense in some areas, and sparse or even absent in other important areas (IISD, 1999).

Frameworks form one of the core-distinguishing factors between different indicator researches. The main differences between frameworks are the way in which they conceptualize the main dimensions of sustainable construction, the inter-linkages between these dimensions, the way they group the issue to be measured, and the concepts by which

they justify the selection and aggregation of indicators (IISD, 2005). The following sections describe commonly used guiding frameworks for sustainable construction.

2.4.1 Capital Accounting Framework

The capital accounting–based framework has its root in economics. It was developed before the development of the concept of sustainable development. This framework is used in environmental accounting where the natural resources are accounted like financial resources -- so for example, a ton of carbon dioxide emitted could be costed at say USD 25. The linking of mainstream accounting with indicators improves the objectivity, quality and comparability of the latter. One of the recent developments in this area is the United Nation's System of Integrated Environment and Economic Accounting (SEEA) (IISD, 2005). SEEA aims to evaluate the change in the state of environment in monetary terms by using a hybrid physical and monetary accounting framework. In monetary indicators, the cost of the produced and natural capital consumption is deducted from conventional economics values to measure sustainable economic activity and growth.

Limitation: The capital accounting framework suffers from the fact that it is not always easy to quantify environment resources, particularly the qualitative ones. In addition, the philosophy of common monetary denomination of manufacturing goods and environmental resource, which makes the latter replaceable by former, is inherently debatable. Also, social indicators are yet to be included in this environmental-economic accounting framework (Lundin, 2002).

2.4.2. Ecological Economics

Later it was recognized that conventional economic knowledge tools were inadequate to deal with the use of environmental resources, and the need both for an alternative worldview and for 'special indicators' was highlighted (Bossel, 1999). This is because such indicators are outside the categories of conventional economics (Bell, 1999). The alternative worldview was captured in ecological economics, where the human economy was considered as an open sub-system of the biosphere, which itself is a source of capital, the depletion of which must be accounted for.

2.4.3. Triple Bottom Line

Later it was acknowledged that human well-being within social systems is another such source of capital. The practical sustainability indicators that flowed out of these ideas were called the triple bottom line; namely economic, social and environmental sustainability.

2.4.4 Sectoral or Domain Framework

This is not a framework by itself but is used mostly in conjunction with other frameworks. Under sectors, we can consider areas such as transport, domestic, commercial and industry; these sometimes correspond to the departments of administrative bodies (e.g. government ministries). In the case of domains, the divisions can be like land, water, energy etc, which are specific disciplinary areas or areas of expertise. The Sustainable Seattle program followed a sectoral approach where citizens from ten different sectors of society such as education, transportation, health, culture and recreation, population, and community participation contributed to the process of developing sustainable development indicators (Sustainable Seattle, 2004) whereas, in the Australian model (Australia, 1998) indicators are classified into domains: energy, water, urban design, transport and accessibility, population, housing, indoor air, health, noise and waste. South Africa is another example where domain-based classification is used (South Africa, 2004).

In general domains tend not to overlap each other, although sectors could. Domains and sectors can be seen as orthogonal classifiers – so we can speak of an energy indicator for transportation or a waste indicator for the residential sector. A large number of sustainability accreditation systems are now available, based on such indicators. Apart from being classified into domains and sectors, these indicators can be seen as flowing out of environmental, economic and health & community concerns (Papadopoulos and Giana, 2009) – in other words, emanating from the triple bottom line framework.

2.4.5. Evolution of frameworks

The evolution of frameworks can be depicted as in Figure 2.2. Along the x-axis we see that the amount of information presented by the frameworks increases, because of the increasing number of indicators employed. Along the Y-axis however, the simplicity of frameworks shows a corresponding decrease. A dollar basis would make comparisons between alternatives very simple (although arriving at such dollar values may be both difficult and controversial). Having a multiplicity of indicators on the other hand, although much more transparent and easier to arrive at, would involve a high degree of complexity when trying to compare alternatives, especially because consensus must be reached on the relative impacts corresponding to the various domains. This will either involve some sort of weighting scheme or a method of multi-dimensional representation and comparison.

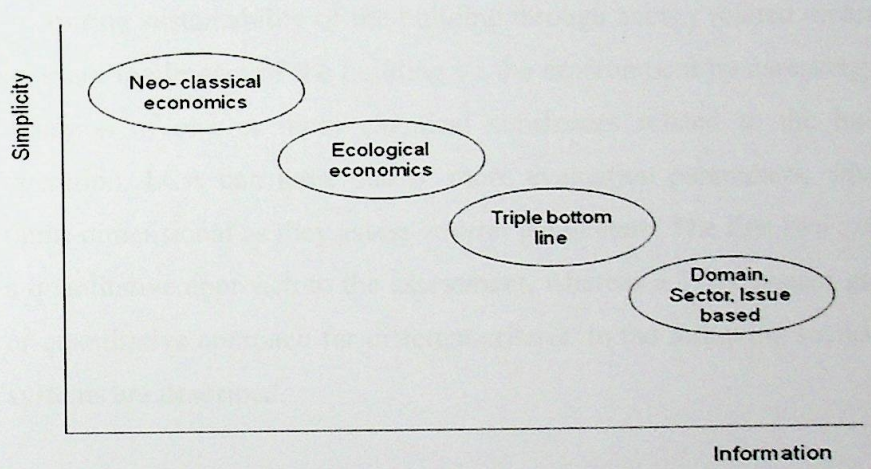

Figure 2.2 - Evolution of sustainability frameworks

2.5 Sustainability Rating Systems and Tools

According to ISO 15392 (2008), construction sustainability includes 'considering sustainable development in terms of its three primary aspects (economic, environmental and social), while meeting the requirements for technical and functional performance'. At present more than 600 sustainability assessment rating systems are available worldwide (BRE, 2008). New systems are continually proposed and the most diffused ones receive a yearly update. This evolving situation has led to release of the standards Sustainability in Building Construction – Framework for Methods of Assessment of the Environmental Performance of Construction

Works–Part 1: Buildings (ISO 21931 –1, 2010) and Sustainability of Construction Works – Sustainability Assessment of Buildings – General Framework (ISO 15643 –1, 2010). Systems for sustainability assessment span from energy performance evaluation to multi-dimensional quality assessment. According to Hastings and Wall (2007), they can be grouped into

- Cumulative Energy Demand (CED) systems, which focus on energy consumption
- Life Cycle Analysis (LCA) systems, which focus on environmental aspects
- Total Quality Assessment (TQA) systems, which evaluate ecological, economic and social aspects.

The above division should not be considered as strict, since many assessment systems do not fit perfectly into one category. CED systems are often mono-dimensional and aim at measuring sustainability of the building through energy related measurements. LCA systems measure the impact of the building on the environment by assessing the energy demand and emission of one or more chemical substances related to the building construction and operation. LCA can have one or more evaluation parameters, whereas TQA systems are multi-dimensional as they assess several parameters. The first two categories of systems have a quantitative approach to the assessment, whereas a TQA system generally has a qualitative or quantitative approach for different criteria. In the following sections CED, LCA and TQA systems are described.

2.5.1 Cumulative Energy Demand Systems

CED systems measure and evaluate the energy consumption of the building. Energy is furnished to buildings to cover needs such as heating, ventilation, air conditioning, water heating, lighting, entertainment and telecommunications. The specification of the energy request is of primary importance as CED systems can refer to just some of the above consumptions (often, just heating and hot water consumption) or can consider all needs without distinction regarding the final use. CED systems evaluate the energy consumption over a time unit, which generally corresponds to one year. However, monthly or semi-annual evaluations have been proposed (Marszal et al., 2011). Energy consumption for residential buildings in developed countries at middle latitudes assumes values of some hundreds of kilowatt hours per square meter net floor surface per year (kWh/m2a): for example, heat

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consumption of traditional European and US buildings is 300kWh/m^2 on average (Butera, 2010). Referring to traditional buildings, operating energy demand dominates the building CED during the life cycle, being 80% of the total energy consumption (Suzuki and Oka, 1998). A small energy percentage is consumed for material manufacture and transportation, construction and demolition. Consequently, energy saving policies have typically only given attention to operation energy performance (EC, 2003). Energy consumption requirements of new buildings are greatly decreasing under the pressure of more stringent requirements. In the US, zero energy buildings (or ZEBs) are discussed in the Energy Independence and Security Act (EISA, 2007), whereas the recast of the European Energy Performance of Buildings Directive (EC, 2010) has established that only ZEBs should be built after 2020. A ZEB can be defined as a building with a very high level of energy efficiency, so that the overall annual primary energy consumption is equal to the onsite energy production from renewable energy sources. A universally accepted definition of ZEBs is still lacking (Marszal et al., 2011), and several proposed methodologies for ZEB calculations differ for the metric of the analysis (energy, CO_2 emission, costs), the balancing time and the type of energy use considered in the assessment. As highly efficient buildings are built, the energy needs during construction and demolition processes, together with the embodied energy in construction materials, become relatively more significant. Hernandez and Kenny (2010) have defined the life cycle zero energy building (LC-ZEB) concept for energy consumption equity in a whole life perspective. A life cycle evaluation of energy use implies enlarging time and space boundaries in the assessment (Suzuki and Oka, 1998), and represents the trend for energy based sustainability assessment in the construction sector. CED systems are a mono-dimensional analysis, which considers the energy flux. Apart from an energy analysis, some researchers have accounted for other measurement units, such as exergy (Tronchin and Fabbri, 2008) or emergy (Pulselli et al., 2007). Exergy is the maximum useful work that brings the system into heat reservoir equilibrium, whereas emergy is the available solar energy directly and indirectly used in a transformation. These units of measurement are related to thermodynamic principles of resource use, and may be more appropriate than energy to evaluate building consumption (Marszal et al., 2011), although energy data are more common in the literature.

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2.5.2 Life Cycle Assessment Systems

Several systems have been developed for the environmental assessment of manufactured products, such as Environmental Risk Assessment (ERA), Material Flow Accounting (MFA), Input Output Analysis (IOA) and Life Cycle Analysis (LCA). These systems generally break down products and processes into elementary parts. LCA is the most commonly used of the above systems. It divides a building into elementary activities and raw materials to assess the environmental impact over a life cycle from manufacture and transportation to deconstruction and recycling (Seo et al., 2006). LCA is a robust methodology refined on the basis of manufacturing sector experiences. LCA assessments consist of four phases (ISO 14040, 2006): the goal and definition phase, the life cycle inventory, the life cycle impact assessment and the improvement assessment phase. LCA systems allow the comparison of products on the basis of the same functional quality. This describes the quality of a product service as well as its duration, e.g. square meters of a building element with a substitution rate every 50 years. The scientific rigor of LCA is inherent to assessments from cradle to grave phases; although it is limited by uncertainties in collecting data relating to building processes. LCA diffusion in the building sector is limited by a lack of information (Seo et al., 2006). In fact, the specificities of the construction processes require data for every building material in any region. Databases have been created for LCA evaluations and implemented in specifically designed software in several geographic areas: BEES in the US, BOUSTEAD and ENVEST in England, SIMAPRO and Eco-Quantum in the Netherlands, Ecoinvent in Switzerland and GaBi in Germany. However, these databases are only valid for assessments in a specific region. The United Nations Environment Program's Sustainable Buildings and Climate Initiative (UNEP-SBCI) has recently adopted the Common Carbon Metric (CCM). This system allows emissions from buildings around the world to be consistently assessed and compared. The assessment reports the Carbon Intensity, which is the evaluation in weight of carbon dioxide equivalent emitted per square meter per year (kg CO_2 eq/m^2a). The assessment is mainly based on the operational consumption, but it can be extended to the whole life cycle of the building. An obstacle for LCA diffusion is its specialist structure: outputs of LCA systems are represented by environmental impacts expressed through chemical substances, which are not easily understood by construction sector actors (Langston and Ding, 2001). LCA systems assess the environmental paradigm of sustainability without considering social and economic impacts. Some studies relate the disaggregation analysis

necessary for an LCA to an evaluation of economic costs. Such an approach is interesting for the building sector, as life cycle cost (LCC) analysis represents a familiar paradigm to construction stakeholders. Combined LCA – LCC can, hence, be useful to evaluate environmental and economic aspects in life terms by assigning a price to chemical elements. For example, BEES and GaBi systems already permit the selection of cost effective environmentally preferable products.

2.5.3 Total Quality Assessment Systems

TQA systems aim at considering the three aspects of sustainability of buildings: environmental issues such as GHG emission and energy consumption, economic aspects such as investment and equity and social requirements such as accessibility and quality of spaces. The most common TQA systems are the multi-criteria systems. They are greatly increasing the attention for sustainable assessment of buildings, as they are well related to market interests and stakeholders' culture (Newsham et al., 2009). Multi-criteria systems base the evaluation on criteria measured by several parameters, and compare real performances with reference ones. Each criterion has a certain number of available points over total assessment and the overall evaluation of sustainability comes out by summing the results of assessed criteria. A critical aspect of multi-criteria systems is their additive structure, as they assign scores for positively evaluated elements (Hahn, 2008). Multi-criteria systems are generally easy to understand and can be implemented in steps for each criterion. Moreover, a step implementation is allowed during the analysis: in fact, these systems enable the assessment of the building at several stages, from the concept design to the final construction, and can be used during construction too. Several multi-criteria systems exist to assess building sustainability worldwide. As many are just adaptations of more well-known ones to a regional level or for specific scopes, only the most adopted systems are considered here. These are BREEAM, LEED, CASBEE, SBTool and Green Globes. Other well-known rating systems are the Australian Building Greenhouse Rating (ABGR), the Green Home Evaluation Manual (GHEM), the Chinese Three Star, the US Assessment and Rating System (STARS) and the South African Sustainable Building Assessment Tool (SBAT).The United Kingdom was the first country to release a multi-criteria system for sustainability assessment before this concept entered into the agenda of international policies with the Rio Conference. The British Building Research Establishment Environmental Assessment Method (BREEAM)

was planned at the beginning of the 1990s by the British Research Establishment, and was released in 1993. The system has a large diffusion in the United Kingdom, where almost 10,000 buildings have been certified. Since 2009, as a consequence of the worldwide attention garnered by this system, an international version has been released, and currently BREEAM has adapted versions for Canada, Australia and Hong Kong. The system is differentiated for 11 building typologies and its evaluations are expressed as a percentage of successful over total available points: 25% for pass classification, 40% for good, 55% for very good, 70% for excellent, 85% for outstanding. The evaluation categories are management, health and wellbeing, energy, transport, water, materials, land use, ecology, pollution and innovation.

A widely spreading rating system is LEED (Leadership in Energy and Environmental Design), which was released in 1998 by the US Green Building Council (GBC).This system is currently available for ten building typologies. There are six evaluation categories to obtain the 110 possible points of the standard in version 4: location and transportation (16), sustainable site (10 points), water efficiency (11), energy and atmosphere (33), material and resources (13), indoor environment quality (16), innovation (6) and regional priority (4). LEED points accumulated are divided into the following categories: at least 40 points for certified buildings, 50 for silver, 60 for gold and 80 for platinum. Although released in the US, the GBC has been diffused worldwide over the years, and recently the World GBC has opened regional chapters in countries in Europe, Africa, America and Asia. Almost 20,000 buildings are registered for certifications, and current requests for new certifications concern buildings in 110 countries.

CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) 3 is a Japanese rating system developed in 2001, also available in English. CASBEE covers a family of assessment tools based on a life cycle evaluation: pre-design, new construction, existing buildings and renovation. This system is based on the concept of closed ecosystems and considers two assessment categories, building performance and environmental load. Building performance covers criteria such as indoor environment, quality of services and outdoor environment, whereas environmental loads cover criteria such as energy, resources and materials, reuse and reusability, and off-site environment. By relating the previous two main criteria, CASBEE results are presented as a measure of eco-efficiency on a graph with

environmental loads on one axis and quality on the other, so that sustainable buildings for CASBEE have the lowest environmental loads and highest quality. Not many buildings have been certified with this system, although the number is rapidly increasing.

At the end of the 1990s, the Sustainable Building Council promoted an internationalization of rating systems under the leadership of Natural Resources Canada (NRC). Towards this initiative a common protocol, SBMethod, was developed. Using the general scheme, several countries then proposed national versions of this system, such as Verde in Spain, SBTool PT in Portugal and SBTool CZ in the Czech Republic. In Italy, this protocol was implemented in 2000 as SBTool IT, updated in April 2011 and now known as ITACA. Moreover, ten Italian regions have adopted modified versions of the system to better cover regional specificities.

In 2005, adapting the Canadian version of BREEAM, the Green Building Initiative (GBI) launched a new rating system, known as GreenGlobes. Criteria of this include project management, site, energy, water, indoor environment, resource, building materials and solid waste.

2.5.4. Comparison of Rating Systems

A critical aspect of multi-criteria systems is the selection of criteria and weight given to each criterion: in fact, reasons behind choices are not explicit. These show which aspects of building performance are given more consideration in sustainability assessments. In one study, weights were assigned to above six TQA systems, grouping the criteria of each into seven main categories. Selection of these categories was based on main sustainability building aspects (Langston and Ding, 2001): site selection, energy efficiency, water efficiency, material and resources, indoor environmental quality, waste and pollution. The category 'others' contains criteria that do not fit into the other six categories. When more than one version of the same system existed, the one applicable to new construction was selected. The attribution of each system criterion into previous categories resulted in some difficulties because the system structures were not always easily accessible and criteria among systems did not perfectly overlap. For this reason, the attribution was performed by the author, and then repeated by two sustainability experts to check coherence in attribution of criteria in the seven categories. Credits assigned in the LEED system for low-emitting materials (6 points

out of 69) were assigned to the IEQ category; however, they could also be assigned to the waste and pollution category. Management and innovation criteria have been included in the category 'others'. For example, LEED assigns 7% of its credits to innovations, BREEAM has 15% for construction management and Green Globe has 12.5% for project management. Moreover, in the category 'others' there are points given by CASBEE for mitigation and off-site solar energy and by GBTool for the cultural perception of sustainability. The result of the weight comparison among rating systems agrees with similar studies (Fowler and Rauch, 2006, BRE, 2008). It is interesting to note that energy efficiency among assessment systems is always considered the most important category (weight average among the six systems 25.5%), followed by IEQ (17.7%), waste and pollution (15.9%), sustainable site (13.2%) and material and resources (11.5%). Green Globes assigns a higher percentage of its assessment weight to energy efficiency (36%): this is established by the inclusion of criteria that are not presented in other systems, such as the correct size energy efficient system or energy efficient transportation. The above averages do not have a rigorous meaning, standard deviations among systems are high and percentages change if other versions of the systems or other assessment systems are considered. However, studies have shown many similarities among sustainability rating systems (Smith et al., 2006).

Finally, it should be remembered that evaluation criteria and weights are just one of the ways to compare systems. Fowler and Rauch (2006) compared the above mentioned systems for other properties (applicability, usability, communicability), again finding some similarities. Differences among the systems have led to creation of the Sustainable Building Alliance in order to establish common evaluation categories and to improve comparability among systems in sustainability assessments. Many studies have discussed the limits of rating systems; however, only limits for weight and criteria are considered here. Unscientific criteria selection has been criticized by both Rumsey and McLellan (2005) and Schendler and Udall (2005). Bower et al. (2006) stated there was a lack of overall life cycle perspective in evaluations. It is clear that, in the selection of assessment criteria, environmental aspects in existing systems receive much more attention than economic and social ones (Sev, 2009). Recently, some multi-criteria rating systems more closely related to a TQA have been released. For example, the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), available since 2009, aims at evaluating sustainability through the quality of the building: economic aspects emerge explicitly, and, in the category of technical quality, paradigms such as

performance, durability and ease of cleaning, as well as dismantling and recycling are considered. More attention is paid to social aspects than in other rating systems. Finally, functional aspects such as space efficiency, safety, risk of hazardous incidents, handicap accessibility, suitability for conversion, public access, and art and social integration are considered.

When comparing TQA systems with LCA ones, Forsberg and von Malmborg (2004) pointed out that qualitative rating systems cannot capture the information that can be obtained from quantitative life cycle approaches. The US National Institute of Standards and Technology (NIST) analyzed the LEED system from an LCA perspective, leading to the conclusion that it is not a reliable sustainability assessment system (Scheuer and Keoleain, 2002). Lee et al (2011) showed that there can be discrepancies between a rating system approach and a quantitative embodied energy approach for assessing the 'materials' domain. However, such quantitative studies are critiqued as covering only a small fraction of the issues associated with sustainability.

Apart from these comparative evaluations of the LCA and TQA approaches, there are two broad critiques of all current assessment approaches. The first suggests that a focus on buildings is not comprehensive enough, and that the scale of assessment be broadened to cover entire cities within which the buildings are placed (Berardi, 2011). Conte and Monno (2012) argue that such broadening to the urban scale will also necessitate the notion of social and economic sustainability, in addition to the environmental sustainability that is covered by current rating systems (see also Nathan and Reddy, 2008). Furthermore, Berardi (2013) argues that even political and cultural sustainability may need to be accounted for. This leads him to suggest that a 'green' building could be very different from a genuinely sustainable one.

It should be noted that accounting for social sustainability will bring a much needed justice-related dimension to these assessments, covering aspects such as access to and use of infrastructure during building use (Berardi, 2013; Conte and Monno, 2012). Even at the construction stage, building elements can be characterized by their man-hour contents (Watermeyer, 1999), just as they have been defined by their energy contents (Pooliyadda and Dias, 2004); and while the latter has found expression in ratings systems, the former has not.

The second critique is even deeper, in its insistence that rating systems are essentially technologically oriented in nature, thus increasing consumption in various ways, rather than encouraging a return to simpler lifestyles, reduced resource use and practices that encourage regeneration of resources (Hahn, 2008; Conte and Monno, 2012). Hahn (2008) documents for example the fourfold increase in per-occupant volume in US houses over 50 years.

2.6 Characteristics of Certified Buildings

In this research sustainability rating systems are used as a proxy variable to analyze the characteristics of certified buildings. The results of constructed buildings can be more useful to understand the state of the art of sustainability assessment in the building sector more than policies, regulations and rating systems. In fact, scores obtained by assessed buildings provide for discussion of their real sustainable characteristics. Sustainable rating systems are, generally, voluntary standards, and their adoption is, hence, partially motivated by signaling factors. This means that the construction firm or the owner of the building decides to perform a sustainability assessment also to communicate something to the outside world (Mlecnik et al., 2010). According to King and Toffel (2007), signalling and intrinsic benefits are mixed together when sustainable rating systems are used. In their analysis, this clearly emerged from the decreasing number of buildings that obtained a larger number of credits than the minimum one for a given certification level. Buildings generally aim at an established certification level, and rarely show higher performance than the minimum ones for the given certification level. However, considering motivations other than sustainability, results of assessed buildings enable the comprehension of the most common choices in the construction of sustainable buildings. In this section, a rating system is chosen to discuss aspects of sustainable buildings by looking at statistics of achieved points in certified buildings. Although there is space for improvement in LEED (Bower et al., 2006; Hahn, 2008; Newsham et al., 2009), this is the most diffused system worldwide, and hence it has been chosen for the analysis.

A sample of 490 buildings was selected from the GBC database, from already built projects were assessed with version 2 of LEED (Berardi, 2011). The sample was composed by buildings which had allowed perusal of their evaluation data. Selected buildings belonged to several typologies, with a large majority of commercial (52%) and residential (30%)

buildings. The time of construction was very similar among buildings, i.e. from 2002 to 2009. The findings of Berardi, 2011 were as follows:.

- Sustainable site is an important category in the overall evaluation; however, assessed buildings reach fewer than 50% of the available points on average. The selection of a sustainable site is often influenced by property possibilities, municipal policies and previous land uses, making a free selection difficult.

- Energy and atmosphere is the category with the largest number of points. The ratio of successful points to possible ones is the lowest among categories (38%).

- Indoor environmental quality is the second category for available points but the first contributing to the total score, as average earned points are 56% of available ones.

- Water efficiency receives only a few points in the standard, despite its importance for a sustainable building. The most probable reason for this is that few actions can lead to a significant efficiency in the use of this resource and, in fact, buildings obtained 62% of the available points on average.

- The material and resources category has a considerable number of available points but effectively earned ones are few, with an average of 40%.

- The innovation and design process category has a low number of available points, and on average buildings are successful in this category with 66% of the available points, which means that sustainable buildings are generally able to fulfil requirements in this category.

- With the largest number of achievable points but third in absolute earned points and last in relative earned points to the total achievable ones, the energy and atmosphere category shows abnormal percentages. This suggests that energy requirements are still difficult to achieve, and also that projects aimed at sustainability certification under adopt performances within this category.

2.7 Diffusion of Sustainability Assessment

According to many researchers, sustainability assessment is essential to increase the diffusion of sustainable buildings (Cheng et al., 2008; Ding, 2008). Unfortunately, the construction sector is unfamiliar with performance measurements, and although many assessment systems already exist worldwide their diffusion is still low in obvious terms. Sustainability measurements in the building sector are capturing much attention worldwide, rapidly moving from fashionable certification to current practices. In 2010, 650 million square meters obtained a sustainability certification throughout the world, with projections for 1100 million square meters in 2012 and for more than 4600 million square meters in 2020 (Bloom and Wheelock, 2010). Sustainability building certification programs and rating systems are used worldwide, with the only exceptions being Africa (except South Africa) and Latin America (except Brazil). Referring to the model for innovation diffusion, proposed by Rogers and reinterpreted in 'Crossing the Chasm' (Moore,1991), sustainability assessment diffusion has reached visionaries, the number of early adopters is increasing and the subject is becoming common in specialized press and journals (Bloom and Wheelock, 2010), but even in active countries, it still needs to become a mature practice. In the innovation diffusion theory (Rogers, 2003), communication is generally the most important element for the introduction of a new paradigm among members of its social systems. For this, sustainability assessments and sustainability rating systems represent the framework for sustainable constructions. Proof of this was given by the European Directive EPBD, which required the placement of energy consumption certificates and plaques in the assessed buildings (EC, 2003). The increasing number of certified buildings shows that awareness of sustainability is increasing. Moreover, the assessment scale allowed by many rating systems, which permit definition of several sustainability grades, has shown a trend towards higher sustainability levels in the last few years. For example, few buildings among the first assessed projects were rated as LEED platinum buildings (best rated ones) from 1999 to 2002. Then, in 2003, some of buildings were rated platinum, and currently this rating is common among sustainable buildings (Bloom and Wheelock, 2010).

2.8 Broader Sustainability Assessment in the Construction Sector

In fact, a frequently discussed topic is how sustainability should be measured (Steurer and Hametner, 2011). After the energy crisis in the 1970s, regulations promoted energy consumption limits for buildings around the world. As a result, energy consumption evaluation became the sustainability measure for building assessment. Meanwhile, sustainability consciousness has evolved, and nowadays assessments generally consider energy consumption as just one among other parameters. The complexity of a building often suggested a multi disciplinary approach in sustainability assessment (Langston and Ding, 2001). This is also because buildings cannot be considered as assemblies of raw materials, but they are generally high order products that incorporate different technologies assembled according to unique processes (Ding, 2008). The sustainability of a building should, therefore, be evaluated for every subcomponent, for the integration among them in functional units and assembled systems (e.g. the air conditioning system, the envelope), as well as for the building in its entirety. Finally, it is becoming more and more evident that a building cannot be considered an island, but its sustainability should be considered and assessed by looking at the surrounding environment. A possible approach to sustainability evaluation is through the sustainability assessment of building products. This approach is internationally established for many kinds of product, and only regards environmental evaluations. Three types of product environmental labels exist and defined in ISO14020 (2000). These are the eco certification environmental labels (type I), the self-declared environmental claims (type II) and the environmental declarations (type III). Among these, type III is the most common label for building products. However, environmental evaluations of products are rarely performed by manufacturers, and the diffusion of environmental product declarations (EPDs) in the building sector is low (McGraw-Hill Construction, 2008). Product eco certification assessment systems have been developed in different countries: among others, there is the American Green Seal, the European Eco-Label, the French NF Environment Mark, the German Blue Angel and the Japanese Eco Mark. Moreover, specific evaluations for building products exist, especially for timber and concrete based ones. The above mentioned labels have a binary evaluation and indicate a sustainable product without the ability to measure its content of greenness. Since 2011, the new European Construction Products Directive (CPD) states that a sustainable resource use evaluation is part of the assessment for the CE mark (CPR, 2011), which should imply a larger diffusion of environmental assessments for the

construction sector, at least in Europe. Energy labels represent another way of assessing product sustainability, although they are only useful for equipment (e.g. heat pumps). Finally, the adoption of certified sustainable materials is not sufficient to obtain a sustainable building, because the complexity of such requires a holistic and integrated evaluation (Ding, 2008). For example, the sustainability assessment of a building product needs to consider difficulties in predicting factors such as transportation distance or wastes. In this sense, product labels only constitute a database for a sustainability analysis. Construction is a complex input-output sector where the material flux is difficult to standardize and rarely a priori programmed (Cole, 1998). Some research states that building sustainability can be better evaluated by looking at the building as a process because it never finishes, but evolves through occupancy. Weather, orientation and local parameters continually influence the operational needs of the building. Moreover, buildings are constructed according to a specific design defined according to clients' requests. These aspects prevent buildings from being considered as manufactured standardized products. Finally, construction stakeholders constitute a variegated network of subjects (de Blois et al., 2011) and differences among them imply several possible points of view in sustainability assessment. In this sense, Cole (1998) stated that sustainability varies according to stakeholders: a community aims at low construction wastes whereas an occupant looks at indoor environmental quality. Given that sustainability assessment should include the evaluation of social and economic parameters, definition of a universally accepted comprehensive assessment system is a long way away.

2.9 Sustainability Indicator Growth

2.9.1 Sustainable Building Indicators

Sustainable construction deals with both

- the service that is offered by constructions as well as with
- the impacts caused by constructions in terms of ecological, economic as well as social and cultural aspects in local, regional and global scale.

The positioning of these aspects is problematic in relation to the actual behaviour of a construction and the consequences in terms of changes in the environment and effects for people. In several approaches, which try to indicate either the environmental soundness or the

entire sustainability of constructions, both the performance as well as the caused impact is looked at. The majority of the systems of sustainable building indicators deal with parameters like harmful emissions and the use of resource as well as with aspects like air quality, thermal comfort and flexibility. These approaches do not define the building performance as the reference unit, but uses the performance aspects as indicators of 'environmental quality' in addition to the environmental pressure indicators.

Sustainable building indicators exist in abundance. Much research has been done on sustainability indicators, exploring their usefulness as a concept and the different type of indicator that might be used for different things. An indicator in essence is simply a "sign or signals that relay a complex message, from potentially numerous sources, in a simple and useful manner" (Kurtz et al, 2001). They need to be quantified; qualitative scales may be appropriate, but they have to be measurable in some way so that comparison can take place.

Their real importance is, of course, in the influence they have upon decisions; the use the information is put to following interpretation of results. To make assessments of building sustainability, which in turn will assist in making decisions about building worth, this indicator set must provide information about factors that relate directly to building operation and which accurately reflect the sustainability of a building in use.

One of the problems related with sustainability building indicator systems is that they tend to stabilise the beneficial and least unfavourable aspects of performance. This is acceptable with reference to environmental burdens - the lower the burdens the better; but this might not be good when it comes to location and building performance related aspects. Building performance should rather be dealt with on the basis of user and owner needs, which may vary from case to case.

2.9.2 Characteristics of Useful Indicator Sets

The background literature provides a number of lists of characteristics that sustainable building indicators should display if they are going to be suitable for their intended purpose. Some of these characteristics make useful criteria against which possible indicators can be assessed (Herger and Meyer, 1996, cited in Bell and Morse 1999):

- Simplicity
- Scope: they should cover the particular aspect or issue and overlapping should be minimum
- Quantification: they should be measurable
- Assessment: they should allow trends with time to be determined
- Sensitivity: they should be sensitive to change, and
- Timelineess: they should allow timely identification of trends.

This provides a useful set of criteria against which most indicators could be judged. All aspects like simplicity, scope, quantification and timeless would be equally useful characteristics. Also, the indicators must be capable of change over time in terms of weighting, ranking and composition of the matching.

Pastille (2002) provides another checklist notating that indicators should be:

- Scientifically valid or analytically sound, including responsive to change that is occurring
- Measurable according to standard methods and based on available data
- Comparable, not ambiguous and robust or independent of assumptions
- Limited in number
- Related to a reasonable time horizon and relevant spatial area
- Capable of relating to other indicators and capable of aggregation, and
- Transparent and accountable

When the indicators are being selected, regard should be paid to these characteristics if the set is to be robust and defensible. This approach in this research is to concentrate on the use of existing indicators that are already understood and recognized as valid. This research is not seeking to develop any new indicators as that predictably would present greater difficulty in acceptance. So for this research an additional required characteristic would be that the data set from which the indicator is generated must either already exist or be easily collected.

2.9.3 Existing Indicators

ISO TS 21929 (ISO 2006) defines a framework for sustainability indicators of buildings. The framework is based on the premise that sustainable construction brings about the required

performance with the least unfavourable environmental impact, while encouraging economic, social and cultural improvement at a local, regional and global level.

Environmental indicators address environmental aspects in terms of environmental loadings or impacts assessed on the basis of life cycle inventory or assessment. Environmental loadings are the use of resources and the production of waste, odours, noise and harmful emissions to land, water and air. However, consequential environmental indicators are also needed and used in requirements setting, design and selection of products for sustainable building. Consequential environmental indicators express environmental impacts in terms of building performance or location either quantitatively or qualitatively.

These kinds of indicators have been developed for cities, built environment, buildings and other construction assets and building products in various research projects like in the European CRISP (Häkkinen et al. 2002) and TISSUE (2004) projects. TISSUE developed sustainability indicators for cities; the building related indicators dealt especially with land use and accessibility related issues

According to ISO TS 21929 the following economic flows are related to the life cycle of a building:

– investment: site, design, product manufacturing, construction,
– use: energy consumption, water consumption, waste management etc.,
– maintenance and repair,
– deconstruction and waste treatment,
– development of the economic value of a building, and
– revenue generated by the building and its services

The economic indicators indicate monetary flows connected to the building life cycle. Social indicators of buildings are used to describe how buildings interact with issues of concern related to sustainability at the community level. Community level issues that may be relevant are for example urban sprawl, mixed land use, access to basic amenities, availability of green and open space, attractiveness of city centres, development of brownfields, availability of housing, social segregation, cultural quality and protection of cultural heritage, safety, noise and air quality. Social aspects can also be addressed at the building level like for example (ISO 2006):

– quality of buildings as a place to live and work,
– building related effects on health and safety of users,
– barrier free use of buildings,
– access to services needed by users of a building,
– user satisfaction,
– architectural quality of buildings and
– protection of cultural heritage.

Building and construction needs life cycle assessment methods and sustainability indicators in order to be able to state performance and lifecycle requirements, to be able to design for required performance and life cycle, and to be able to make decisions between alternative options. Sustainable buildings should be delivered by methods which support requirement setting and concept definition, design for desired building performance and life cycle performance and the assessment of the conformity of the design with reference to the stated requirements. The process should include the following three main steps:

– Defining performance and lifecycle requirements

– Design for required performance, service life, life cycle impacts

– Assessment of conformity with the defined requirements.

An important challenge is that these methods should be able to assess alternative systems with help of generally accepted indicators without favouring any specific solutions, and to be able to support the consideration of user needs and requirements.

2.9.4 Number of Indicators

The number of indicators adopted seems entirely arbitrary and examples range from as few as ten to one hundred, or more. The European Commission advocate that a "*large number of indicators are needed to properly assess the multidimensional nature of SD*" (EC, 2005b: 4), but there arises again the need for compromise between maintaining a sufficient level of detail whilst achieving simplification for 'manageability' (Bell and Morse, 2003). Bell and Morse (2003:38) note that 20 appears to be the 'magic number' in reviews of local SD strategies, but the real trade off is to have as few as possible, whilst as many as necessary.

The indicators are also can be structured into layers, based on the intended use, pyramid style, to 'facilitate communication' with each level assumed appropriate for different assessment needs and corresponding to the related 'theme' (EC, 2005b: 5). This method can provide more detailed analysis of intricate and complex issues, aimed at a more 'specialised audience' (EC, 2005: 5).

Similarly, the OECD (1998) describes 'a pyramid of indicator sets' (in Bell and Morse, 2003: 45) from numerous data for scientists and technical experts; through indicators for policy makers and managers to condensed indices for the public; and Kelly and Baker (2002) provide a further example of a tiered approach between spheres, domains and themes, which echoes the UK approach of domains, families and themes (Morrey, 1997).

2.9.5 Analyzing Indicator Results; Benchmarking

It is required for indicator data to be compared to existing information, thus highlighting the need for a 'reference condition', a benchmark with which to compare indicator values or a target that can provide a measurable commitment to achieving goals that should be challenging yet achievable (DSCWG, 2001). This may well be predetermined by legislation; for example, nationally set targets for carbon dioxide emissions would provide an acceptable, if not mandatory, goal. When no such target exists, an element of subjectivity may be inevitable. Bell and Morse (2003: 47) describe four possible approaches to setting the 'reference condition':

I. using historical trends or data - this assumes a sustainable state occurred in the past

II. using a current system assumed to be sustainable for comparison

III. taking a theoretical approach and constructing a reference condition based on principles rather than actual events

IV. or consulting stakeholders to establish 'best' and 'worst' case scenarios.

As with the process of indicator selection, setting targets and limits is value-laden and hence it is vitally important to pursue wide consultation and participation to ensure that *"value judgments which are made truly reflect the consensus of the society and the people most concerned, rather than being imposed by a minority or an outside group"* (Dahl, 1997:81).

Likewise, Waldron and Williams (2003) suggest that linking monitored trends to sustainability goals requires both a baseline (to illustrate change since that time) and a benchmark (to illustrate progress towards a goal or away from an identified threat). However, they do point out that the interpretation of whether a trend is 'progress' will depend on the values of the interpreter.

2.10 Sustainability Assessment Trends

Trends of sustainability assessment systems have been of interest since the study by Crawley and Aho (1999). As seen above, single and multi-dimensional systems exist. Sustainability assessment was originally based on a single, often energy related, parameter. However, assessments through a single dimension have received much criticism (Nijkamp et al., 1990; Janikowski et al., 2000), as a single criterion is generally unable to measure the sustainability complexity. An increasing awareness of externalities, risk and long term effects have suggested a larger diffusion for multi-criteria systems. Available multi-criteria systems have been accused of a lack of completeness as they neglect some criteria: for example, they rarely take into account the economic dimension of the development. This lack prevents the evaluation of the economic consequences of sustainable choices and, therefore, constitutes a great limit for sustainability rating systems (Ding, 2008). In fact, by neglecting the evaluation of economic aspects, sustainability rating systems contradict one of the development dimensions and allow the additive logic for adoption of only environmentally sustainable choices, which can surely be criticized. The research has shown that this limit affects any system, as almost no system incorporates economic and social evaluations.

The importance of economic and social evaluations has recently emerged in defining systems for developing countries, where it is more evident that the environment cannot be the only assessment category, but economic and social equity are fundamental (Gibberd, 2005). This should re-establish a sustainability perspective to assessment systems which actually seem too focused on the environment. A comprehensive approach to the evaluation has led to design systems that require much detailed information. For example, the last version of GBTool comprises more than 120 criteria. The complexity of criteria has been pointed out as a limit for the diffusion of sustainable rating systems (Mlecnik et al., 2010). Complexity is one of the barriers highlighted by Rogers in his innovation diffusion theory (2003), and if sustainability rating systems, and sustainability itself, are perceived as too complex

by building stakeholders then sustainability practices will be adopted only slowly. A balance between completeness in coverage and simplicity of use is hence necessary to spread sustainability building assessment systems. The greater diffusion of multi-criteria TQA systems rather than LCA ones is probably due to their simplicity and check list structure. In fact, although LCA analyses are often more rigorous than multi-criterion systems, they are still complex to understand and their diffusion is limited to a few specialists. The importance of simple systems is also emerging as a factor in making them useful as design tools. In order to introduce sustainability rating systems early in the construction process they must be structured not to need detailed information before they are generated.

An open aspect of sustainability rating systems regards possible regional adaptations in assessment criteria. The Italian experience of SBC-ITACA shows that regions are adapting the original system to local characteristics and priorities with regional criteria. It is evident that sustainability evaluation needs site adaptations, in order to fit sustainable requirements with contextual aspects. This approach is shared more and more worldwide. For example, the new version of the LEED system, version 3, has introduced points for regional priority to assess local aspects too. However, local aspects, priorities and benchmarks are complex to establish, especially when it is necessary to manage weights and optimal performance values as in multi-criteria systems.

Reviews of some sustainability rating systems has shown a trend for whole life perspective analysis as the assessment is moving to cover the construction and operation phases, and sometimes the dismantling phase. Limits of sustainability assessments suggest that more complete rating systems are necessary to assess the multi-dimensional aspects of sustainability and to improve the triple bottom line of buildings. An important trend in sustainability assessment is seen in the increasing attention to the neighborhood and construction site. The first assessment systems considered the building as a manufactured product, and evaluated it almost in isolation. However, the importance given to the surrounding site is greatly increasing; for example, available points for sustainable sites have increased from 15 to 23% from version 2.2 to version 3 of LEED. Energy requirements have also become stronger in the latest versions of this and others assessment systems. This can certainly have been motivated by the more rigid requests of energy regulations worldwide, but also by the greater attention being given to energy saving in buildings. Energy

performance is generally considered the most important criterion in building sustainability assessment, being the only one in CED and the most important one in almost every TQA system. Results of certified buildings have shown that energy performances are well below the optimal ones even in sustainable buildings: reasons for this are often the high cost of energy saving measures and the low preparedness of construction actors. In contrast, indoor environmental quality, which is highly considered among criteria of sustainability rating systems, is generally reached at a high rate by sustainable buildings.

2.11 Dependency Between Sustainability Aspects

The question of dependency between aspect scores has also been addressed to a small extent in the literature, but mostly regarding business and production sustainability (Tseng *et al.* 2009, Wagenhals *et al.* 2014). Therefore, it can be argued that dependencies play an important role when considering sustainability performance. Nevertheless, these influences or dependencies are often imprecise and uncertain, and sometimes information is inadequate.

Techniques such as fuzzy set theory (Alsulami and Mohamed 2012; Tseng 2013), compositional modelling approach (Falkenhainer and Forbus, 1991) and integrated assessment methods (Andriantiatsaholiniaina et al. 2001; Trandabat 2012) have been attempted to model these dependencies.

For example, Wagenhals et al (2014) adopt a method by Krajnc and Glavic (2005) which comprises the following steps: (1) Selection of sustainability indicators according to the appropriate criteria; (2) Identification and evaluation of the existing dependencies and their intensities; (3) Normalisation of indicator values; (4) Weighting of indicators based on their importance towards sustainability; (5) Calculation of sustainability index.

2.12 Gaps in Knowledge and Pointers to the Present Study

The following are some gaps in knowledge that can be identified from the literature: (i) How can the differences in domain weights across national rating systems be explained? (ii) Although aspects are classifying into domains are there other ways of classifying them? (iii) How can we arrive at local benchmarks? (iv) Although some buildings fail to get rated under

current rating systems, is there a way of giving credit to the level of sustainability contained in them? (v) How can we assess dependencies among aspects and their implications?

Our study, which tackles all the above questions, is based on a sectoral framework and only focused on the building sector, considering the environmental sustainability, although we argue that the methodology can be used to cover social and economic sustainability as well. Furthermore, the study engages with the Total Quality Assessment (TQA) approach, which is essentially a qualitative assessment, but one that is comprehensive and can accommodate new aspects.

Although we generate new data relevant to the Sri Lankan context, we also make comparisons across rating systems from different countries and will seek to understand differences in their domain weights. The study will also use diverse and meaningful indicators derived from literature for the identified aspects and suggest alternative methods to arrive at an overall sustainability score. Furthermore, we will also study dependencies between indicator scores and demonstrate the implications of such dependencies for the environmental sustainability assessment of buildings.

Chapter Three

Weights for Domains and Aspects

3.1 Introduction

Some of the early studies on the quantification of sustainability employed life cycle analyses (LCA) of energy use and carbon emissions, inclusive of embodied energy and carbon (Chen et al, 2001; Yohanis and Norton, 2002). Dias and Pooliyadda (2004) employed an energy quality concept for such life cycle approaches, where energy inputs were weighted depending on whether the source was biomass, fossil fuel or electricity. Such studies aim at being theoretically rigorous, and fall within the ecological economics paradigm. However, they are critiqued as covering only a small fraction of the issues associated with sustainability.

This is why the latest phase of sustainability frameworks makes an attempt to broaden the scope of assessment by employing a total quality assessment (TQA) approach having a wide range of indicators. The frameworks are organized on the basis of sectors and domains. Energy, water and waste are examples of *domains* of interest, forming as they do areas where environmental concerns have arisen. On the other hand, transportation, commercial, industrial, construction and residential activity are considered to be *sectors* for analysis. In general domains tend not to overlap each other, although sectors could. Domains and sectors can be seen as orthogonal classifiers – so one can speak of an energy indicator for transportation or a waste indicator for the residential sector. A large number of sustainability accreditation systems are now available, based on such indicators. Apart from being classified into domains and sectors, these indicators can be seen as flowing out of environmental, economic and health & community concerns (Papadopoulos and Giana, 2009) – in other words, emanating from the triple bottom line framework.

There are many formal sustainability rating systems for buildings in worldwide use today, with LEED (2013) and BREEAM (2013) probably the best known. Each of these systems allocates marks or scores to various aspects of sustainability. If these aspects are grouped into domains, and the maximum possible marks for the aspects aggregated, the aggregate maximum marks for each domain can be arrived at, and hence the relative weight assigned to

each domain by the rating system. A comparison of such relative weights used in the Pacific Northwest was made by Fowler and Rauch (2006) and summarized in Table 3.1. There are a number of issues here. At the outset, there is the question of how the aspects were grouped. In this, the above authors have followed the Whole Building Design Guide (WBDG, 2006) principles as the basis for comparison. The technical content domains are (1) Optimize site potential; (2) Optimize energy use; (3) Protect and conserve water; (4) Use environmentally preferable products; (5) Enhance Indoor environmental quality (IEQ); and (6) Optimize Operational & Maintenance practice. Although some aspects are listed under 'other', it is nevertheless possible to find significant agreement on the way that the major domains should be labelled. Of course the weights assigned to them are different, but that probably reflects contextual concerns and is an area this chapter seeks to explore in particular. More recently, a review of six rating systems (including the four in Table 3.1) was made by Berardi (2012), who arrived at virtually the identical weights as Fowler and Rauch (2006) for the four systems in common.

Table 3.1: Comparison of rating systems using WBDG principles (Fowler and Rauch, 2006)

System	Weightage (%)						
	Site (1)	Energy (2)	Water (3)	Materials (4)	IEQ (5)	O & M (6)	Other
BREEAM	15%	25%	05%	10%	15%	15%	15%
CASBEE	15%	20%	02%	13%	20%	15%	15%
Green Globes	11.5%	36%	10%	10%	20%		12.5%
LEED	20%	25%	07%	19%	22%		07%

Ali and Al Nsairat (2008) have developed an effective green building rating system for residential units in Jordan considering that local context. The results obtained show the following weights for 7 domains: (1) Site selection - 10.3%; (2) Energy efficiency - 23.0%; (3) Water efficiency - 27.7%; (4) Materials and resources - 10.3%; (5) Indoor environmental quality - 11.8%; (6) Waste and pollution - 6.4%; (7) Economics - 10.0%. The high weight for water efficiency should be noted, something that would be of concern in a water scarce region. The point to note however, is that there is significant similarity between the choice of domains, apart from the somewhat out of place domain of 'economics'. Developing a local

assessment system was considered necessary for Jordan because it has significant variations from the developed world.

Rating systems have gained acceptance because they attempt to embody the concept of 'total quality' (Berardi, 2012) with respect to sustainability in a comprehensive way rather than focusing on a specific issue such as energy or emissions. Nevertheless there are various outstanding issues that need to be resolved, one of which is that the allocation of marks is essentially a qualitative approach that can lead to a lack of objectivity. Ding (2008) has proposed indicators rather than marks in order to overcome this, with an overall indicator arrived at through a weighted sum approach, but the weights would still be subjective. Malmqvist et al (2011) have also used quantitative indicators for various aspects, but the aggregation of aspect measures to domain ones and thereafter to overall ratings is qualitative. Forsberg and von Malmborg (2004) point out that qualitative rating systems cannot capture the information that can be obtained from quantitative life cycle approaches. Lee et al (2011) show that there can be discrepancies between a rating system approach and a quantitative embodied energy approach for assessing the 'materials' domain. It should also be noted that there are differences in the actual process of certification (e.g. the number of steps involved) and also the degree of sustainability reflected in the outcome labels - e.g. the best (i.e. "excellent") rating in BREEAM is probably better than the best (i.e. "platinum") one in LEED (Reed et al., 2009).

Rating systems involve both weights and scores, both of which are qualitative to a large extent. As described above, some work has been done to make the scores more quantitative and hence objective (see also Chapter 4). This chapter concentrates on the assigning of weights, regarding which much less work has been done. One way in which the subjectivity of weights can be assessed is to study the extent to which they are inter-subjective – i.e. the degree to which there is agreement (at least among building sector professionals) regarding the allocation of weights to aspects and domains. The differences for domain weights in different rating systems (e.g. see Table 3.1) can also be seen as embodying subjectivity. However, these systems have arisen from differing national contexts, e.g. LEED (2013) from the U.S. and BREEAM (2013) from the U.K. This chapter attempts to explain such differences in domain weights by correlating them with national indices that are reflective of

the concerns embodied in the domains. There are no such correlations described in the literature to date, other than arising from this research (Chandratilake and Dias, 2013).

The main objectives of this chapter are twofold:

1. To arrive at a weighting scheme for various domains and aspects corresponding to the building sector for a particular local context – in this case Sri Lanka; and to assess the degree of agreement across professionals on the resulting weights for domains and aspects.

2. To compare the domain weights arrived at with schemes developed in other national contexts; and to explain differences in the weights for some domains by correlations with appropriate context-related indices.

3.2 Identification and Definition of Domains and Aspects

This study focuses on the building sector and relevant domains were identified though comprehensive analysis of available assessment systems. Site, energy efficiency, water efficiency, material, indoor environmental quality and waste and pollution are the identified domains for the study.

The naming of the domains and aspects was done following the above mentioned studies and other literature. Other comparative studies of sustainability frameworks have also identified similarly common domains (Reed et al., 2009; Retzlaff, 2008; Papadopoulos and Giama, 2009; Xiaoping et al.,2009; Fenner and Ryce, 2008; Berardi, 2012). Six domains were chosen and named, as shown in Table 3.2. The correspondence between these labels on the one hand, and the 6 numbered columns in Table 3.1 and the first 6 domains in the Jordanian study on the other, can be clearly seen. In addition, each domain is divided into various aspects, as seen in Table 3.2. These aspects are largely based on the widely accepted LEED (2013) rating system, but draw on other work too.

Table 3.2: Domains and aspects based on existing rating systems and literature

Domain	Aspects
Site	Land use
	Site selection
	Infrastructure efficiency
	Transportation
	Housing density
	Microclimate
	Landscape design
Energy Efficiency	Energy usage
	Building envelope performance
	Lighting efficiency
	Greenhouse gas emission
	Renewable energy
Water Efficiency	Water conservation
	Water efficient landscaping
	Sustainable water technologies
Materials	Local/regional materials
	Renewable material
	Recycle material
	Reuse material
	Embedded energy
	Carbon content
	Durability
Indoor Environmental Quality	Occupant health & safety
	Thermal comfort
	Daylight
	Acoustic & noise control
	Visual quality
	Indoor air quality
Waste & Pollution	Waste reduction
	Waste management strategies
	Waste water management
	Operational waste
	Flexible building plan

3.3 Weighting Domains and Aspects

3.3.1 Survey in Sri Lanka

The objective of the survey was to develop for a given local context, namely Sri Lanka, a set of weights to reflect the relative importance of various domain elements. The weights were derived from an expert survey that was conducted among key professionals in the Sri Lankan construction industry, with 17 respondents each from architects, civil engineers and quantity surveyors making a total of 51 respondents. The author (of this thesis) was present during the filling of the questionnaires, but only to make clarifications when required.

Prior to the above survey, a pilot survey was undertaken among three key professionals (two engineers and one architect) in order to finalise the list of domains and their aspects. This is the only measure that was taken to ensure that the domains and aspects covered all dimensions of environmental sustainability. The entire group of 51 respondents were not allowed to incorporate any additional dimensions; they did not express any significant requirement to do so either.

Two methods were used to obtain the top level domain weights. In the direct ranking method, the respondents were first asked to rank the domains, and using this as a basis, to distribute weights, so that a total of 100% was obtained. In the pair-wise comparison method, the respondents were asked to compare the importance of each domain with each of the others in turn – the well documented analytic hierarchy process (AHP) (Saaty, 1994) was used, both for the comparison and the subsequent analysis of results. This AHP methodology is described in the next section. The aspects within each domain were weighted too, but only the direct ranking method was employed. All respondents were visited and interviews conducted, so that the response rate was 100%. It should be noted that the respondents were shown the aspect labels when ranking the domains, and also a fairly detailed description of the aspects (see Appendix 1) when ranking those aspects within a domain.

Apart from the main responses above, the respondents were asked about their experience in sustainable construction projects and awareness of existing sustainable accreditation systems. However, this information was not used to filter the results of the survey. The questionnaire instrument is given in Appendix 02.

3.3.2 Analytic Hierarchy Process and Method of Analysis

The Analytic Hierarchy Process (AHP) is a multi criteria decision making method that was originally developed by Prof. Thomas L. Saaty (1994). It is a method to derive ratio scales from paired comparisons. The input can be obtained from actual measurement such as price, weight etc., or from subjective opinions such as satisfaction and preference. AHP allows for some inconsistency in judgment because a human is not always consistent. The ratio scales are derived from the principal Eigen vectors and the consistency index is derived from the principal Eigen value.

As mention in chapter 3.2, this study focuses on six domains. To explain the process of the AHP method let us consider two of the domains 'site' and 'energy efficiency', for which respondents were asked to compare the importance of domains (in pairs). If the respondents judge 'site' to be more important than 'energy efficiency' they need to mark a number between 1 and 9 on the left side of a scale (see Table 3.3), while if 'energy efficiency' is considered more important 'site', then it is the right side of the scale that needs to be marked. These numbers 1to 9 in steps of two is a relative scale where 1 indicates equal ranking and 3, 5, 7 and 9 indicate increasing differences in importance between the two aspects being compared. The scaling does not need to be 1 to 9 but for qualitative data such as preference, ranking and subjective opinions, it is the scale suggested by Saaty (1994). The numbers correspond to the following differences in importance levels for the above ranking:

1 – Both domains have **Equal** importance
3 – **Slightly High** importance over the other domain
5 – **Moderately high** importance over the other domain
7 – **High** importance over the other domain
9 – **Very high** importance over the other domain

For instance if a respondent decides that 'energy efficiency' domain has a high importance compared to 'site' domain, it would be indicated as in row1 of Table 3.3. Since there are six domains, then the pair wise comparison could be represented as in Table 3.3. The number of comparisons for n domains would be the sum of the integers from 1 to (n-1), i.e. n(n-1)/2, and hence 15 for n = 6.

The next step is to represent the above in a matrix. Because there are six domains for comparisons, there will be a 6 by 6 matrix (see Table 3.4). The diagonal elements of the matrix will be a comparison of each domain with itself and will always be 1. Only the upper triangular part of the matrix needs to be filled as values for the lower traingular cells can be obtained from these values. We use the following rules to fill up the upper triangular part of the matrix, noting that each cell entry a_{ij} denotes the comparison between the domains indicated in the ith row and jth column

1. *If the judgment value is on the **left** side of 1, we enter the **actual** value.*
2. *If the judgment value is on the **right** side of 1, we need to put the **reciprocal** value.*

Table 3.3 – Sample AHP response from the survey for comparing domains

Site	9	7	5	3	1	3	5	7	9	Energy Efficiency
Site	9	7	5	3	1	3	5	7	9	Water Efficiency
Site	9	7	5	3	1	3	5	7	9	Material
Site	9	7	5	3	1	3	5	7	9	IEQ
Site	9	7	5	3	1	3	5	7	9	Waste & Pollution
Energy Efficiency	9	7	5	3	1	3	5	7	9	Water Efficiency
Energy Efficiency	9	7	5	3	1	3	5	7	9	Material
Energy Efficiency	9	7	5	3	1	3	5	7	9	IEQ
Energy Efficiency	9	7	5	3	1	3	5	7	9	Waste & Pollution
Water Efficiency	9	7	5	3	1	3	5	7	9	Material
Water Efficiency	9	7	5	3	1	3	5	7	9	IEQ
Water Efficiency	9	7	5	3	1	3	5	7	9	Waste & Pollution
Material	9	7	5	3	1	3	5	7	9	IEQ
Material	9	7	5	3	1	3	5	7	9	Waste & Pollution
IEQ	9	7	5	3	1	3	5	7	9	Waste & Pollution

Taking the comparison between site and energy efficiency in Table 3.3, since the respondent has ranked energy efficiency with **high** importance with respect to site, we put 1/7 in the (row 1, column 2) cell of the matrix. Comparing site and water efficiency, the respondent has ranked site with moderately high importance over water efficiency; hence we enter 5 in the (row 1, column 3) cell. It is the row entries that in fact reflect how important the domain in that row is with respect to the domains listed in the columns. After filling the upper triangular part of the matrix in this way, the lower triangular part of the matrix can be filled by using the reciprocal values of the upper triangular cells in the cells that are symmetrical to those cells about the principal diagonal. If a_{ij} is the element of the ith row and jth column of the matrix, then the value for the symmetrical cell a_{ji} is obtained as $a_{ji} = 1/a_{ij}$. All the element in the comparison matrix are positive, or $a_{ij} > 0$.

Table 3.4 – Matrix representation of the comparisons

	Site	Energy Efficiency	Water Efficiency	Material	IEQ	Waste & Pollution
Site	**1**	1/7	5	7	5	7
Energy Efficiency	7	**1**	9	7	7	9
Water Efficiency	1/5	1/9	**1**	5	1	3
Material	1/7	1/7	1/5	**1**	1/5	1/7
IEQ	1/5	1/7	1	5	**1**	3
Waste & Pollution	1/7	1/9	1/3	7	1/3	**1**

The average values obtained from the 17 quantity surveying professionals (for example) are shown in Table 3.5. We compute column sums of these as in Table 3.5.

Table 3.5 – Average matrix (obtained from the 17 quantity surveying professionals)

	Site	Energy Efficiency	Water Efficiency	Material	IEQ	Waste & Pollution
Site	**1.0000**	1.9543	2.7486	1.9644	1.1409	1.9930
Energy Efficiency	0.5117	**1.0000**	2.7200	2.1600	2.9600	2.4743
Water Efficiency	0.3638	0.3676	**1.0000**	1.6399	2.4209	1.6209
Material	0.5091	0.4630	0.6098	**1.0000**	2.4209	2.4629
IEQ	0.8765	0.3378	0.4131	0.4131	**1.0000**	2.3429
Waste and Pollution	0.5018	0.4042	0.6169	0.4060	0.4268	**1.0000**
SUM	**3.7629**	**4.5269**	**8.1084**	**7.5834**	**10.3695**	**11.8940**

In the next step, we divide each cell by its corresponding column sum to get the cell values in Table 3.6. Now the row sums are computed and each row sum divided by the overall total (which will be numerically equal to the number of domains, n (and 6 in our case). This will result in the average weight proportion attributed to each domain by the group; this can also be represented as a percentage.

Table 3.6 – Group comparison matrix

	Site	Energy Efficiency	Water Efficiency	Material	IEQ	Waste & Pollution	SUM		%
Site	0.266	0.432	0.339	0.259	0.110	0.168	1.573	**0.262**	**26.2%**
Energy Efficiency	0.136	0.221	0.335	0.285	0.285	0.208	1.471	**0.245**	**24.5%**
Water Efficiency	0.097	0.081	0.123	0.216	0.233	0.136	0.887	**0.148**	**14.8%**
Material	0.135	0.102	0.075	0.132	0.233	0.207	0.885	**0.148**	**14.8%**
IEQ	0.233	0.075	0.051	0.054	0.096	0.197	0.706	**0.118**	**11.8%**
Waste & Pollution	0.133	0.089	0.076	0.054	0.041	0.084	0.477	**0.080**	**8.0%**
SUM	1.000	1.000	1.000	1.000	1.000	1.000	**6.000**	1.000	100.0%

The normalized principal Eigen vector can be obtained by averaging across the rows (individual row SUM divided by total column SUM). The normalized principal Eigen vector is also called the priority vector. Since it is normalized, the sum of all elements in priority vector is 1. The priority vector shows relative weights among the things that need to be compared. Accordingly weights for domains were obtained as, site 26.2, Energy efficiency 24.5, water efficiency 14.8, material 14.8, IEQ 11.8 and waste and pollution 8.0. Table 3.6 shows the results for quantity surveying professionals.

3.3.3 Results and Discussion

The average domain weights according to the respondent category, and the overall average weights are given in the Table 3.7 for the direct ranking method. Coefficients of variance (CoV) have been stated within parentheses. Table 3.8 gives the corresponding results obtained from the pair-wise comparison method using the analytic hierarchy process (hereafter called the AHP method); no CoV values are given as the method is used by considering all the responses as a group.

Table 3.7: Domain weights from ranking method

Respondents	Average weight (%) (CoV)					
	Site	Energy Efficiency	Water Efficiency	Material	IEQ	Waste & Pollution
Quantity Surveyors	23.7 (0.27)	21.7 (0.31)	14.5 (0.29)	16.9 (0.22)	10.9 (0.59)	12.3 (0.47)
Architects	28.9 (0.25)	21.1 (0.32)	14.2 (0.23)	13.5 (0.31)	12.2 (0.42)	10.1 (0.24)
Engineers	24.4 (0.22)	23.8 (0.16)	14.4 (0.30)	13.1 (0.26)	13.8 (0.30)	10.5 (0.20)
Overall Average	25.7 (0.26)	22.2 (0.27)	14.4 (0.27)	14.5 (0.28)	12.3 (0.44)	10.9 (0.35)

Table 3.8: Domain weights from AHP method

Respondents	Average weight (%)					
	Site	Energy Efficiency	Water Efficiency	Material	IEQ	Waste & Pollution
Quantity Surveyors	26.2	24.5	14.8	14.8	11.7	8.0
Architects	26.5	25.1	16.5	11.9	11.1	8.9
Engineers	26.3	29.9	14.1	10.3	12.1	7.3
Overall Average	26.3	26.6	15.2	12.3	11.5	8.1

The domain weights in Tables 3.7 and 3.8 can be considered as being broadly similar, thus giving us confidence that the weighting is not significantly dependent on the process used. The CoV values in Table 3.7 indicate that there is more variability in the responses (and hence lack of consensus) for the Indoor environmental quality (overall CoV = 0.44) and

Waste & pollution (overall CoV = 0.35) domains. All other CoV values for the overall averages are below 0.30, which is not too high for such qualitative assessments.

If we focus on the differences between the two approaches, the most obvious discrepancy is the consistently lower weights for the lowest ranked domain (i.e. Waste & pollution) in the AHP method. In addition, Energy efficiency has also obtained a significantly higher weight in the AHP method. Thus, both Site and Energy efficiency are similarly ranked on top, whereas Site enjoys a clear top rank in the direct ranking method. Finally, the AHP method shows that Water efficiency is more important than Materials, whereas the order is reversed in the direct ranking method.

By and large, the AHP method tends to accentuate differences, which would be expected in a pair-wise comparison approach. However, the AHP method has been critiqued on the grounds that the final percentage weights are not known to the respondent, as they are obtained through a post-interview process. The expert is therefore unable to rectify any anomalies that may arise. Thus, if percentages of say 30% and 15% are generated for two domains, it does not necessarily mean that the experts as a whole think that the first domain is twice as important as the second; but it would in fact mean precisely that if these percentages are assigned in the ranking method, because the final percentages (at least their own ones) are determined by each expert. In addition, in the direct ranking method, experts are able to view all the domains simultaneously, whereas they focus only on two domains at a time in the AHP method. For the above reasons, it is the results of the direct ranking method that have been used for the rest of the analysis, to compare average responses across professional groups, to obtain the aspect weights (Table 3.9), and also in other parts of this research project. The AHP results have however, through their broad similarity to the direct ranking results, served to validate the latter.

If differences among categories of respondents were considered, in the direct ranking method both architects and engineers display a similar order of ranking for the domains, while it differs slightly for the quantity surveyors. In the AHP method, the similarity is between quantity surveyors and architects, while engineers differ somewhat in the ranking order. In fact the engineers' AHP weights display the largest range of percentages overall (from 29.9% for Energy efficiency to 7.2% for Waste & pollution). This high weight for Energy efficiency

is maybe a reflection of a disciplinary concern. For probably similar reasons, the highest weight for Site (28.88% in the direct ranking method and 26.5% in the AHP method) has been assigned by architects.

When the ranking of aspects is considered (Table 3.9), it can be observed that there is agreement among categories regarding the top ranked aspect in 4 of the 6 domains and agreement regarding the bottom ranked aspect also in 4 of the 6 domains. For instance, the top ranked aspect under the Site domain is 'site selection' for all three categories. There is similar agreement about the top ranking of the aspects 'energy usage' in the Energy efficiency domain; 'water conservation' aspect in the Water efficiency domain; and 'waste reduction' in the Waste & pollution domain.

In the Materials domain however, there is a clear disagreement between the 3 professional categories, where quantity surveyors, architects and engineers have ranked 'renewable material', 'local/regional materials' and 'reuse materials' respectively as the top aspects. Furthermore, there is no matching rank for any aspect in this domain among the three categories. On the other hand, there is full agreement in the ranking of aspects in the Water efficiency domain. One possible reason may be that it has only 3 aspects, which could increase the chances for full agreement.

Table 3.9: Relative and absolute aspect weights

	Quantity Surveyors		Architects		Engineers		Average
	Aspect % Weight (Domain)	Aspect % Weight (Overall)	Aspect % Weight (Domain)	Aspect % Weight (Overall)	Aspect % Weight (Domain)	Aspect % Weight (Overall)	Aspect % Weight (Overall
Site							
Land Use	18	4.26	20	5.78	12	2.93	4.32
Infrastructure Efficiency	20	4.73	17	4.91	18	4.39	4.68
Transportation	14	3.31	12	3.47	14	3.42	3.40
Site Selection	22	5.20	24	6.93	21	5.13	5.75
Housing Density	10	2.37	10	2.89	16	3.91	3.05
Landscape Design	7	1.66	9	2.60	10	2.44	2.23
Microclimate	9	2.13	8	2.31	9	2.20	2.21
	100	**23.65**	100	**28.88**	100	**24.41**	**25.64**
Energy Efficiency							
Energy Usage	30	6.51	34	7.18	26	6.19	6.63
Building envelope Performance	22	4.78	24	5.07	20	4.76	4.87
Lighting Efficiency	20	4.34	14	2.96	17	4.05	3.78
Green House Gases Emission	15	3.26	18	3.80	22	5.24	4.10
Renewable Energy	13	2.82	10	2.11	15	3.57	2.84
	100	**21.71**	100	**21.12**	100	**23.82**	**22.22**
Water Efficiency							
Water Conservation	55	7.99	45	6.41	50	7.21	7.20
Water Efficient Landscaping	15	2.18	20	2.85	20	2.88	2.64
Sustainable Water Technologies	30	4.36	35	4.98	30	4.32	4.56
	100	**14.53**	100	**14.24**	100	**14.41**	**14.40**
Material							
Renewable Material	20	3.39	10	1.35	5	0.65	1.80
Reuse Material	17	2.88	18	2.42	23	3.00	2.77
Recycle Material	15	2.54	16	2.16	18	2.35	2.35
Embedded Energy	14	2.37	15	2.02	17	2.22	2.20
Local/Regional Materials	14	2.37	21	2.83	12	1.57	2.26
Carbon Content s	12	2.03	8	1.08	10	1.31	1.47
Durability	8	1.36	12	1.62	15	1.96	1.64
	100	**16.94**	100	**13.47**	100	**13.06**	**14.49**
Indoor Environmental Quality							
Occupant Health & Safety	25	2.74	20	2.45	20	2.76	2.65
Thermal Comfort	20	2.19	25	3.06	30	4.15	3.13
Daylight	15	1.64	15	1.84	12	1.66	1.71
Visual Quality	10	1.09	12	1.47	8	1.11	1.22
Acoustic & Noise Control	8	0.88	10	1.22	5	0.69	0.93
Indoor Air Quality	22	2.41	18	2.20	25	3.46	2.69
	100	**10.94**	100	**12.24**	100	**13.82**	**12.33**
Waste & Pollution							
Waste Reduction	26	3.18	27	2.71	30	3.14	3.01
Waste Management Strategies	25	3.06	18	1.81	16	1.68	2.18
Waste Water Management	20	2.45	25	2.51	21	2.20	2.39
Operational Waste	16	1.96	16	1.61	18	1.89	1.82
Flexible Building Plan	13	1.59	14	1.41	15	1.57	1.52
	100	**12.23**	100	**10.05**	100	**10.48**	**10.92**

3.4 Comparisons and Correlations

3.4.1 Comparisons

Considering the overall results in Table 3.7, the Site domain has received the top ranking, with Energy efficiency a close second. Together, both these domains account for around 50% of the percentage weighting. The dominance of these two domains is confirmed in Table 3.8 too. The domains Water efficiency and Materials are next in line, receiving roughly equal weights in Table 3.7. The domain Waste & pollution receives the lowest weight in both Tables 3.7 and 3.8.

Table 3.10 shows a comparison of the Table 3.7 overall values (argued previously as being better than the Table 3.8 ones) with domain weight values from eight other schemes. These domain weights are obtained by first allocating all the aspects in a given scheme to one of the six domains identified in Table 3.2; and then aggregating the maximum marks assigned for all the aspects within each domain. Then the ratios between these maximum marks can be used to obtain the relative percentage weights for each domain. In so doing, we leave out any weights for aspects such as 'economics' (Ali and Al Nsairat, 2008), and increase correspondingly the weights for the other six domains. Hence, the domain weights from the eight other schemes have been redistributed so that all 100% of the weights are allocated among the 6 broadly common domains identified. Each scheme is also identified with a country where the scheme was developed. It should be noted that some of the above schemes have been identified as influential ones by other researchers as well, in particular the LEED and BREEAM ones (Reed et al., 2009; Retzlaff, 2008; Papadopoulos and Giama, 2009; Xiaoping et al., 2009; Fenner and Ryce, 2008).

For each scheme, the top ranked domain is both underlined and depicted in boldface in Table 3.10, while the second ranked domain is depicted in boldface only. It can be seen that the Energy efficiency domain has been either top or second ranked in 8 out of 9 cases. Water efficiency is top ranked in the two Middle Eastern contexts considered. The Site and IEQ domains are also highly (mostly second) ranked 4 times each, while the Waste & pollution domain is bottom ranked in 8 of the 9 schemes. It can be also seen from these comparisons that there can be significant variations among the weights of different schemes, presumably

according to the local importance of particular domains. Those variations and reasons for the same will be explored next.

Table 3.10: Comparison of modified domain weights

Scheme	Domain weight (%)					
	Site	Energy Efficiency	Water Efficiency	Material	IEQ	Waste & Pollution
LEED (USA)	**26.0**	**35.0**	08.5	12.0	14.0	04.5
BREEAM (UK)	15.8	**29.5**	06.3	**25.2**	11.6	11.6
SABA (Jordan) -JOR	11.5	**25.7**	**30.9**	11.5	13.2	07.2
Pearl Rating (UAE)	16.6	**25.5**	**27.4**	10.2	14.6	05.7
GBI (Malaysia) -MAL	15.4	**32.1**	12.8	07.7	**26.9**	05.1
Green Star (NZ)	**22.2**	**27.8**	11.1	11.1	**22.2**	05.6
Green Star (Australia)-AUS	18.8	19.6	09.8	**25.9**	**23.2**	02.7
CASBEE (Japan) -JAP	**20.0**	**26.7**	02.7	17.3	**26.7**	06.6
Sri Lanka Survey (SL)	**25.7**	**22.2**	14.4	14.5	12.3	10.9

3.4.2 Correlations

It can be argued now that the variations in domain weights for different schemes in Table 3.6 can be linked to the contextual differences among those countries. The necessity for such customization has been pointed out by Reed et al (2009) too; they also illustrate this through the different weights for water efficiency in schemes emanating from different countries. This study consider three of the six domains, namely Energy efficiency (which is highly ranked in most of the schemes), Water efficiency (which is top ranked in the Middle Eastern countries) and Site (which is highly ranked in 4 schemes). These domains are particularly important for buildings, which in the U.S. account for 39% of energy consumption and 12% of water consumption (Retzlaff, 2008). Where these domains are concerned, it has been possible to find country indicators that are reflective of the sustainability issues in the domain. So for example, it would be reasonable to posit that countries with a high per capita consumption of energy would seek to reduce consumption by giving a high domain weight for Energy efficiency – in other words there should be a direct correlation between the per capita energy consumption of countries and the domain weight for Energy efficiency in their sustainability rating systems. Similarly, countries with a high water stress would rate Water efficiency

highly, resulting in another direct correlation. The domain weight for Site would probably be related to urban population densities.

Energy consumption data should be based on primary energy consumption, since forms of energy such as electricity tend to consume correspondingly more energy in terms of oil required to fire generating plants. Data on such consumption is obtained from World Bank Indicators (2013a). Figure 3.1 shows the correlation between the domain weights for energy efficiency and the annual per capita primary energy consumption in tonnes of oil equivalent (TOE) for seven countries, leaving out Australia and the United Arab Emirates. The coefficient of determination (R^2) obtained is 0.63, which implies a fairly good degree of correlation for this type of data. It should be noted that that primary energy consumption of the USA is about 15 times that of Sri Lanka, and this is reflected in the differing domain weights for energy efficiency. Australia and the United Arab Emirates are considered outliers and not part of the correlation. The justification for leaving them out is the fact that both those countries have large exports of energy (i.e. large negative imports) compared to their consumption - see Table 3.11, column 3; data from World Bank Indicators (2013b). Hence energy considerations may not be so important in rating systems emanating from these two countries, resulting in the correspondingly lower weights for Energy efficiency. In fact Horne and Hayles (2008) have demonstrated that Australian housing has inferior energy related performance compared to a selection of similar countries.

More than one-third of the total world population lives under conditions of relative water scarcity (Vörösmarty et al, 2000). Water stress is measured in terms of the percentage of land area of a given country that experiences such scarcity (Alcamo et al, 2007) and the data obtained from NationMaster statistics (2013), based on research at the University of Kassel (CESR, 2013). Figure 3.2 shows the remarkably high coefficient of determination of 0.98 between the weights for the Water efficiency domain and the percentage of land area that is under water stress. The high water stress in Jordan and the UAE is immediately evident. Jordan has the highest weight of 30.9% for Water efficiency.

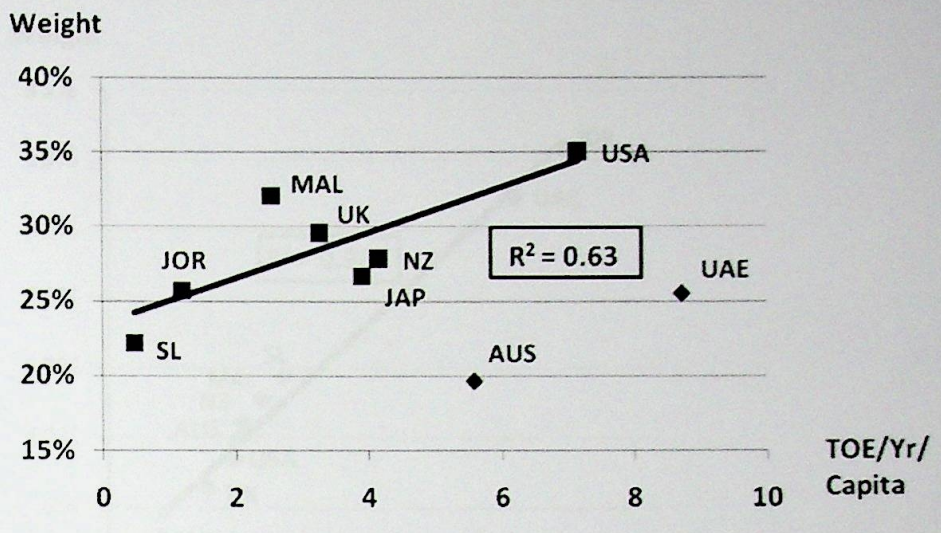

Figure 3.1: Trend of primary energy used in relation to weight for energy efficiency given by accreditation schemes

Table 3.11: Some national statistics used in correlations

Country	Largest city agglomeration and its population (x1000)	Energy Imports as % of energy use
United States (USA)	New York, NY-NJ-CT (20,673)	22%
United Kingdom (UK)	London (9,576)	27%
Jordan (JOR)	Amman (2,630)	96%
United Arab Emirates (UAE)	Dubai (3,319)	**-184%**
Malaysia (MAL)	Kuala Lumpur (6,608)	18%
New Zealand (NZ)	Auckland (1,310)	7%
Australia (AUS)	Sydney (3,956)	**-149%**
Japan (JAP)	Tokyo-Yokohama (37,239)	81%
Sri Lanka (SL)	Colombo (2,177)	44%

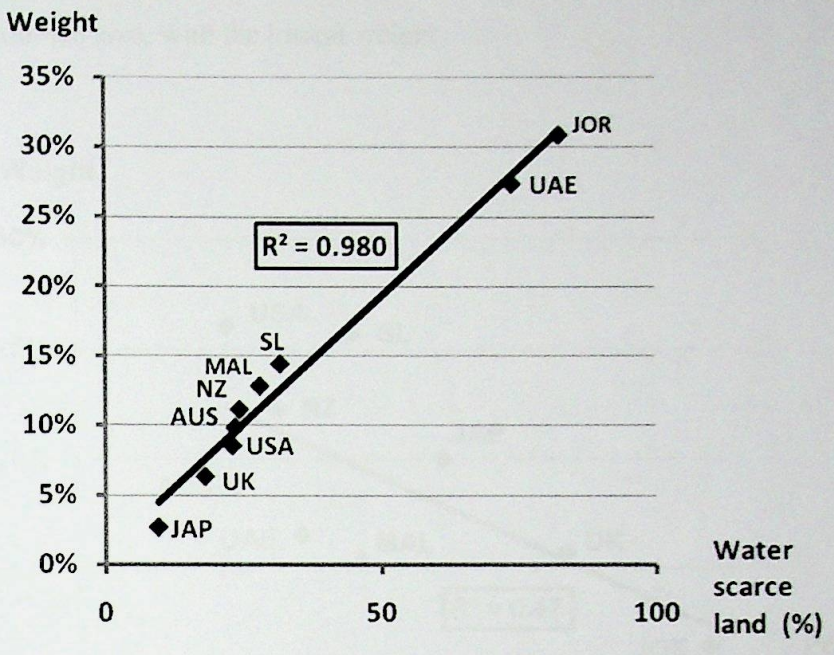

Figure 3.2: Trend of water stress in relation to weight for water efficiency given by accreditation schemes

When considering land availability for correlation with the domain weights for Site, it was thought better to use urban population density, since most of these sustainability rating systems are developed with urban infrastructure in mind. The statistic chosen was the population density of the largest urban agglomeration in the country concerned. The relevant agglomerations and total populations are given in Table 3.11, column 2. This data, together with the population density data is from the Demographia World Urban Atlas, 9th edition (2013). It should be noted that the population density corresponds not to the most densely populated area of a city but to an agglomeration as a whole. Figure 3.4 indicates a coefficient of determination (R^2) of 0.47, which is not as good as the other correlations, but still acceptable for the type of data being related. Of greater interest is the fact that the correlation is inverse in nature, and somewhat counter intuitive. It appears that nations with lower urban population densities have a higher weight for the Site domain. It may be that it is possible to apply stricter criteria in such nations where space is available for better planning, whereas nations with more crowded agglomerations may not be able to impose them. The USA has the lowest agglomeration density of 1800 persons/km^2 in the New York agglomeration (extending to New Jersey and Connecticut too), and also the highest weight for the Site

domain; whereas Jordan the highest agglomeration density of 7600 persons/km^2 in the Amman area, with the lowest weight.

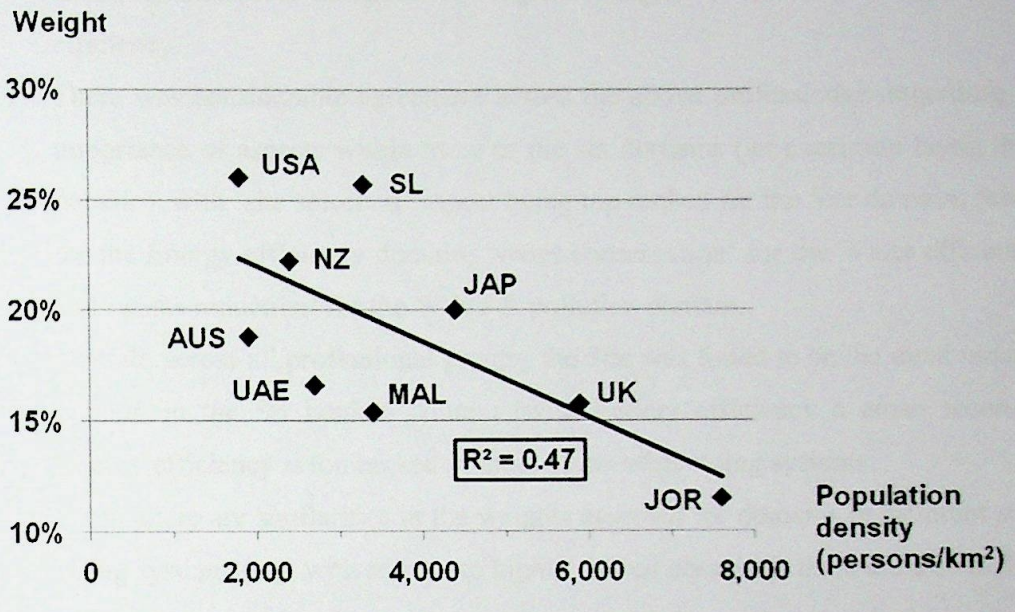

Figure 3.3: Trend of largest city population density in relation to weight for site given by accreditation schemes

In summary, we can say that when considering the differences in weights across different building sector professionals in a given national context (i.e. Sri Lanka), such differences are fairly small, because (i) coefficients of variation of the weights within each professional group (quantity surveyors, architects and engineers) are not that large; and (ii) differences in average weights and domain ranking order across the groups are also small. On the other hand, differences in weights for domains from one country to another could be explained by relevant national priorities, and demonstrated for the domain weight differences corresponding to 'site', 'energy efficiency' and 'water efficiency'.

3.5 Conclusions

1. In the reported survey of construction sector professionals, the direct ranking and analytic hierarchy process (AHP) methods yielded results that were sufficiently similar to give confidence in the weights obtained. The AHP method tended to somewhat accentuate differences somewhat across domains.

2. There were no significant differences in weights assigned to the major domains by the three professional groups, i.e. architects, engineers and quantity surveyors. Their disciplinary backgrounds may have influenced the slight differences obtained – for example, architects assigned the highest weight to Site while engineers to Energy efficiency.
3. There was considerable agreement across the above professionals regarding the relative importance of aspects within most of the six domains (an exception being the Materials domain), with 'site selection' aspect being top ranked for the Site domain; 'energy usage' for the Energy efficiency domain; 'water conservation' for the Water efficiency domain; and 'waste reduction' for the Waste & pollution domain.
4. Overall, across all professional groups, the Site was found to be the most important major domain in the Sri Lankan context (with Energy efficiency a close second), whereas Energy efficiency is top ranked in most of the other rating systems.
5. While there are similarities in the weights assigned for domains in different sustainability rating systems (e.g. with respect to highly ranked domains), there are also differences that reflect the national context.
6. National statistics on relevant indicators from 9 countries (from which the 9 rating systems originated) were used to demonstrate good correlation between those indicators and the corresponding domain weights for three of the six domains, namely Site, Energy efficiency and Water efficiency. This demonstrates that national contexts have influenced domain weights in rating systems.

Chapter Four

Development, Classification and Aggregation of Indicators

4.1 Introduction

The previous chapter explored the subjectivity associated with the assignment of weights for the range of sustainability indicators covered by sustainability rating systems. It was demonstrated that there is reasonable agreement among building sector professionals in a given country on the weights to be assigned for 33 indicators; it also provided evidence that differing weights for domain indicators in different schemes reflect the national priorities of the countries out of which those schemes emerged. This chapter concentrates on indicators and their scores.

In most schemes, the aspects are given scores by the evaluators, thus making them somewhat subjective. This is in contrast to quantitative studies that employ life cycle analyses of energy use and carbon emissions, inclusive of embodied energy and carbon (Chen et al, 2001; Yohanis and Norton, 2002). However, such quantitative studies are critiqued as covering only a small fraction of the issues associated with sustainability. Ding (2008) has proposed indicators rather than marks for aspect scores, with an overall indicator arrived at through a weighted sum approach. Malmqvist et al (2011) have also used quantitative indicators for various aspects.

TQA approaches (embodied in rating systems) require both weights and scores for each of the aspects being assessed. Cole (1998) has pointed out that most systems do not define weights in an explicit way, but rather create them indirectly by the maximum points obtainable for each aspect. Thus the range of scores would vary from aspect to aspect. He argues that the systems would be more consistent and comprehensible if all aspects had similar ranges for scores and if differences in the importance of aspects were dealt with by explicit weights. This is the approach proposed and demonstrated in this research.

The work in this chapter builds both on work done by previous researchers and on approaches embodied in various rating systems. However, there are two main innovations proposed for assessment schemes that are presented here, together with other new ways of classifying indicators and using them to arrive at an overall sustainability index. In proposing these innovations, we engage mainly with the LEED (2013) rating system, since most other rating systems are based on it.

The first innovation is the notion of 'comparative assessment'. Ding (2008) classifies building assessment tools into two categories, namely assessment and rating tools. She says "Assessment tools provide quantitative performance indicators for design alternatives, whilst rating tools determine the performance level of a building in stars". This distinction is broadly similar to the debates in the literature (described in the introduction above) about quantitative LCA models (typically for energy use and carbon emissions) and qualitative scoring schemes embodied in rating systems. However, Ding's (2008) distinction above also hints at *comparative* assessments, and it is this we focus on in our research. But we wish to make these comparisons using the rating system TQA paradigm because of its comprehensive approach; rather than focusing narrowly for example on energy contents and carbon emissions by using life cycle computations.

One of the features of rating systems is that certain minimum requirements have to be met for each aspect before getting any credit for that aspect; a building with an aspect that is judged as being just below this threshold does not get any credit towards its overall score from this aspect. This may be appropriate for buildings that seek to get 'star' ratings, but is inappropriate when comparing the overall sustainability contents of buildings or design alternatives. Hence, we argue that 'step functions' for scores be replaced with continuous functions.

Another feature of most rating systems is the allocation of marks by evaluators, which can be subjective to an extent. We propose that each aspect score be based on the ratio between a well defined quantity and the benchmark for that aspect (also defined in the scheme), resulting in a 'normalized score'. The defined quantity should reflect the given aspect of sustainability being assessed. We acknowledge that quantification could diminish the richness of representation, but propose it as a measure for reducing subjectivity. In any case,

it is a new contribution to the discourse on sustainability indicators, constitutes a move towards the spirit of quantification, and represents our second innovation. It should be noted that if each aspect indicator is at its benchmark level, all aspects would have identical normalized scores of unity, thus addressing one of Cole's (1998) concerns mentioned earlier. When combined with the explicit weights described in Chapter 3, this approach is arguably more consistent and comprehensible than those in current rating systems.

The objectives of this chapter are:

1. To define quantifiable indicators for the aspects of sustainability; and also to determine appropriate benchmarks for them.
2. To classify indicators in order to identify the most significant contributions to building sustainability.
3. To propose alternative score functions for arriving at an overall index for the environmental sustainability of buildings.
4. To demonstrate the use of the proposed schemes through case studies of office buildings.

4.2 Developing Quantitative Indicators

As mentioned before, the assessment scheme proposed has six domains and 33 aspects. Table 4.1 gives examples of the variety of quantitative indicator types arrived at for each of the qualitatively defined aspects (see Appendix 1 for the entire list of aspect indicators). It can be seen that the qualitative description for the aspect has been represented by an unambiguous quantity, namely the indicator. The sample presented in Table 4.1 covers aspects from four of the six domains. Two of four indicators presented are from the LEED (2013) rating system, but the other two, including benchmarks, are from the wider literature. Most of the indicators and benchmarks are based on LEED (2013), but some on BREEAM (2013) too. Other sources are Reppe (1999), Pullen (2000), Iwaro and Mwasha (2010), Buchanan (1991), De Silva and Vithana (2008), Environmental Product Declaration (2008), The Code for Sustainable Homes (2008) and GREEN-SL (2013).

Some of the indicators are ratios (i.e. without units) while others have units associated with them. Since combining such indicators constitutes an "adding apples and oranges" problem, we first normalize each of them with respect to the value of the identified benchmark, which itself will be either a ratio or have the same units as the proposed indicator. The normalized

indicators will therefore all be ratios and non-dimensional. They are obtained in a way that a higher value will signify a better sustainability score. In order to do this, some normalized indicators are obtained as Standard (Std) ratios, where the original indicator is divided by the benchmark; or as Inverted (Inv) ratios, where the benchmark is divided by the indicator – see Table 4.1.

Table 4.1: Variety of quantitative indicator types

Aspect (Domain)	Indicator	Life-cycle	Hier-archy	Indicator reference	Benchmark (reference)	Normal-ised ratio
Land Use (Site) Consider the foot print of the building compared to the total land area. Carefully site the building to minimize disruption on existing ecosystems and natural features.	Land building ratio = [Total un-built area]/ [Total area of the site]	Con	Bldg	LEED, 2013	Institutional = 50% Non- institutional = 25% (LEED, 2013)	Std
Energy Usage (Energy) Consider the methods and practices which minimize the operational energy of the building.	Operational energy = [Energy used in operation]/ [Area][% time occupied]	Oper	Sys	Reppe, 1999	180 kWh/m^2 p.a. office buildings (Iwaro & Mwasha, 2010)	Inv
Embedded Energy (Material) Select building materials and components with minimum embedded energy. Consider assembly methods which minimize energy consumption	Embedded energy = Total embedded energy (GJ)/ Area of the building (m^2)	Mat	Mat	Pullen, 2000	11 GJ/m^2 (Pullen, 2000)	Inv
Waste Water Management (Waste and Pollution) Specify high efficiency fixtures and dry fixtures to reduce wastewater volumes. Use of onsite mechanical and/or natural wastewater treatment systems.	Waste water treatment ratio = (Amount of waste water treated on site to tertiary standards)/ (Total amount of waste water generated on site)	Oper	Sys	LEED, 2013	50% (LEED, 2013)	Std

As may be expected, not every aspect would fit neatly into an indicator. Hence, five of the aspects needed two sub indicators each. For example, the transportation aspect in the Site domain has to do with the availability of public transportation access to the building site. This required two sub indicators, namely the planned/available number of rail stations within a half mile distance, and the same figure relating to bus stations. No aspect was divided into more than two sub indicators. The weight for the aspect was divided equally between the sub indicators, in order to obtain the combined normalized value for the indicator.

4.3. Classification of Indicators

4.3.1 Classification into Lifecycle Stages

The lifecycle of a building can be described by the stages of materials, construction, operation and demolition. The number of indicators corresponding to each stage and the total weights corresponding to those indicators were distributed among these four stages. Figure 4.1 shows the results in number of indicators (small figures at top left of cells) and percentage weights (large figures at bottom right of cells).

Lifecycle	Material	Site	Water Efficiency	Energy Efficiency	IEQ	Waste & Pollution	Total
Demolition						1 2.18%	1 2.18%
Operation			3 14.39%	5 22.21%	6 12.33%	3 5.73%	17 54.66%
Construction	2 5.12%	7 25.65%				1 3.01%	10 33.78%
Material	5 9.38%						5 9.38%
							Domains

Figure 4.1: Lifecycle based classification of indicators and aspect weights – Sri Lankan survey

It is evident that the operation stage is the most critical phase in the lifecycle, having 17 indicators and aspect weights of approximately 55%. Apart from that it shows that the construction phase also important having 10 indicators and aspect weight of approximately 34%.

As a means of comparison, the relevant aspects weights in the LEED assessment system was put into the same format and Figure 4.2 shows the results. It carries only aspects weights obtained from scores, since the LEED scheme itself assigns weights only indirectly, by giving different maxima for different aspects. Hence the number of indicators is irrelevant. Even though significant variations are found in the local importance of selected aspects compared to LEED, the overall lifecycle weights of aspects are conspicuously similar. It can

be observed that the operation phase has an aspect weight of approximately 57% and construction phase one of approximately 40%.

It is evident that the material and demolition phases are not that significant in either of the above two cases. Even though those aspects may be rich in number of aspects (or indicators), weights assigned to them are much lower. On the other hand much of the weight carried by the most critical phase (i.e. operation) is due to its key domain of energy efficiency. Similarly for the construction phase, it is due to the site domain.

Lifecycle	Material	Site	Water Efficiency	Energy Efficiency	IEQ	Waste & Pollution	Total
Demolition							
Operation			8.08%	35.36%	11.11%	2.02%	56.57%
Construction	8.08%	26.26%			3.03%	2.02%	39.39%
Material	4.04%						4.04%
							Domains

Figure 4.2: Lifecycle based classification of indicators and aspect weights – – LEED rating scheme

4.3.2. Classification into Hierarchical Levels

In the product modelling literature (Bjork, 1989; Dias, 1996) a building can be decomposed into systems (e.g. structural skeleton), components (e.g. beams) and materials (e.g. steel). The sustainability indicators can be placed within this building, system, component, materials, hierarchy. There is very little literature if any available on arranging aspects and indicators within the building hierarchy. Therefore the number of indicators corresponding to each level and the corresponding total weights were distributed among the four levels of the building hierarchy, to identify their importance, as done above for the lifecycle stages. The results are presented in Figure 4.3 - number of indicators in small figures at top left of cells and percentage weights in large figures at bottom right of cells.

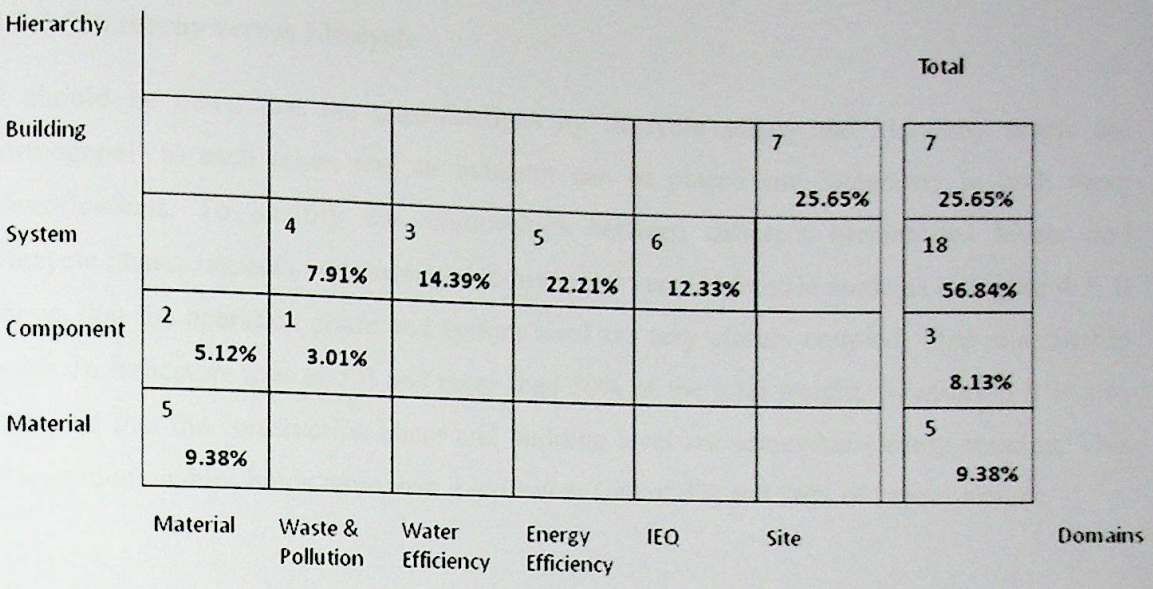

Figure 4.3: Hierarchy based classification of indicators and aspect weights – Sri Lankan survey

It is evident that system is the most critical level in the building hierarchy (with 18 indicators and approximately 57% aspect weight) and it is very significant as there is no other level close to contending with it. But the importance of the building level still cannot be ignored as it is represents seven indicators and approximately 26% aspect weight.

A similar exercise was applied to the LEED assessment system and results are presented in Figure 4.4. The results obtained from the local study were endorsed by those results, showing approximately 60% weight for the system level and 30% for the building level. It has to be noted that again the energy efficiency and site domains are the significant contributors for the system and building levels respectively.

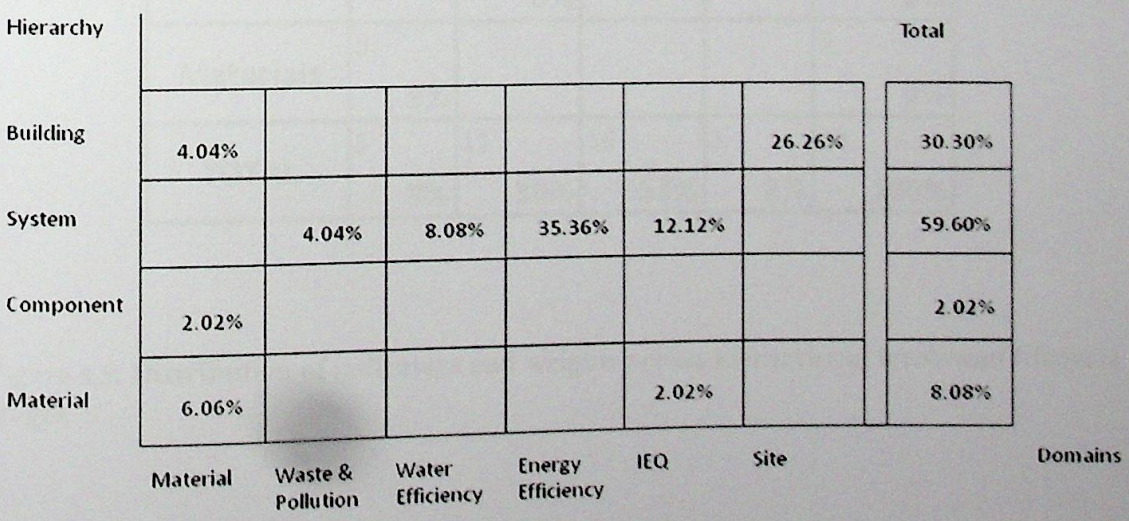

Figure 4.4: Hierarchy based classification of indicators and aspect weights – LEED rating system

4.3.3. Hierarchy versus Lifecycle

It should be noted that the classifications by lifecycle stages and hierarchy levels are 'orthogonal' to each other, and an indicator can be placed simultaneously in both these classifications. To identify the relationships between different hierarchical levels and lifecycle phases, aspects were arranged in hierarchy versus lifecycle mode as in Figure 4.5. It shows that the operation phase and system level are very closely coupled. That relationship holds 16 indicators (out of 33) and more than 50% of the total weight. In addition it is also observed that the construction phase and building level are somewhat closely coupled. This pair of relationships holds more than 7 indicators (out of 33) and 26% of aspect weight.

	Materials	Construction	Operation	Demolition	TOTAL
Building		7 **26%**			7 **26%**
System		1 **2%**	16 **53%**	1 **2%**	18 **57%**
Component		3 **8%**			3 **8%**
Materials	5 **9%**				5 **9%**
TOTAL	5 **9%**	11 **36%**	16 **53%**	1 **2%**	33 **100%**

Figure 4.5: Distribution of indicators and weights across hierarchical levels and lifecycle stages

4.4. Step Functions versus Continuous Functions for Indicator Scores

Consider now the innovation proposed with respect to the continuous rather than step functions for the aspect scores. Figure 4.6 shows the step function in LEED (2013) for the wastewater management indicator, where the benchmark is that 50% (0.5) of the wastewater should be treated – anything more than this does not get any extra credit (points); anything lower gets no points at all. The normalized indicator 'Basic' demonstrates how the above step effect is ameliorated, with better performing buildings given greater scores and buildings even below the benchmark getting the scores they 'deserve'. Buildings that perform better could get scores much higher than others because of this continuous (in fact linear) function effect. However, because each indicator score is factored by a weight, the largest of which is less than 0.08 (Table 3.9), the influence on the overall sustainability index will not be unreasonably influenced by a single or few high normalized indicator scores.

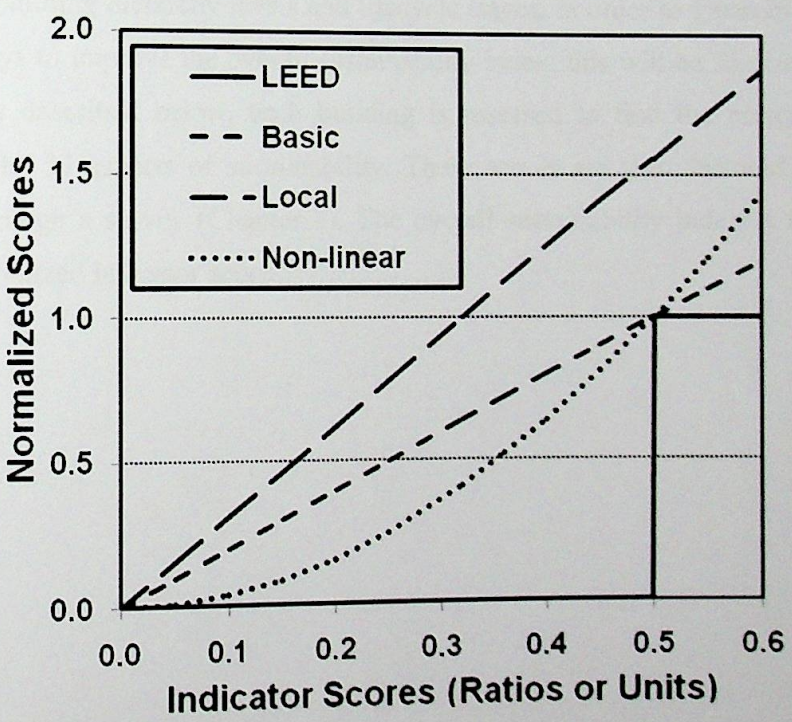

Figure 4.6: Step functions and continuous functions

Two variations from the basic normalized indicator are given in Figure 4.6. The normalized indicator 'Local' is based not on the benchmark in Table 4.2, but on the average indicator

score (i.e. 0.32) from a survey of 10 local buildings (described later in this paper). The normalized indicator score functions Basic and Local in Figure 4.6 are linear, but 'Non-linear' is obviously not. It should also be noted that some aspects in LEED (2013) do in fact give varying marks for varying performance, generally in a series of step functions; the marking scheme for energy usage is a case in point.

4.5 Combining Indicators

The tree diagram in Figure 4.7 gives an overview of this chapter, which is focused on sustainability indicators. The main left and right branches are related to scores and weights respectively. In Chapter 3, we described how indicator weights can be arrived at through a national survey, both by a ranking method and an analytic hierarchy process (AHP). In this chapter, as described above, the focus is on the indicator scores, with the objective of arriving at normalized values for these scores. It also classified indicators with respect to their location in building hierarchy levels and lifecycle stages, in order to glean information about possible ways to improve the overall sustainability index; this will be illustrated later. In the case studies described below, each building is assessed to find the normalized indicator scores for the 33 aspects of sustainability. These scores are then factored by the weights obtained through a survey (Chapter 3). The overall sustainability index is then a weighted sum of normalized indicator scores.

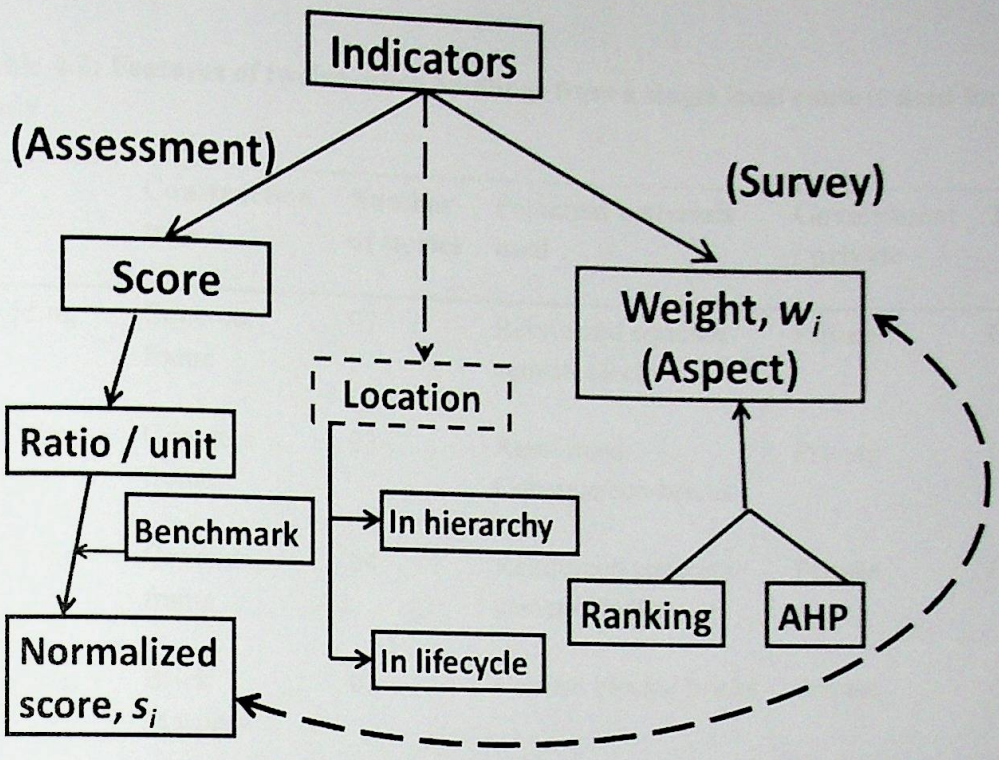

Figure 4.7: Overall scheme for arriving at sustainability score

Table 4.2 gives the features of twelve office buildings from a single local context (i.e. urban areas in Sri Lanka), the first 9 designed as green buildings and the tenth retrofitted as one, with the last two (shown in italics) not constructed with any 'green' considerations. Table 4.3 presents the results for the overall sustainability indices arrived at. It should be noted that the Table 4.3 values, which can be called 'Basic' sustainability indices (as defined in Figure 4.6) are obtained from equation (4.1) below, where the total index, S_B is given by the weighted sum

$$S_B = \Sigma\,(s_i, w_i), \qquad \text{(equation 4.1)}$$

Here the s_i are the normalized scores (which would be unity if an aspect indicator is at its baseline value) for the 33 aspects (i.e. i values range from 1 to 33). The w_i are weights for the 33 aspects that add up to 100, and given in Table 3.9.

The table gives the scores for each of the six domains, and the final sustainability score in bold. The difference between the green buildings and the last two is clear. The greatest

Table 4.2: Features of twelve office buildings from a single local context used for case study

	Construction type	Number of stories	Principal materials used	Government / private	Type
Building 01	Concrete frame	07	Reinforced concrete/ cement blocks	Private	Green
Building 02	Concrete frame	03	Reinforced Concrete/eco-bricks	Private	Green
Building 03	Concrete frame	04	Reinforced concrete cement blocks	Private	Green
Building 04	Brick Masonry	01	Cement blocks/ bricks	Private	Green
Building 05	Concrete frame	04	Reinforced concrete/ cement blocks	Government	Green
Building 06	Concrete frame	10	Reinforced concrete/ cement blocks	Private	Green
Building 07	Concrete frame	03	Reinforced concrete/ bricks	Private	Green
Building 08	Concrete frame	03	Reinforced concrete/ cement blocks	Private	Green
Building 09	Concrete frame	02	Reinforced concrete/ bricks	Government	Retrofitted Green
Building 10	Concrete frame	04	Reinforced concrete/ cement blocks	Private	Green
Building 11	Concrete frame	04	Reinforced concrete/ cement blocks	Private	Non Green
Building 12	Concrete frame	03	Reinforced concrete/ cement blocks	Private	Non Green

differences in scores obtained for the best (Building 1) and worst two (Buildings 11 and 12) cases are in the energy efficiency, water efficiency and waste & pollution domains. Most of the indicators in these domains would probably fall into systems level of the building hierarchy, and would hence also be related to the operational phase of the lifecycle. This means that it may be possible to retrofit a building during its operational phase, even if it had not originally been designed as a green building. Building 10 is in fact such a retrofitted building. Even though it has only the third lowest score, it can certainly be seen as part of the population of green buildings 1 to 10. Note that the indicator scores for each aspect are given in Appendix 3. They are normalised with respect to both global and local benchmarks in Appendix 4.

Table 4.3: Overall sustainability indices arrived at for twelve office buildings

Building ID	Site	Energy Efficiency	Water Efficiency	Materials	IEQ	Waste & Pollution	TOTAL
Bldg 1	27.7	23.7	17.4	12.8	13.2	15.7	**110.5**
Bldg 2	36.9	21.7	12.1	9.7	10.1	8.8	**99.2**
Bldg 3	34.9	21.3	9.3	9.0	8.8	9.5	**92.7**
Bldg 4	24.4	21.9	11.9	9.2	10.2	9.9	**87.5**
Bldg 5	24.8	23.4	13.5	8.1	9.6	10.3	**89.7**
Bldg 6	23.7	28.9	15.7	8.0	7.3	12.3	**96.0**
Bldg 7	29.6	21.3	10.7	6.4	10.9	11.1	**90.0**
Bldg 8	30.6	23.0	12.9	6.8	9.4	11.0	**93.8**
Bldg 9	23.2	24.8	10.4	7.6	9.6	9.5	**85.1**
Bldg 10	23.4	21.7	12.4	6.4	11.0	9.6	**84.4**
Bldg 11	*24.4*	*13.7*	*6.2*	*6.7*	*7.5*	*4.6*	***63.2***
Bldg 12	*21.7*	*12.2*	*5.2*	*9.0*	*9.5*	*6.9*	***64.5***

4.6 Possible Variations

Now consider the possible variations of the above scheme, the first to do with the value of the benchmark, and the other with accentuating scores for important indicators. We have already dealt with using local averages for benchmarks in describing Figure 4.6. Table 4.4 now

presents the minima, maxima and averages for all 33 aspect scores (normalized with respect to global benchmarks), obtained from the survey of the 10 green buildings (see Table 4.4). Note that we did not consider Buildings 11 and 12, the 'non-green' buildings, in arriving at these averages. This is because even if local average values are used in place of global benchmarks, those averages should be for buildings that at least have obtained green certification.

Table 4.4: Spread of aspect indicator scores for a Sri Lankan context, divided by the corresponding global benchmarks

	Minimum	Maximum	Average	Std Dev
SITE				
Land Use	0.18	1.29	0.39	0.33
Infrastructure Efficiency	0.30	2.00	1.09	**0.49**
Transportation	0.50	3.00	1.32	**0.65**
Site Selection	0.90	1.50	1.20	0.21
Housing Density	0.40	2.80	1.60	**0.74**
Landscape Design	0.12	1.89	0.56	**0.52**
Microclimate	0.50	1.30	0.88	0.25
ENERGY EFFICIENCY				
Energy Usage	0.78	1.00	0.89	0.07
Building envelope	0.70	1.00	0.84	0.10
Lighting Efficiency	0.80	1.60	1.13	0.22
Green House Gases	0.71	0.95	0.87	0.08
Renewable Energy	0.00	1.20	0.26	0.36
WATER EFFICIENCY				
Water Conservation	0.70	1.42	1.08	0.21
Water Efficient Landscaping	0.65	0.95	0.79	0.08
Sustainable Technologies	0.00	1.03	0.32	0.31
MATERIALS				
Renewable Material	0.00	1.60	0.29	**0.47**
Reuse Material	0.00	0.21	0.05	0.07
Recycle Material	0.08	1.25	0.37	0.38
Embedded Energy	0.72	1.83	1.00	0.32
Local/Regional Materials	0.52	1.10	0.70	0.18
Carbon Contents	0.75	1.11	0.94	0.12
Durability	0.78	1.20	0.97	0.14
IEQ				
Occupant Health & Safety	0.00	1.00	0.80	**0.42**
Thermal Comfort	0.25	0.90	0.55	0.18
Daylight	0.70	1.13	0.91	0.17
Visual Quality	0.56	1.11	0.81	0.18
Acoustic & Noise Control	0.80	1.50	1.04	0.20
Indoor Air Quality	0.80	1.15	0.99	0.14
WASTE & POLLUTION				
Waste Reduction	0.90	2.00	1.25	0.32
Waste Management Strategies	0.70	1.13	0.96	0.14
Waste Water Management	0.23	1.10	0.63	0.30
Operational Waste	0.65	1.50	1.02	0.25
Flexible Building Plan	0.76	1.30	1.02	0.16

An average score of unity in Table 4.4 indicates that the proposed local benchmark as at the same level as the global one, whereas one above unity signifies that it is higher than the global one and vice versa. We can see that only 10 of the 33 averages are above unity. This means that most of the local benchmarks are below the global ones.

Table 4.4 also gives the standard deviations for all 33 aspect scores. High values indicate considerable variability from one building to another. Values exceeding 0.4 are indicated in bold type and found mostly in the Site domain (where 4 out of 7 values are high). This is not surprising because differences in building location could give rise to widely differing scores. The scores for Renewable materials in the Materials domain and for Occupant health & safety in the IEQ domain also have high variability, probably because of differing attitudes of design professionals towards these aspects.

Now we can recalculate the overall sustainability scores for all the buildings based on the 'average' values rather than the assigned global benchmarks (based on the literature). Note that the average values to be taken as local benchmarks will be the values in the "average" column of Table 4.4, multiplied by the corresponding global benchmark. (Since all values in Table 4.4 are normalised with respect to global benchmarks) The comparison between the base case and this variation (i.e. 'Local', using local averages as benchmarks) is shown in Table 4.5. It can be seen that the scores have generally increased, suggesting that the average Sri Lankan performance is somewhat lower than reflected by global benchmarks. On the other hand, it could be argued that using the averages as benchmarks is more relevant in the Sri Lankan national context, and that the higher scores should be used to 'reward' buildings that perform well in a context where the average performance is relatively low. As average performance improves with time, the benchmarks will also become more stringent.

Table 4.5: Comparison between the base case and variations

Building ID	Basic	Local	Non-linear	LEED
Bldg 1	111	141	122	72
Bldg 2	99	105	102	70
Bldg 3	93	105	96	61
Bldg 4	88	89	91	61
Bldg 5	90	98	94	55
Bldg 6	96	106	107	68
Bldg 7	90	90	95	58
Bldg 8	94	96	104	57
Bldg 9	85	87	89	63
Bldg 10	84	87	87	61
Bldg 11	63	63	59	**17**
Bldg 12	65	65	59	**19**

The second variation (i.e. 'Non-linear') has to do with accentuating the scores that are obtained for more highly weighted indicators. This could be seen as double weighting, but is not unreasonable, given that obtaining better performance in more important aspects is to be desired. Recall that the total of 33 aspects and hence 33 indicators (5 of them composite as described before since they include 2 sub indicators each). If each of the aspects were equally weighted, the weights (given as percentages) would be 100/33 = 3.03. However, the actual average weights, obtained from a national survey (Table 3.9) range from 7.20 (for water conservation) to 0.93 (for acoustic & noise control). If the original score for an aspect i is s_i and its weight is w_i, one way to implement this variation is to raise s_i to the power (w_i/3.03), prior to weighting it as usual by w_i. This should be done however, only for w_i values greater than 3.03, i.e. scores are adjusted only for aspects that are weighted above the average weight. The scores could either increase (if greater than the benchmark) or decrease (if less

than the benchmark) through this variation – see the curve of the normalized indicator 'Non-linear' in Figure 4.6. Now, whereas the original (or base case) sustainability score is obtained as

$\Sigma (s_i . w_i)$, (equation 4.1)

The overall score based on the variation 'Non-linear' would be given by

$\Sigma \{[s_i \hat{} (w_i/3.03)] . w_i\}$, where $(w_i/3.03)$ is taken as not less than unity. (equation 4.2)

There are two reasons for not allowing the index $(w_i/3.03)$ to fall below unity. First, as explained above, we are only interested in accentuating scores for highly weighted aspects. Second, if the index fell below unity, scores above the benchmark would decrease rather than increase from those in the 'Basic' curve. This may be acceptable, since the aspects concerned are not weighted highly, and the resulting 'Non-linear' curve would be closer to the LEED step function for scores above the benchmark. However, the scores in the region below the benchmark would be higher than those in the 'Basic' curve, and this is not what we desire.

The scores thus obtained for the 12 buildings are also given in Table 4.5. Once again it should be noted that the scores have generally increased over and above the base case (with a few exceptions), but not to the extent of that in 'Local'. This indicates that the 'green buildings' surveyed have generally obtained higher scores in more highly weighted aspects, and this scheme rewards the buildings for that. However, the 'non green' Buildings 11 and 12 have in fact obtained lower scores than in the base case. It should also be noted that despite raising the scores' powers to greater or lower than unity, the overall scores have not been skewed too much from the base case, suggesting that this variation is robust as opposed to being overly sensitive to any single parameter. The application of equation 4.2 to the case studies demonstrates that although the equation is somewhat arbitrary, it does in fact achieve the objective of accentuating differences in the scores that are obtained for more highly weighted indicators.

The last column of Table 4.5 presents the scores obtained based on the LEED (2013) rating system. These scores are not related to the others in any way, but once again we see that the assessment schemes suggested in this paper do not deviate too much from the tried and tested LEED one. The 'non green' buildings are however severely penalized by the LEED marking

scheme, and this justifies are of the objectives of this research – namely to provide a more 'gradual' assessment scheme, rather than a rating scheme where marks can be scored only above a threshold (see Figure 4.6). Even the 'non-green' buildings would have some sustainable features and this is given credit in our assessment scheme, which therefore arguably presents a more realistic picture of differences between the sustainability levels of buildings.

Finally, Figure 4.8 depicts the correlation between the base case overall scores (on the x-axis) and the scores obtained for the two variations and the LEED scheme. Good correlations (R^2 values of 0.893 and 0.975) are obtained for the two variations. In addition, the corresponding equations indicate that the scores for the variations would have a greater spread than in the base case, as described above, since the slopes of the linear equations are greater than unity (being 1.54 and 1.33 respectively). The scores from the LEED scheme are not so well correlated with the base case, but even here an R^2 value of 0.501 is obtained, with a pattern clearly discernible. Furthermore the three top ranked buildings in the base case preserve their rank in the LEED scheme. The 'non-green' buildings are of course outliers on the LEED scheme and not included in the above correlation.

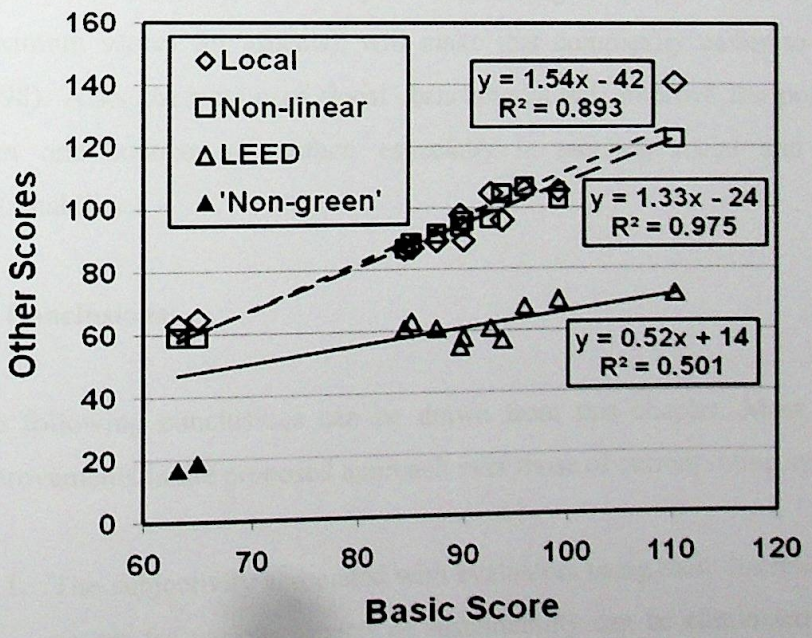

Figure 4.8: Correlation between the base case overall scores (on the x-axis) and the scores obtained for the two variations and the LEED scheme

An overall score of 100 in the assessment scheme would signify that on average all indicators have achieved their benchmarks. Now, considering the regression relation relationship with the LEED scores (see Figure 4.8), an overall score of 100 would translate into a LEED score of (0.52) x 100 + 14 = 66. This is in fact very close to the minimum LEED score of 69 that would be achieved if a building obtained the minimum mark for each aspect evaluated. These LEED scores (of either 66 or 69) would rate a building in the gold category, since in the LEED (2013) rating system scores from 50 to 59 points are given silver ratings, those from 60 to 79 gold ratings and those above 80 a platinum rating. At the same time, based on the same regression relationship above, the LEED score for Building 11 would be (0.52) x 63 + 14 = 47 (and similarly 48 for Building 12). This would not give them any rating (which they probably does not deserve), but they are flagged as a 'certified' building (for which the points range is 40 to 49).

Finally, although this study has focused on the environmental sustainability of buildings, it can easily be extended to cover wider dimensions (e.g. social and economic) and/or scales (e.g. neighbourhoods and cities). This will increase complexity. However, the fact our scheme normalizes aspect scores (so that each aspect has the same range of normalized indicator scores) and explicitly declares weights (rather than implying them through maximum scores for aspects), will make that complexity easier to deal with – see Cole (1998). Also, the notion of 'local' benchmarks will improve the portability of the scheme from one context to another, especially in tackling social and economic aspects of sustainability.

4.7 Conclusions

The following conclusions can be drawn from this chapter. Most of them highlight the improvements in the proposed approach over those of current rating systems.

1. The subjectivity associated with evaluators using their discretion to allocate points or scores for various aspects of sustainability can be eliminated by using well defined quantitative indicators for all the aspects of sustainability that need to be assessed. Such indicators need to be normalized with respect to benchmarks in order that they can be weighted and summed to obtain a composite score.

2. The greatest contribution to sustainability is from the systems level in a building hierarchy, which is allocated 18 out of 33 indicators and 57% of the total weight; also from the operational stage in the lifecycle, which is allocated 16 of the above 18 indicators and 53% of the total weight. There is thus a high degree of coupling between the systems level and operational stage of a building. This means that even a building not constructed as a 'green' building can be retrofitted to achieve a fairly high sustainability score.
3. Using continuous functions for indicator scores rather than step functions will be better for comparing sustainability features in buildings. This can be contrasted with rating systems approaches that use step functions and require threshold levels of achievement for most if not all aspects, in order for buildings to get rated at various levels.
4. Sustainability assessment schemes can be contextualized by using 'local' benchmarks for indicators. These can be based on averages of indicators from buildings that obtain green certification in a given national context.
5. Accentuating differences in scores for sustainability aspects that are more highly weighted can be achieved through a non linear indicator score function that is defined on the basis of the ratio of the aspect weight to the 'average' weight. The method proposed increases higher than benchmark scores and reduces lower than benchmark scores for aspects that are weighted more than the 'average' weight. This has the effect of spreading the range of overall sustainability scores.
6. A score of 100% in the proposed basic sustainability assessment scheme implies that all the benchmarks are just met on average. It corresponds (based on our correlation) to 66 points and a gold rating in the LEED rating system, in which scheme a building will obtain 69 points if all the aspects obtain the minimum points allocated.
7. The LEED rating system, based on step functions for aspect scores, gives an unrealistically low score for 'non green' buildings, and does not reflect much of the sustainability content that is nevertheless embedded in them. This justifies the use of continuous functions for indicator scores, if a comparative assessment of sustainability features is desired rather than a rating for 'high achievement' with respect to sustainability.

Chapter Five

Dependency between Indicator Scores

5.1 Introduction

In statistics, dependence is any statistical relationship between two random variables or two sets of data. Correlation refers to any of a broad class of statistical relationships involving dependence (Boslaugh, 2012). If the change in one variable is accompanied by a change in the other, then the variables are said to be correlated. In statistics correlation is used to understand

- whether the relationship is positive or negative; and
- the strength of relationship

Statistical correlation is measured by what is called the coefficient of correlation (r). Its numerical value ranges from +1.0 to -1.0. It gives an indication of the strength of relationship. In general, $r > 0$ indicates positive relationship, $r < 0$ indicates negative relationship while $r = 0$ indicates no relationship (or that the variables are independent and not related). Hence $r = +1.0$ describes a perfect positive correlation and $r = -1.0$ a perfect negative correlation. The closer the coefficients are to +1.0 or -1.0, the greater is the strength of the relationship between the variables.

However, statistical dependence is not sufficient to demonstrate the presence of a causal relationship (i.e., correlation does not imply causation). The value of 'r' should not be used to say anything about cause and effect relationships. Put differently, by examining the value of 'r', one could conclude that variables X and Y are related. However it does not tell us if X influences Y or the other way round. Statistical correlation should not be the primary tool used to study causation, because of the problem with third variables, which may be causing both X and Y.

Based on Pearson's correlation coefficient (r) the strength of relationship can be defined as follows, with corresponding ranges for negative values too (Boslaugh, 2012)

$r \geq 0.9$	Very strong relationship
$0.7 \leq r < 0.9$	Strong relationship
$0.5 \leq r < 0.7$	Moderate relationship

When an association exists between two variables, it means that the average value of one variable changes as one changes the value of the other variable (Fig. 5.1). A correlation is the simplest type of association called 'linear'. When a correlation is weak (e.g., Model C), it means that the average value of one variable changes only slightly (or occasionally) in response to changes in the other variable. In some cases, the correlation may be positive (Models A, C), or it may be negative (Model B). If the points in such a graph pretty much fall inside a circle or horizontal ellipse such that the "trend-line" through them is horizontal, then a correlation does not exist (i.e. the same as a zero or no correlation).

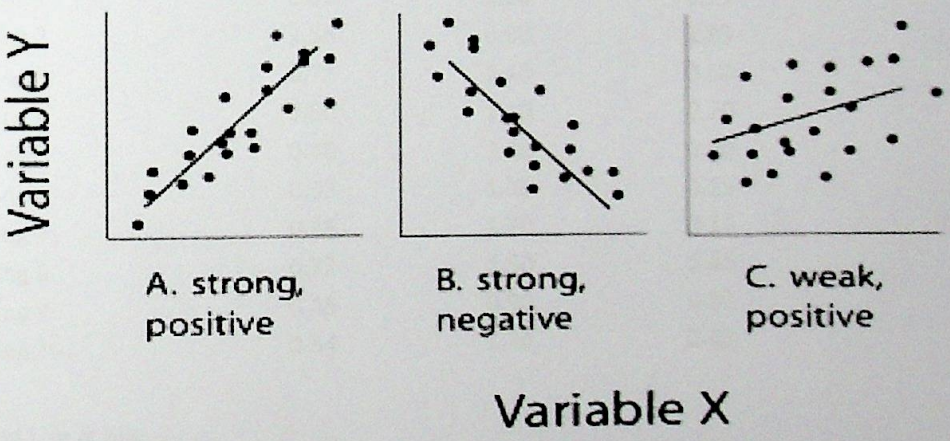

Figure 5.1: Correlation models (Pease and Bull, 2000)

5.2 Correlations of Indicator Scores in Case Studies

In this study, as mentioned in Chapter 4, the overall sustainability indices were arrived at for ten office buildings designed as green buildings from a single local context (i.e. urban areas in Sri Lanka). Only office buildings were selected so as to preserve uniformity; also they are the most common building type for which green building certification is sought (and hence for which data was available).

Appendix 01 shows the aspect indicators, which are either ratios or units. They were normalised (by dividing by the benchmark) to be 'higher the better' in terms of sustainability. Then those normalised values for 10 case studies (see Appendix 4) were used to obtain correlations within domains to assess their dependency.

Consider for example the normalized indicator values for land use, site selection and landscape design for the 10 buildings, as presented in Table 5.1. Even visually, one can guess that high land use scores are associated with low site selection scores; the correlation coefficient of -0.46 (≈ -0.5) confirms this. Even more apparent is the positive correlation between land use scores and landscape design ones – i.e. the scores generally move up or down in tandem. The correlation coeffient is +0.91 and confirms this.

Table 5.1 Normalized indicator values and correlation

	Indicator Value		
	Land Use	Site Selection	Landscape Design
Building 1	0.86	1.20	0.25
Building 2	2.58	0.90	1.89
Building 3	0.75	1.40	0.60
Building 4	0.80	1.10	0.70
Building 5	0.40	1.40	0.20
Building 6	0.35	1.30	0.15
Building 7	0.35	1.20	0.12
Building 8	0.72	1.50	0.45
Building 9	0.45	0.90	0.82
Building 10	0.54	1.10	0.43

r - Land Use & Site selection	-0.46	Moderate negative relationship
r - Land Use & Landscape Design	**0.91**	Very strong positive relationship

5.3 Intra-domain Indicator Correlations

As mentioned in the introduction, correlation does not reflect the causation. But causation essentially results in high correlation. The aim of this exercise is to identify the correlations between aspects of each domain for the normalized indicator scores. As can be observed from the results most of the aspect scores have some relationships.

Aspect correlations for the site domain (Table 5.2) show that there are both positive and negative correlations and most are above moderate relationships. Land use and landscape design show very strong positive correlation (0.91). As all these indicators were developed on the basis of 'higher the score, better the sustainability', when the land use indicator score increases (i.e. building footprint decreases and un-built area increases) the landscape design score likely to be increased, as there is more space available for vegetated areas. Hence the high correlation strongly matches with causality. Similarly a moderate negative relationship (-0.62) can be observed between housing density and landscape design indicators; here when the number of housing units per acre is increased, the area for landscape design will decrease. Here too the moderate negative correlation confirms the causality. But if the said housing density to be achieved with increased height of construction (i.e. multi storied construction) this causality justification will not be so strong; this may be why the correlation is not strong.

It can be noted that in the site domain, most of the correlations between aspects can be justified with demonstrable logical causation. In addition, aspects having negligible and very weak correlations display little or no possible logical causation.

Table 5.2: Aspect correlation - site domain

	Land Use	Infrastructure Efficiency	Transportation	Site Selection	Housing Density	Landscape Design	Micro climate
Land Use	1.00	-0.55	-0.28	-0.46	-0.47	**0.91**	0.59
Infrastructure Efficiency		1.00	0.26	0.36	0.62	-0.55	0.07
Transportation			1.00	0.27	0.62	-0.51	-0.34
Site Selection				1.00	**0.72**	-0.64	-0.49
Housing Density					1.00	-0.62	-0.42
Landscape Design						1.00	0.56
Microclimate							1.00

It can be observed from Table 5.3 that all the aspect scores in the energy domain show positive correlations. There is a strong positive correlation between energy usage and building envelope performance (0.82). The causal explanation is that when building envelope performances is high, it cuts down the thermal heat gain to the building, resulting in less energy consumption to cool the building. The reason for strong correlation (0.78) between lighting efficiency and greenhouse gas emission is that when lighting systems are energy efficient or more natural lighting is used in buildings, demand for grid electricity (produced with fuels resulting in green house gas emissions) can be reduced. The next strong correlation (0.82) exists between greenhouse gas emissions and renewable energy, which again can be simply explained by the fact that renewable energy usage produces little or no greenhouse gas emissions. Similarly almost all the above correlation results can be justified with causative factors and the degrees of correlation are mostly proportionate to the degrees of possible causation.

Table 5.3: Aspect correlation - energy efficiency domain

	Energy Usage	Building envelope Performance	Lighting Efficiency	Green House Gases Emission	Renewable Energy
Energy Usage	1.00	**0.82**	0.55	0.57	0.37
Building envelope Performance		1.00	0.20	0.35	0.07
Lighting Efficiency			1.00	**0.78**	0.65
Green House Gases Emission				1.00	**0.82**
Renewable Energy					1.00

The correlation between water conservation and water efficient landscaping is strongly positive according to Table 5.4, which shows that if water consumption for landscaping is reduced there is a high possibility of reducing the aggregate water consumption. The other combination, water efficient landscaping and sustainable water technologies, shows moderate

positive correlation. There is no immediate logical reason why increased efficiency in landscaping should result in sustainable water technologies. But there is a possibility that any facility thinking about water efficient landscaping would think about using such technologies (e.g. reuse water and harvested rain water)

Table 5.4: Aspect correlation - water efficiency domain

	Water Conservation	Water Efficient Landscaping	Sustainable Water Technologies
Water Conservation	1.00	**0.78**	0.29
Water Efficient Landscaping		1.00	0.50
Sustainable Water Technologies			1.00

When considering the correlations in the materials domain (Table 5.5), there are one very strong and four strong positive relationships. Renewable materials and embedded energy show the highest positive correlation (0.90). Rapidly renewable materials contain less embodied energy compared to materials with long lifecycles. The strong positive correlation (0.74) between recycle materials and embedded energy is because when a material is used a number of times in construction, the total embedded energy for a single use is heavily reduced. But there is no specific reason for rapidly renewable materials to have high recyclability, even though there is strong positive correlation between the two aspects (0.87). The same absence of causality applies to the strong positive correlations between renewable materials and local & regional material (0.82) and between recycled materials and local & regional material (0.89) too.

Table 5.5: Aspect correlation - material domain

	Renewable Material	Reuse Material	Recycle Material	Embedded Energy	Local Regional Materials	Carbon Contents	Durability
Renewable Material	1.00	-0.22	**0.87**	**0.90**	**0.82**	0.58	0.16
Reuse Material		1.00	-0.06	-0.11	-0.37	-0.12	0.43
Recycle Material			1.00	**0.74**	**0.89**	0.63	0.22
Embedded Energy				1.00	0.63	0.23	0.03
Local/Regional Materials					1.00	0.56	0.26
Carbon Contents						1.00	0.11
Durability							1.00

In the indoor environmental quality domain (Table 5.6) there is only one strong positive correlation (0.87), which exists between the day light aspect score and the indoor air quality score. But there is no causation explanation, unless daylight heat creates a stack effect causing passive ventilation.

Table 5.6: Aspect correlation - indoor environmental quality domain

	Occupant Health & Safety	Thermal Comfort	Daylight	Visual Quality	Acoustic & Noise Control	Indoor Air Quality
Occupant Health & Safety	1.00	0.30	-0.30	-0.13	0.12	-0.41
Thermal Comfort		1.00	0.07	0.48	0.61	-0.02
Daylight			1.00	0.45	0.22	**0.87**
Visual Quality				1.00	0.42	0.58
Acoustic & Noise Control					1.00	0.19
Indoor Air Quality						1.00

Even though all aspect scores show positive correlations in the waste and pollution domain (Table 5.7) there are no very strong or strong correlations.

Table 5.7: Aspect correlation - waste and pollution domain

	Waste Reduction	Waste Management Strategies	Waste Water Management	Operational Waste	Flexible Building Plan
Waste Reduction	1.00	0.14	0.60	0.50	0.68
Waste Management Strategies		1.00	0.19	0.04	-0.11
Waste Water Management			1.00	0.52	0.27
Operational Waste				1.00	0.69
Flexible Building Plan					1.00

5.4 Inter-domain Indicator Correlations

Section 5.3 presented only correlations among aspects within each of the six domains. It is such intra-domain correlations that are likely to signal causality and dependence, dealt with at length in Section 5.5. However Appendix 5 gives an overview of correlations among all the aspects, including those across domains. Apart from the intra-domain correlations mentioned above, there are quite a few other highly correlated relationships across domains. However, because causal links across domains may not be very strong, these inter-domain correlations are not analysed any further; they can be addressed in extensions to this research.

5.5 Direct and Indirect Influences between Indicator Scores

As discussed before, although there are correlations that exist between domain aspects, such correlation does not imply the causality; although causality will essentiality result in correlation. The aim of this section is to identify possible influences between aspect indicators that imply causality.

An aspect can directly influence other aspects, while influencing some other aspects indirectly. Similarly some aspects are susceptible to be directly and indirectly influenced by the influencing aspects. The overall influence may not necessary be same as the direct influences. Figure 5.2 depicts both direct and indirect influences for a 3 aspect system; we can call the aspects P, Q and R. In addition to the indirect influences depicted, 'cyclic' influences are also possible and described later. The methodology presented here follows that of Boulanger (2012) although there the P, Q and R are physical entities in an ecosystem, while here they are aspects which show dependencies on each other.

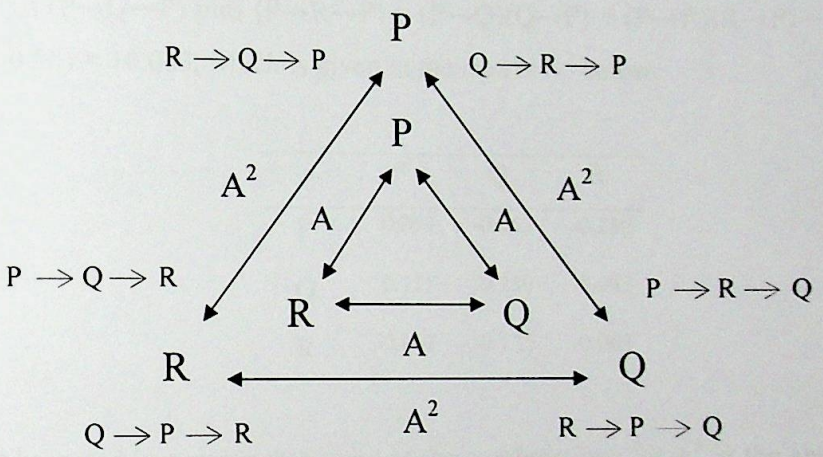

Figure 5.2: Direct and indirect influences of aspects

We can use a matrix of influences such as the one below (we can call it matrix A) to represent the direct influences. Unlike a matrix of correlations, a matrix of influences need not be symmetrical, as we shall see later.

	P	Q	R
P	0	+0.5	+0.25
Q	+0.25	0	-0.5
R	-0.25	-0.25	0

The matrix A indicates for example that the (direct) influence of P on Q (P→Q) = +0.5 and that of P on R (P→R) = +0.25. The direct influence of R on Q (R→Q) = -0.25. Note that the principal diagonal has zeros because there is no direct influence of an aspect on itself.

It is intuitive that the 'first level' indirect influence of P on Q (P→R→Q) will be the product of the direct influences of P on R and R on Q, i.e. (+0.25) x (-0.25) = -0.063. It can be shown that the matrix of these 'first level' indirect influences is obtained by multiplying the matrix A by itself to obtain A^2. The matrix A^2 is shown below; it indicates that (A→C→B) is indeed -0.063. The other thing to note is that the principal diagonals are now non-zero. This is because of 'cyclic' indirect influences. So, the first level indirect influence of A on A will be obtained as (P→Q→P) plus (P→R→P) = (P→Q)(Q→P) + (P→R)(R→P) = (+0.5)(+0.25) + (+0.25)(-0.25) = +0.063, which is given in the matrix A^2 below.

	P	Q	R
P	0.063	-0.063	-0.250
Q	0.125	0.250	0.063
R	-0.063	-0.125	0.063

It should be noted in passing that some of the combinations for A^3 in the above example (for influences starting with P) will be (P→Q→P→Q); (P→Q→P→R); (P→Q→R→P); (P→Q→R→Q); (P→R→P→Q); (P→R→P→R); (P→R→Q→P); and (P→R→Q→R).

The 'total influence' matrix will be the sum of A and A^2. However, in addition to the 'first level' indirect influence, there will be higher level ones as well, the 'second' level being depicted by the matrix A^3, and the third by the matrix A^4, and so on. If the original set of influences in the initial direct influence matrix A are depicted by numbers less than unity, then progressive multiplications will cause the higher order matrices to have very small terms and the sum of $A + A^2 + A^3 + ...A^n$ will soon converge.

5.6 Generating a Matrix Representation of Influences

We now consider the generation of matrix of influences, considering only intra-domain indicator influences, and focusing on the two most highly weighted domains, namely the site

and energy efficiency domains. We can consider each aspect in turn and think of logical reasons as to whether a change in the indicator value for that aspect will tend to increase or decrease the indicator value for each of the other aspects. If any indicator score causes another to be increased a plus mark was assigned to the matrix cell corresponding to the row containing the influencing indicator and column containing the influenced indicator. If the influence is significant, two plus marks were assigned. Negative influences were also assigned minus marks in a similar manner. The correlation coefficients played the role of corroborating the above judgements, but did not dominate them. Table 5.8 shows the r values and the plus or minus marks assigned to the aspects in the site domain. The rationale for assigning the marks is given below:

Land use → Housing density (-): When unbuilt area increases number of possible housing units will reduce (r = -0.47)

Land use → Landscape design (+ +): When unbuilt area increases there is more space available for landscaping (r = +0.91)

Land use → Microclimate (+): When there is more unbuilt area more chances for landscaping which reduce heat island effect (r = + 0.59)

Infrastructure efficiency → Transportation (-): When number of services available around the development less transportation required (r = +0.26)

Infrastructure efficiency → Housing density (+): When number of basic services in the area increases there is more demand for housing (r = +0.62)

Transportation → Infrastructure efficiency (-): When good transportation is available people will travel large distances for basic services (r = +0.26)

Transportation → Housing density (+): When transportation facilities increases there will be more demand for housing, which increase the density (r = +0.62)

Site selection → Infrastructure efficiency (+): When dense site is selected it would have good services (r = +0.36)

Site selection → Transportation (+): It is more likely to have good transportation facilities for previously developed sites (r = +0.27)

Site selection → Housing density (+ +): Developing previously developed sites increases housing density (r = +0.72)

Housing density → Land use (- -): When housing density increases total foot print of the built area will increase; as a result foot print of unbuilt area will decrease (r = -0.47)

Housing density → Infrastructure efficiency (+): When housing density increases there is more demand for infrastructure (r = +0.62)

Housing density → Transportation (+): When the housing density is high there would be good transportation (r = +0.62)

Housing density → Landscape design (-): When developing previously developed sites landscaped area can be reduced (r = -0.62)

Landscape design → Land use (+): When more area to be used for landscaping foot print available for construction reduces (r = + 0.91)

Landscape design → Microclimate (+): Good landscaping can reduce heat island effect (r = +0.56)

There are a number of issues that arise from the above procedure. First, the approach can be challenged, since it is not based on evidence, but rather on judgement. The response to this is twofold, namely (i) that future research can confirm the above statements via questionnaire surveys or other means; and (ii) that the judgements are guided by the correlation coefficients from actual data on indicator scores. It is not possible to rely only on the correlations however because (i) correlation does not imply causality and (ii) correlation may imply causality in one direction but not the other.

For example, a strong positive causality (+ +) has been identified from site selection to housing density, and this is corroborated by a high positive correlation (+0.72), but no causality can be identified in the reverse direction. Similarly the strong positive causality (+ +) from land use to landscape design is also backed up with the very high positive correlation (+0.91), but the reverse causality is only moderate (+). Then again, moderate negative causality (-) has been posited in both directions between infrastructure efficiency and transportation, but the correlation coefficient obtained is positive, although negligible (+0.26).

Ideally such discrepancies should be minimized in future research. Further the above list of causalities may not be exhaustive either, but they would be indicative of important trends. What is important is that we are attempting to identify and analyse dependencies between indicator scores, something that has not been done before.

Table 5.8: Dependency relationships for the site domain

	Land Use	Infrastructure Efficiency	Transpor -tation	Site Selection	Housing Density	Landscape Design	Micro -climate
Land Use		(r = -0.55)	(r = -0.28)		(- -) (r = - 0.47)	(+ +) (r = + 0.91)	(+) (r = + 0.59)
Infrastructure Efficiency	(r =-0.55)		(-) (r = +0.26)	(r = +0.36)	(+) (r = +0.62)	(r = -0.55)	(r = +0.07)
Transportation	(r = -0.28)	(-) (r = +0.26)		(r = +0.27)	(+) (r = +0.62)	(r = -0.51)	(r = -0.34)
Site Selection	(r = -0.46)	(+) (r = +0.36)	(+) (r = +0.27)		(+ +) (r = +0.72)	(r = -0.64)	(r = -0.49)
Housing Density	(- -) (r = - 0.47)	(+) (r = +0.62)	(+) (r = +0.62)	(-) (r = +0.72)		(-) (r = -0.62)	(r = -0.42)
Landscape Design	(+) (r = + 0.91)	(r = -0.55)	(r = -0.51)	(r = -0.64)	(r = -0.62)		(+) (r = +0.56)
Micro climate	(r = +0.59)	(r = +0.07)	(r = -0.34)	(r = -0.49)	(r = -0.42)	(r = +0.56)	

5.7 Analysing Intra-domain Influences – Site Domain

Table 5.8 shows the influences of indicator scores in plus and minus form. If there is a strong positive influence exists among the indicator scores two pluses are assigned. If moderate influence exists one plus is assigned. For the negative influences minuses were assigned accordingly.

The above mentioned pluses and minuses are now converted to a range of +2 to -2 as shown in Table 5.9. The row sums give an indication of the 'net positive' influence of a given indicator, while the column sums given an indication of the degree to which they are influenced. In order to convert the cell numbers to absolute values less than unity, they are divided by the maximum row sum, as shown in Table 5.10. (In some cases, some cell entries may not be below unity, but most will; and the method below will probably be applicable even in such cases).

Table 5.9: Matrix representation with +2 to -2 range – site domain

	Land Use	Infrastructure Efficiency	Transportation	Site Selection	Housing Density	Landscape Design	Micro climate	
Land Use	0	0	0	0	-2	2	1	**1**
Infrastructure Efficiency	0	0	-1	0	1	0	0	**0**
Transportation	0	-1	0	0	1	0	0	**0**
Site Selection	0	1	1	0	2	0	0	**4**
Housing Density	-1	1	1	0	0	-1	0	**0**
Landscape Design	1	0	0	0	0	0	1	**2**
Microclimate	0	0	0	0	0	0	0	**0**
	0	**1**	**1**	**0**	**2**	**1**	**2**	

The first matrix 'A' in Table 5.10 represents the direct influences. The highly influential indicators are site selection (having a row sum of 1.0) and then landscape design and land use successively (having row sums of 0.50 and 0.25 respectively). On the other hand the housing density and micro climate indicators shows high susceptibility to get influenced from other indicator scores (having column sums of 0.50 for both indicators).

As shown in Table 5.10 the first matrix A was multiplied with itself to get the A^2 matrix and matrix A was multiplied with A^2 to arrive matrix A^3. This progressive multiplication will converge at some point where there is not much further change in the sum $A + A^2 + A^3 + ...A^n$. The sum of influence matrices is shows in Table 5.11.

Table 5.10: The direct and indirect influence matrices – site domain

A	Land Use	Infrastructure Efficiency	Transportation	Site Selection	Housing Density	Landscape Design	Micro climate	
Land Use	0.00	0.00	0.00	0.00	-0.50	0.50	0.25	**0.25**
Infrastructure Efficiency	0.00	0.00	-0.25	0.00	0.25	0.00	0.00	**0.00**
Transportation	0.00	-0.25	0.00	0.00	0.25	0.00	0.00	**0.00**
Site Selection	0.00	0.25	0.25	0.00	0.50	0.00	0.00	**1.00**
Housing Density	-0.25	0.25	0.25	0.00	0.00	-0.25	0.00	**0.00**
Landscape Design	0.25	0.00	0.00	0.00	0.00	0.00	0.25	**0.50**
Microclimate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
	0.00	**0.25**	**0.25**	**0.00**	**0. 50**	**0.25**	**0.50**	
A^2	0.188	-0.063	-0.063	0.000	0.000	0.063	0.125	
	-0.063	0.125	0.063	0.000	-0.063	-0.063	0.000	
	-0.063	0.063	0.125	0.000	-0.063	-0.063	0.000	
	-0.125	0.063	0.063	0.000	0.125	-0.125	0.000	
	-0.063	-0.063	-0.063	0.000	0.188	-0.125	-0.125	
	0.000	0.000	0.000	0.000	-0.063	0.125	0.063	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
A^3	0.016	0.016	0.016	0.000	-0.078	0.094	0.063	
	0.000	-0.031	-0.047	0.000	0.063	-0.016	-0.031	
	0.000	-0.047	-0.031	0.000	0.063	-0.016	-0.031	
	-0.063	0.016	0.016	0.000	0.063	-0.094	-0.063	
	-0.078	0.063	0.063	0.000	-0.016	-0.078	-0.047	
	0.047	-0.016	-0.016	0.000	0.000	0.016	0.031	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
A^4	0.043	-0.023	-0.023	0.000	0.004	0.027	0.027	
	-0.020	0.027	0.023	0.000	-0.020	-0.016	-0.004	
	-0.020	0.023	0.027	0.000	-0.020	-0.016	-0.004	
	-0.039	0.012	0.012	0.000	0.023	-0.047	-0.039	
	-0.016	-0.020	-0.020	0.000	0.051	-0.035	-0.039	
	0.004	0.004	0.004	0.000	-0.020	0.023	0.016	
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

A^5

0.006	0.007	0.007	0.000	-0.022	0.021	0.018
0.001	-0.011	-0.012	0.000	0.018	-0.005	-0.009
0.001	-0.012	-0.011	0.000	0.018	-0.005	-0.009
-0.018	0.003	0.003	0.000	0.016	-0.025	-0.021
-0.021	0.018	0.018	0.000	-0.006	-0.021	-0.013
0.011	-0.006	-0.006	0.000	0.001	0.007	0.007
0.000	0.000	0.000	0.000	0.000	0.000	0.000

A^6

0.011	-0.007	-0.007	0.000	0.002	0.009	0.007
-0.006	0.007	0.007	0.000	-0.006	-0.004	-0.001
-0.006	0.007	0.007	0.000	-0.006	-0.004	-0.001
-0.010	0.003	0.003	0.000	0.006	-0.013	-0.011
-0.004	-0.006	-0.006	0.000	0.014	-0.009	-0.010
0.001	0.002	0.002	0.000	-0.006	0.005	0.004
0.000	0.000	0.000	0.000	0.000	0.000	0.000

A^7

0.002	0.002	0.002	0.000	-0.006	0.005	0.005
0.000	-0.003	-0.003	0.000	0.005	-0.001	-0.002
0.000	-0.003	-0.003	0.000	0.005	-0.001	-0.002
-0.005	0.001	0.001	0.000	0.004	-0.007	-0.006
-0.006	0.005	0.005	0.000	-0.002	-0.005	-0.003
0.003	-0.002	-0.002	0.000	0.000	0.002	0.002
0.000	0.000	0.000	0.000	0.000	0.000	0.000

A^8

0.003	-0.002	-0.002	0.000	0.001	0.002	0.002
-0.002	0.002	0.002	0.000	-0.002	-0.001	0.000
-0.002	0.002	0.002	0.000	-0.002	-0.001	0.000
-0.003	0.001	0.001	0.000	0.001	-0.003	-0.003
-0.001	-0.002	-0.002	0.000	0.004	-0.002	-0.003
0.000	0.001	0.001	0.000	-0.002	0.001	0.001
0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 5.11: Matrix of total influence (SUM = $A+A^2+A^3+...A^n$) – site domain

	Land Use	Infrastru -cture Efficiency	Transpo -rtation	Site Selection	Housing Density	Landscape Design	Micro climate	
Land Use	0.27	-0.07	-0.07	0.00	-0.35	0.72	0.50	**0.99**
Infrastructure Efficiency	-0.09	0.12	-0.22	0.00	0.25	-0.10	-0.05	**-0.10**
Transportation	-0.09	-0.22	0.12	0.00	0.25	-0.10	-0.05	**-0.10**
Site Selection	-0.26	0.35	0.35	0.00	0.74	-0.31	-0.14	**0.72**
Housing Density	-0.44	0.25	0.25	0.00	0.23	-0.53	-0.24	**-0.48**
Landscape Design	0.32	-0.02	-0.02	0.00	-0.09	0.18	0.37	**0.75**
Microclimate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
	-0.29	**0.40**	**0.40**	**0.00**	**1.02**	**-0.15**	**0.39**	

It can be observed from Table 5.11 that the indicator which is highly influencing others, considering total direct and indirect influences is land use. But with the direct influence alone it was the site selection aspect. On the other hand the housing density aspect remains as the one which is getting most influenced by other indicator scores and the column total has increased (from 0.5 to 1.02). The influence of the micro climate aspect has remained constant at 0.0, as has the susceptibility of the site selection aspect to being influenced (also constant at 0.0). So it is clear that there are considerable dependencies and influences that exist between aspects and their indicator scores. What is less clear is what this implies and how it should be used, both in decision making and in the designating TQA of aspects. It should also be noted that the methodology above is an improvement on that by Wagenhals et al. (2014), because (i) our marks for the original influences are guided by actual indicator score correlations found from data (whereas they used subjective measures); and (ii) we have considered many levels of indirect influence (whereas they have considered only direct influences).

5.8 Analysing Intra-domain Influences– Energy Efficiency Domain

Table 5.12 shows the influences of indicator scores in plus and minus form for the energy domain. If there is a strong positive influence of one aspect on another, two pluses are assigned to the cell containing the row of the influencing aspect and the column of the influenced aspect. If only a moderate influence exists one plus is assigned. It has to be noted that there are no negative influences between the aspects of this domain. Table 5.12 also shows the r values, which are also all positive. The rationale for assigning the marks is given below:

Energy usage → Greenhouse gas emission (+ +): When operational energy is less greenhouse gas emission is reduced (r = +0.57)

Building envelope performance → Energy usage (+ +): When heat gain from the building envelope is less operation energy demand is reduced (r = +0.82)

Building envelope performance → Lighting efficiency (+ +): When building envelope is good more natural lighting can be gained with low heat gain (r = +0.20)

Building envelope performance → Greenhouse gas emission (+): When heat gain from the building envelope is less operational energy demand is reduced and thereby GHG emission is reduced (r = +0.35)

Building envelope performance → Renewable energy (+): When heat gain from the building envelope is less operation energy (renewable) demand is reduced (r = +0.07)

Lighting efficiency → Energy usage (+ +): When more natural lighting used less operational energy is consumed (r = +0.55)

Lighting efficiency → Greenhouse gas emission (+ +): When more natural lighting/ energy efficient lighting is used greenhouse gas emission is reduced (r = +0.78)

Lighting efficiency → Renewable energy (+): When more natural lighting/ energy efficient lighting used renewable energy requirement is reduced (r = +0.65)

Renewable energy → Energy usage (+): When more renewable energy is used to promote sustainability, total operational energy usage tends to reduce (r = +0.37)

Renewable energy → Greenhouse gas emission (+ +): When renewable energy is used there are no greenhouse gas emission (r = +0.82)

Table 5.12: Dependency relationships for the energy efficiency domain

	Energy usage	Building envelope performance	Lighting efficiency	Green House gases emission	Renewable energy
Energy usage		(r = +0.82)	(r = +0.55)	(+ +) (r = +0.57)	(r = +0.37)
Building envelope performance	(+ +) (r = +0.82)		(+ +) (r = +0.20)	(+) (r = + 0.35)	(+) (r = +0.07)
Lighting efficiency	(+ +) (r = +0.55)	(r = +0.20)		(+ +) (r = +0.78)	(+) (r = +0.65)
Green House gases emission	(r = +0.57)	(r = + 0.35)	(r = +0.78)		(r = +0.82)
Renewable energy	(+) (r = +0.37)	(r = +0.07)	(r = +0.65)	(+ +) (r = +0.82)	

Similar to what we have done for the site domain, the above mentioned pluses and minuses are now converted to a range of +2 to -2 and represented in a matrix, as shown in Table 5.13. The row and column sums are also shown, and Table 5.14, the Matrix 'A', is obtained by dividing all the cell entries by the largest row sum.

Table 5.13: Matrix representation with +2 to -2 range – energy efficiency domain

	Energy usage	Building envelope performance	Lighting efficiency	Green House gases emission	Renewable energy	
Energy usage		0	0	2	0	**2**
Building envelope performance	2		2	1	1	**6**
Lighting efficiency	2	0		2	1	**5**
Green House gases emission	0	0	0		0	**0**
Renewable energy	1	0	0	2		**3**
	5	**0**	**2**	**7**	**2**	

Matrix 'A' (Table 5.15) represents the direct influences. The highly influential aspects are building envelope performance (having a row sum of 1.0) and then lighting efficiency and renewable energy successively (having sums of 0.83 and 0.50 respectively). On the other hand, the green house gases emission aspect shows high susceptibility to get influenced from other indicator scores (having a column sum of 1.17), and the energy usage aspect has one of 0.83.

Table 5.14: The direct and indirect influence matrices – energy efficiency domain

A	Energy usage	Building envelope performance	Lighting efficiency	Green House gases emission	Renewable energy	
Energy usage	0.00	0.00	0.00	0.33	0.00	**0.33**
Building envelope performance	0.33	0.00	0.33	0.17	0.17	**1.00**
Lighting efficiency	0.33	0.00	0.00	0.33	0.17	**0.83**
Green House gases emission	0.00	0.00	0.00	0.00	0.00	**0.00**
Renewable energy	0.17	0.00	0.00	0.33	0.00	**0.50**
	0.83	**0.00**	**0.33**	**1.17**	**0.33**	

Similar to what we have done in site domain, we can obtain the matrix of total influences, which is given in Table 5.15.

Table 5.15: Matrix of total influence (SUM = $A+A^2+A^3+...A^n$) – energy efficiency domain

	Energy usage	Building envelope performance	Lighting efficiency	Green House gases emission	Renewable energy	
Energy usage	0.00	0.00	0.00	0.33	0.00	**0.33**
Building envelope performance	0.48	0.00	0.33	0.51	0.22	**1.55**
Lighting efficiency	0.36	0.00	0.00	0.51	0.17	**1.04**
Green House gases emission	0.00	0.00	0.00	0.00	0.00	**0.00**
Renewable energy	0.17	0.00	0.00	0.39	0.00	**0.56**
	1.01	**0.00**	**0.33**	**1.74**	**0.39**	

It can be observed from Table 5.15 that indicator score which is highly influencing others, considering both direct and indirect influences is the building envelope performance. With the direct influence alone too this was the case, but now there is a considerable increase in the row sum (from 1.0 to 1.55). On the other hand the green house gases emission aspect remains as the one which is mostly getting influenced by other indicator scores and the column sum has increased considerably (from 1.17 to 1.74). The energy usage indicator (with an initial column sum of 0.83) has increased to 1.01 when the indirect influences are also considered. In fact none of the row and column sums decrease from their values in the original (direct influence) A matrix, while some of them increase significantly, because the energy efficiency domain has only positive causalities.

5.9 Implications of Influences

The most influencing and influenced aspects for both site and energy domains were identified in the previous section. The converged sums for all aspects in the site domain are given in Table 5.16.

Table 5.16: Aspect influences in site domain

	Degree of Influencing (row sum)	Degree to which Influenced (column sum)
Land Use	0.99	-0.29
Infrastructure Efficiency	-0.10	0.40
Transportation	-0.10	0.40
Site Selection	0.72	0.00
Housing Density	-0.48	1.02
Landscape Design	0.75	-0.15
Microclimate	0.00	0.39

The R^2 value obtained for the above degrees of influencing and being influenced is -0.96, and shows a very strong negative correlation (Figure 5.3). This implies that aspects which are most influencing other aspects are getting least influenced from those other aspects. This is to be expected, but it validates the matrix based approach used to analyse influences.

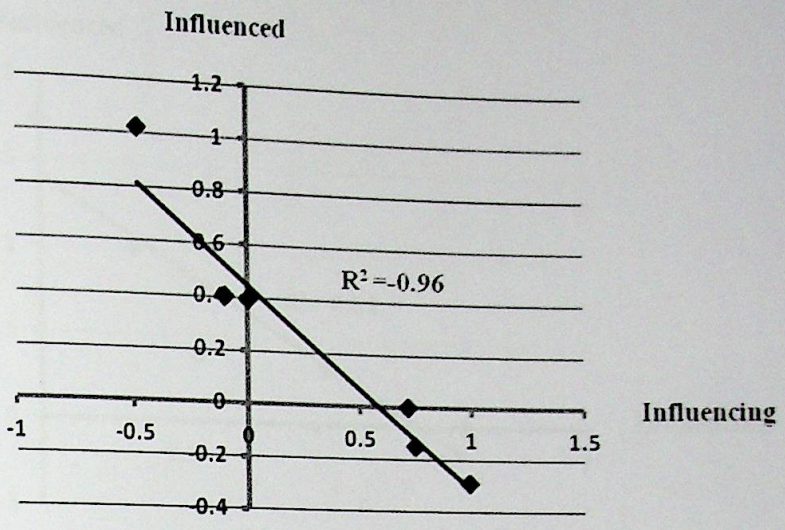

Figure 5.3: Correlation between degrees of influencing and being influenced exhibited by site domain aspects

Similarly the R^2 value obtained for the degrees of influencing and being influenced (Table 5.17) among aspects in the energy efficiency domain is -0.91, another very strong negative correlation (Figure 5.4). This confirms the result for the site domain.

Table 5.17: Aspect influences in energy efficiency domain

	Degree of Influencing (row sum)	Degree of being Influenced (column sum)
Energy usage	0.33	1.01
Building envelope performance	1.55	0.00
Lighting efficiency	1.04	0.33
Green House gases emission	0.00	1.74
Renewable energy	0.56	0.39

Note again that in the energy domain there are no negative values obtained because all dependencies were positive.

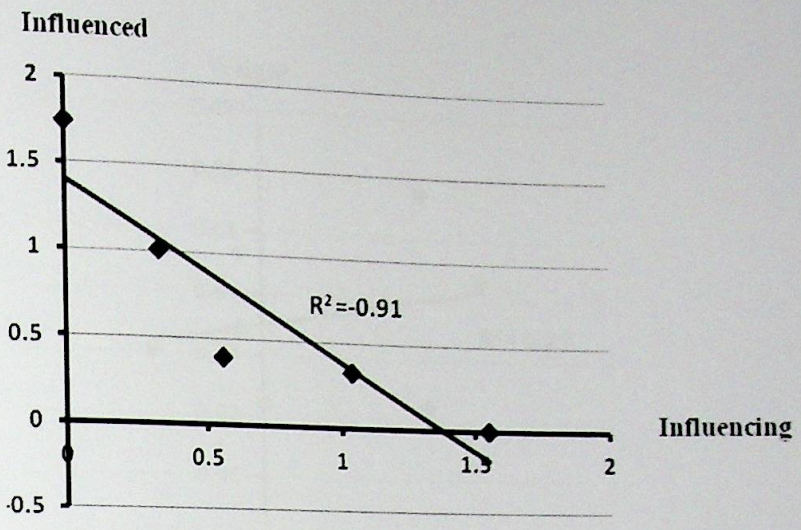

Figure 5.4: Correlation between degrees of influencing and influenced exhibited by energy efficiency domain aspects

The question arises as to the relationship between the weights obtained for these aspects (Chapter 3) and the degrees to which they influence or are influenced by other aspects. If say an aspect strongly influences other aspects (as discovered above), should that be reflected in its weight or should the weight merely reflect the impact on the environment? On the other hand, even though an aspect is strongly influenced by other aspects (with little or no influence on those others), can its weight still not be high, because its environmental impact is high? This research only begins to answer such questions, but they are questions well worth pursuing in further studies.

What we have done here is to take the aspect weights (from Chapter 3) and the degrees of influence (from above) and see whether there is any correlation. The resulting R^2 value obtained for the site domain aspects is 0.29 (Figure 5.5). This means that only 29% of the change in aspect weights is explained by their degree of influence. Similarly for the aspects in the energy efficiency domain the R^2 value is -0.06 (Figure 5.6), and hence much less. This limited exploration appears to indicate that the aspect weights do not primarily reflect their influence on other aspects, but rather their own environmental impact. In other words, we could tentatively say that aspects weights are independent of their influence on other aspects.

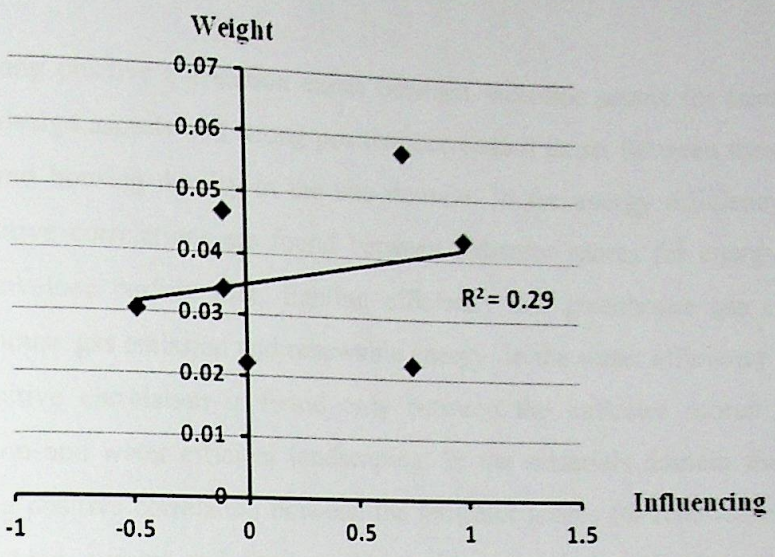

Figure 5.5: correlation between influencing and aspect weights – site domain

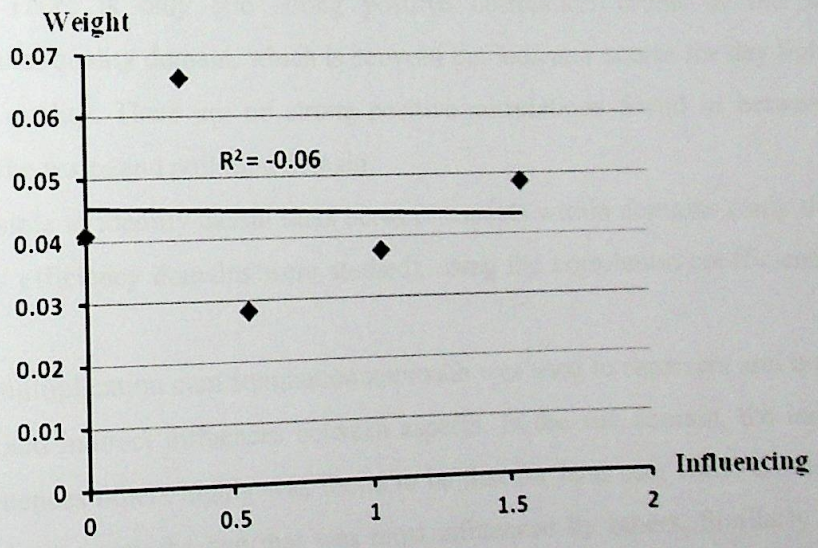

Figure 5.6: correlation between influencing and aspect weights – energy domain

The information obtained about the degrees and directions of influence of a given aspect with respect to the others will have implications for what levels their indicators can be at simultaneously. For example if aspect X has a very strong negative influence on aspect Y, it is unlikely that the indicators for both can assume very high values simultaneously. The constraints arising from this dependence are explored in Chapter 6.

5.10 Conclusions

1. A very strong positive correlation exists between indicator scores for land use and landscape design aspects and strong positive correlation exists between those for site selection and housing density in the site domain. In the energy efficiency domain strong positive correlations are found between indicator scores for energy use and building envelope performance; lighting efficiency and greenhouse gas emissions; and greenhouse gas emission and renewable energy. In the water efficiency domain a strong positive correlation is found only between the indicator scores for water conservation and water efficient landscaping. In the materials domain there is one very strong positive correlation between the indicator scores for renewable materials and embedded energy and four strong positive correlations between renewable materials and recycled materials; renewable materials and local/ regional materials; recycled materials and embedded energy; and recycled materials and local/ regional materials. There is only one strong positive correlation found in the indoor environmental quality domain, which is between the indicator scores for day light and indoor air quality. There are no strong positive correlations found in between the aspects of the waste and pollution domain.
2. It was possible to identify causal links between aspects within domains (only the site and energy efficiency domains were studied), using the correlation coefficients as a guide.
3. A matrix multiplication cum summation approach was used to represent and quantify the direct and indirect influences between aspects. In the site domain, the indicator which influences others highly was found to be that for land use; while the housing density indicator was the one that was most influenced by others. Similarly in the energy domain the indicator that most influenced others was found to be that for building envelope performance; while the one that was most influenced by others was found to be the indicator for greenhouse gas emissions.
4. Very high negative R^2 values between the degrees of influencing and being influenced for both site and energy domain aspects show that the results obtained by matrix operations for the degrees of influencing and being influenced are robust and dependable.

5. Low or negligible R^2 values between aspect weights and their degrees of influencing other aspects indicate that the weights reflect the actual environmental impacts made by the aspects much more than their influence on other aspects. This means that aspects weights appear to be independent of their influence on other aspects.

Chapter Six

Optimal Combination of Environmental Sustainability Strategies

6.1 The Concept of Optimization

Optimization deals with the study of those kinds of problems in which one has to minimize or maximize one or more objectives that are functions of some real or integer variables. In other words it is a process of finding an alternative with the highest achievable performance under given constraints, by maximising desired factors and minimising undesired ones. This is executed in a systematic way by choosing the proper values of real or integer variables within an allowed set. Given a defined domain, the main goal of optimization is to study the means of obtaining the best value of some objective function. An equally important goal is to find the values of the variables that will cause optimization. In some cases, different sets of variable values will result in near optimal solutions, and in practical situations this may be all that is required. It will also result in differing combinations of variable values that can be selected to reach near an optimal condition. This in fact is the basis of approaches such as genetic algorithm optimization (Goldberg, 1989). The practice of optimization is restricted by the lack of full information, and the lack of time to evaluate what information is available.

6.2 Increasing the Overall Sustainability Index via Optimization

In this study, the overall sustainability index is obtained as the weighted sum of normalized indicator scores. The optimum sustainability score can be obtained by indicator score combinations that maximize that score. However, since optimization problems are traditionally set up as minimization problems, we can write the objective function for minimization as:

$$\text{Objective function} = 1/\Sigma\,(s_i, w_i),$$

where w_i are the weights and s_i is normalised score values for the i indicators.

The point of normalization is to facilitate the adding together of score values – i.e. to "add apples and oranges". This can be achieved by dividing the score value by the benchmark values for the scores. For the exercise in this chapter, the average scores from the survey of 10 Sri Lankan green buildings (Section 4.5) were taken as the benchmarks. The weights are obtained from the survey of professionals described in Section 3.3.

The following steps describe in the process

- Select all combinations of possible s_i
- If any combination of scores violates a constraint, add a (large) penalty
- Find minimum value for above objective function

In the exercise that follows, the s_i are not ones obtained from actual buildings, but rather hypothetical ones. In fact, the s_i can take only three values for each variable, namely a high, average and low value. The values used are the maximum, average and minimum values obtained from the survey of 10 Sri Lankan green buildings (Section 4.5). The intention in the optimization exercise presented is to find the s_i combinations that will yield a (near) optimal solution. The emphasis therefore is not on the optimum score, but rather on the optimum combinations; and since there are more than one combination that will give near optimum solutions, this will constitute a flexibility of strategies for achieving high overall, sustainability scores.

It may appear at first sight that the single best strategy would be to set all the s_i at their maximum values. We have seen from Chapter 5 however, that there are some negative correlations among aspect scores. This is seen mainly in the Site domain, but also evident to some extent in the Materials and IEQ domains (Section 5.3). In any case, the Site domain has considerable influence on the overall sustainability strategy, accounting as it does for 26% of the domain weight (Table 3.10). If there is say a strongly negative correlation between two indicator scores (for example land use and housing density in the Site domain), it is very unlikely that both can be at their maximum values, and this is why we need an optimization approach to identify combinations that will deliver optimal or near optimal overall performance. We can then strategise at the design stage to deliver such combinations. These

negative correlations (or causations – see Section 5.7) can be introduced as the constraints in the optimization exercise and the specifics are discussed in Section 6.3.

In solving optimisation equations subject to constraints, the penalty method is a well known procedure (Ilanko and Bharathy, 2012). Recent publications show that with a combination of positive and negative penalty parameters, constraint violations can be determined and controlled. Several methods exist to account for the constraint relations (Barlow 1982). The method used in this study is very straightforward. With the aspect score correlations and influences in Chapter 5, likely or acceptable combinations between the indicators were identified. Single point constraints are then used - these are applied at the indicator combination point (aspect level) to penalize the generation of unlikely combinations

Imposing a constraint through penalty functions implies that the constraint equation is multiplied with a user-defined number (known as the penalty parameter), and that the resulting term added to the objective function. Else, the penalty parameter can merely be added to the objective function, if a constraint violation is signalled by some logical (IF..THEN) test. This latter method is the one used in our exercise. Since the optimization problem is a minimization one, a large positive penalty is added.

6.3. Dealing with Negative Influences

6.3.1 Strong Negative Influences

Consider the land use and housing density indicator scores in the Site domain. Table 5.8 indicates that the influence of land use on housing density is represented by two minus signs (strong negative), indicating that the housing density indicator cannot take high values if the land use indicator is high. In fact, because of this strong negative influence, we can deem that housing density can take values greater than low only if the land use indicator is at a low value. Thus, the acceptable or likely combinations are given in Table 6.1.

Table 6.1: Acceptable combinations between land use and housing density indicator scores in the Site domain for strong negative influences

Aspect	Acceptable combinations		
Land Use	L	M	H
Housing Density	L,M,H	L	L

Here, H, M and L represent High, Medium and Low indicator scores respectively. Figure 6.1 shows the acceptable combinations given in Table 6.1

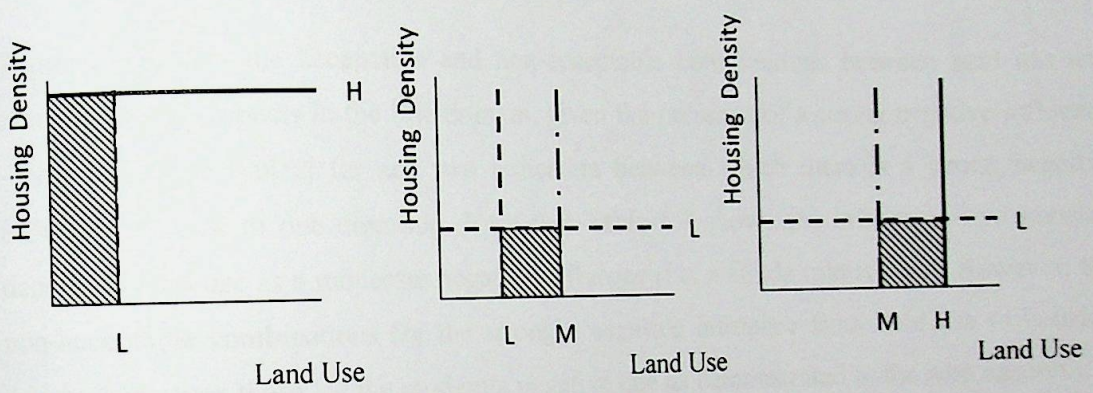

Figure 6.1: Graphical presentation of acceptable combinations between land use and housing density aspects in site domain for strong negative influences

The above can be explained as follows. In a given situation where the land use indicator score is low (meaning that un-built area and total land area ratio is low and less open space is available in the site), the housing density indicator (number of housing units per acre) can take any value of low, medium or high. On the other hand, when the land use indicator is high (reflecting a very high amount of open space or high un-built area), it is likely that the housing density indicator would take only a low value; we do not allow even a medium value because the influence of the land use indicator on the housing density one is very strongly negative. For the same reason, when the land use indicator is medium, we allow only a low value for the housing density indicator.

The inverse of Table 6.1 and Figure 6.1 is represented in Table 6.2 – these are the non-acceptable combinations If these combinations are generated in a randomized optimization (i.e. minimization) scheme, a large penalty parameter should be added to the objective function.

Table 6.2: Non-acceptable combinations between land use and housing density aspects in site domain for strong negative influences

Aspect	Non-acceptable combinations			
Land Use	M	M	H	H
Housing Density	M	H	M	H

Figure 6.2 shows the acceptable and non-acceptable combinations between land use and housing density aspects in the Site domain, given the presence of a strong negative influence – this would be typical for any two indicators between which there is a strong negative influence at least in one direction. Note that Table 5.8 shows the influence from housing density to land use as a moderate negative influence (i.e. a single minus sign). However, the non-acceptable combinations for the strongly negative influence from land use to housing density subsumes those for the moderate negative one as demonstrated in the next section.

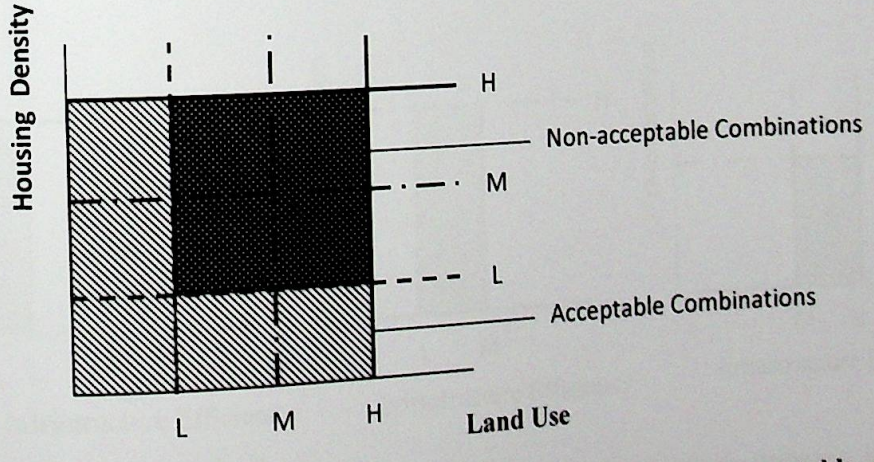

Figure 6.2: Graphical presentation of acceptable and non-acceptable combinations between land use and housing density aspects in the site domain for strong negative combinations

6.3.2 Moderate Negative Combinations

Consider the infrastructure efficiency and transportation indicator scores in the Site domain. Table 5.8 indicates that the influence infrastructure efficiency and transportation is represented by a single minus signs (moderate negative) – in this case in both directions. This indicates that the transportation indicator cannot take a high value if the land use indicator is high; and vice versa. However, because of the negative influence is only moderate, we can deem that the only unacceptable combination is for both the indicators to be at high values. Thus, the acceptable or likely combinations are given in Table 6.3.

Table 6.3: Acceptable combinations between infrastructure efficiency and transportation aspects in the Site domain for moderate negative influences

Acceptable	**Acceptable combinations**		
Infrastructure efficiency	L	A	H
Transportation	L,M,H	L,M,H	L,M

Here, H, A and L represent High, Average and Low indicator scores respectively. Figure 6.3 show the acceptable combinations given in Table 6.3

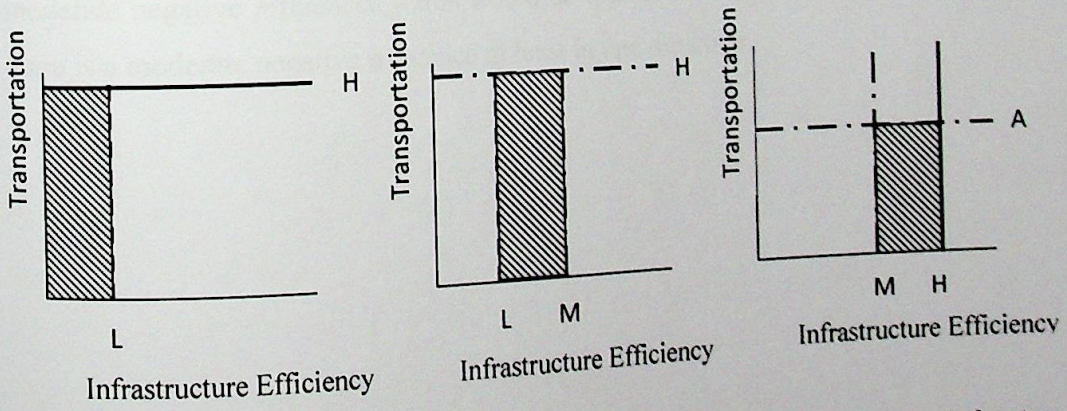

Figure 6.3: Graphical presentation of acceptable combinations between infrastructure efficiency and transportation aspects in the Site domain for moderate negative influences.

The above can be explained as follows. When infrastructure efficiency indicator is high (meaning that the number of basic services within walking distance is high), the need for transportation is likely to be low or average. Similarly, if the transportation indicator is high, the infrastructure efficiency is likely to be low or medium.

The inverse of Table 6.3 and Figure 6.3 is represented in Table 6.4 – there is only a single non-acceptable combination If this combinations are generated in a randomized optimization (i.e. minimization) scheme, a large penalty parameter should be added to the objective function.

Table 6.4: Non-acceptable combinations between infrastructure efficiency and transportation aspects in site domain for moderate negative combinations

Aspect	Non-acceptable combinations
Infrastructure efficiency	H
Transportation	H

Figure 6.4 shows acceptable and non-acceptable combinations between infrastructure efficiency and transportation aspects in the Site domain, given the presence of mutually moderate negative influences – this would be typical for any two indicators between which there is a moderate negative influence at least in one direction.

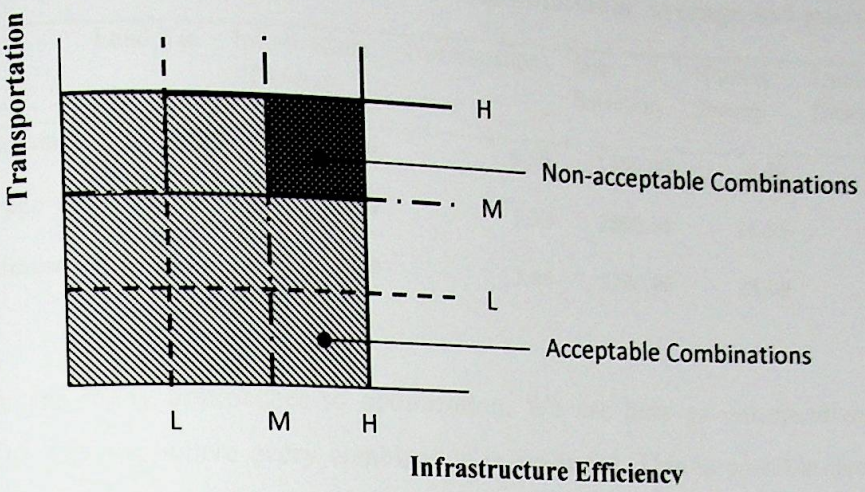

Figure 6.4: Graphical presentation of acceptable and non-acceptable combinations between infrastructure efficiency and transportation aspects in the Site domain for moderate negative influences

It can be seen that there is a difference between strong negative influences and moderate negative influences. The non-acceptable combinations are much less in the latter. However, if at least one of the influences is strongly negative, the non-acceptable combinations between the two indicators arising from that (see Figure 6.2) will subsume the non-acceptable combinations arising from the moderately negative influence (Figure 6.4).

6.4 Generating Possible Combinations

We will now present a proof of concept demonstration about how to arrive at possible combinations to obtain near optimality for sustainability scores. We do so however only for the Site domain, because as stated before, it is the one with the greatest number of negative influences. Recall also that we are proposing this as a planning exercise. In other words, in the the site domain, given that all indicators will not be at their maximum values, what are the combination of indicator values we should aim for? Table 6.5 shows the minimum, average and maximum values obtained for case study indicator scores in the Site domain (Table 4.3 gives these scores after dividing by the global benchmarks; Appendix 03 gives the raw scores). The above minimum, average and maximum values are taken to represent low, medium and high values that can be expected from a design solution.

Table 6.5: Case study indicator score values (minimum, average and maximum)

	Land Use	Infrastructure Efficiency	Transportation	Site Selection	Housing Density	Landscape Design	Microclimate
Minimum	**0.09**	**3.00**	**0.50**	**1350.00**	**4.00**	**0.02**	**0.25**
Average	**0.20**	**10.90**	**1.32**	**1800.00**	**15.95**	**0.11**	**0.44**
Maximum	**0.65**	**20.00**	**3.00**	**2250.00**	**28.00**	**0.38**	**0.65**

There are many approaches to optimization. We use here an enumerative (or exhaustive search) scheme, where every combination is evaluated. This is possible because the search space (i.e. possible combinations) are small within the single Site domain. Because the domain has 7 indicators (Table 6.5), each at 3 levels, the number of combinations is $7^3 = 343$. However, we use a binary number representation of the variables (i.e. indicators) and their levels (i.e. high, medium, low), because such a representation can subsequently be converted to a genetic algorithm based approach, which can significantly reduce the search space (Goldberg, 1989).

Binary numbers 00, 01, 10 and 11 are assigned (as shown in Table 6.6) to the minimum, average, average and maximum values in Table 6.5 (in Table 6.6 however normalised by dividing by each corresponding average values). Thus, the average values for all indicators in Table 6.6 is 1.0, while there are two binary numbers used for the average values. This is because a 2 digit binary number can represent 4 distinct states, whereas we have only 3 levels. If we then concatenate the seven 2 digit binary numbers, we have a 14 digit (2 x 7 =14) binary number that represents a distinct combination of indicator levels. (Since the average values are given two binary numbers, there may be some repetition of combinations).

Table 6.6: Normalised Values (Value/ Average) assigned with binary numbers

Binary code	Land Use	Infrastructure Efficiency	Transportation	Site Selection	Housing Density	Landscape Design	Micro climate
00	**0.462**	**0.275**	**0.379**	**0.750**	**0.251**	**0.178**	**0.566**
01	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**
10	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**
11	**3.250**	**1.835**	**2.273**	**1.250**	**1.755**	**3.455**	**1.477**

With the above combination of values the optimisation objective function, for this demonstration a maximization function, was defined as

Optimisation objective function = $\Sigma (s_i, w_i)$

Where w is the weight (see Table 3.9) and s is the normalised score value (i.e. Table 6.6 values).

A Java Program was developed to generate all possible combinations with above set of binary values. Disallowed combinations (see Tables 6.2 and 6.4) were programmed to generate a zero score. An alternative would be to minimize $\{1/\Sigma (s_i, w_i)\}$ while adding a penalty factor for disallowed combinations (Section 6.2).

The Java program was successfully compiled and run on a Windows system. Part of the program output that shows the lowest non zero solutions is shown in the Figure 6.5. The lowest value obtained from the above operation is 11.28 and is generated when the levels for all seven indicators is LOW.

File Edit

All Combinations in Values

Bit Ccombinations	Scores
00000000000000	11.2825
00000000000001	12.232800000000001
00000000000010	12.232800000000001
00000000000011	13.2936
00000000000100	13.1111
00000000000101	14.061399999999999
00000000000110	14.061399999999999
00000000000111	15.1222
00000000001000	13.1111
00000000001001	14.061399999999999
00000000001010	14.061399999999999
00000000001011	15.1222
00000000001100	18.5746
00000000001101	19.524900000000002
00000000001110	19.524900000000002
00000000001111	20.585700000000003
00000000010000	13.57
00000000010001	14.520299999999999
00000000010010	14.520299999999999
00000000010011	15.5811
00000000010100	15.3986
00000000010101	16.3489
00000000010110	16.3489
00000000010111	17.4097
00000000011000	15.3986
00000000011001	16.3489
00000000011010	16.3489
00000000011011	17.4097
00000000011100	20.862099999999998
00000000011101	21.8124
00000000011110	21.8124
00000000011111	22.8732
00000000100000	13.57
00000000100001	14.520299999999999
00000000100010	14.520299999999999
00000000100011	15.5811
00000000100100	15.3986

Optimize Combinations

All Combinations	Score
LOWLOWLOWLOWLOWLOW	11.2825
LOWLOWLOWLOWLOWMEDIUM	12.232800000000001
LOWLOWLOWLOWLOWMEDIUM	12.232800000000001
LOWLOWLOWLOWLOWHIGH	13.2936
LOWLOWLOWLOWMEDIUMLOW	13.1111
LOWLOWLOWLOWMEDIUMMEDIUM	14.061399999999999
LOWLOWLOWLOWMEDIUMMEDIUM	14.061399999999999
LOWLOWLOWLOWMEDIUMHIGH	15.1222
LOWLOWLOWLOWMEDIUMLOW	13.1111
LOWLOWLOWLOWMEDIUMMEDIUM	14.061399999999999
LOWLOWLOWLOWMEDIUMMEDIUM	14.061399999999999
LOWLOWLOWLOWMEDIUMHIGH	15.1222
LOWLOWLOWLOWHIGHLOW	18.5746
LOWLOWLOWLOWHIGHMEDIUM	19.524900000000002
LOWLOWLOWLOWHIGHMEDIUM	19.524900000000002
LOWLOWLOWLOWHIGHHIGH	20.585700000000003
LOWLOWLOWLOWMEDIUMLOWLOW	13.57
LOWLOWLOWLOWMEDIUMLOWMEDIUM	14.520299999999999
LOWLOWLOWLOWMEDIUMLOWMEDIUM	14.520299999999999
LOWLOWLOWLOWMEDIUMLOWHIGH	15.5811
LOWLOWLOWLOWMEDIUMMEDIUMLOW	15.3986
LOWLOWLOWLOWMEDIUMMEDIUMMEDIUM	16.3489
LOWLOWLOWLOWMEDIUMMEDIUMMEDIUM	16.3489
LOWLOWLOWLOWMEDIUMMEDIUMHIGH	17.4097
LOWLOWLOWLOWMEDIUMMEDIUMLOW	15.3986
LOWLOWLOWLOWMEDIUMMEDIUMMEDIUM	16.3489
LOWLOWLOWLOWMEDIUMMEDIUMMEDIUM	16.3489
LOWLOWLOWLOWMEDIUMMEDIUMHIGH	17.4097
LOWLOWLOWLOWMEDIUMHIGHLOW	20.862099999999998
LOWLOWLOWLOWMEDIUMHIGHMEDIUM	21.8124
LOWLOWLOWLOWMEDIUMHIGHMEDIUM	21.8124
LOWLOWLOWLOWMEDIUMHIGHHIGH	22.8732
LOWLOWLOWLOWMEDIUMLOWLOW	13.57
LOWLOWLOWLOWMEDIUMLOWMEDIUM	14.520299999999999
LOWLOWLOWLOWMEDIUMLOWMEDIUM	14.520299999999999
LOWLOWLOWLOWMEDIUMLOWHIGH	15.5811
LOWLOWLOWLOWMEDIUMMEDIUMLOW	15.3986

Figure 6.5: Lowest non-zero program outputs.

If we consider the highest generated value (as shown in Figure 6.6) is 44.9. If there are no constraints, then all the levels would have been at HIGH, and the sustainability score would have been 52.5. This shows that the constraints due to the presence of negative influences prevent the maximum sustainability score being reached. It should also be noted that the maximum weight for the Site domain is 25.7 (expressed as a percentage) – Table 3.7. The question arises then as to how the maximum possible (i.e. constraint free) maximum score can reach 52.7. This is because we are using the 'continuous score functions proposed in Section 4.4, combined with the 'Local' alternative – i.e. Sri Lankan benchmarks (Section 4.6). Both these proposed changes will allow the sustainability index to exceed 100 (which is reserved for buildings where all aspects on average are at their benchmarks values only).

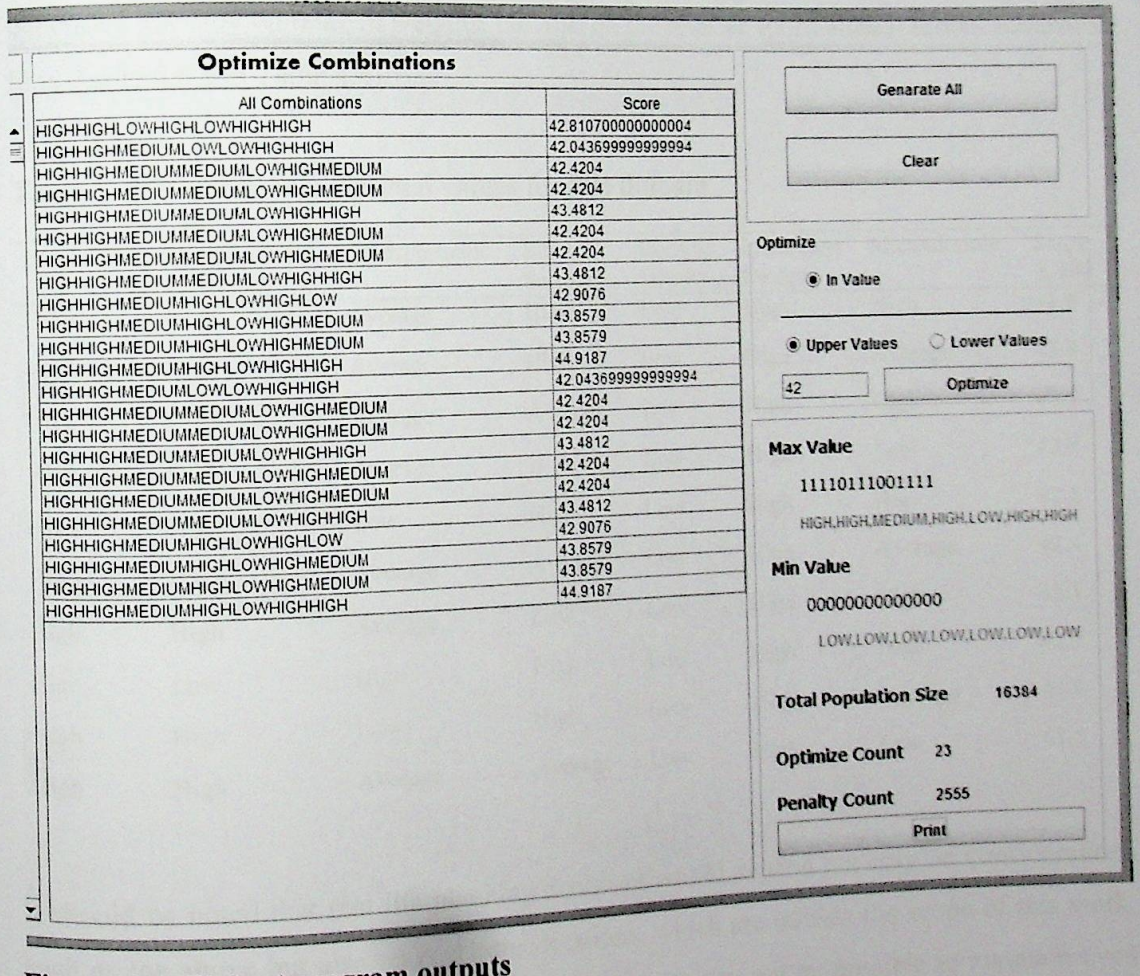

Figure 6.6: Highest program outputs

The highest near optimal combinations, with their respective score values, are shown in Table 6.7. It can be observed that for all these combinations it is suggested that the land use indicator be kept high at the expense of the housing density one, which is 'forced' to be low because of the strong negative influence from the former to the latter. When translated to a planning decision, this would suggest that preserving greater unbuilt areas in a site would contribute to a higher environmental sustainability score than creating greater housing density. It can similarly be shown that in most cases the recommended value for infrastructure efficiency would be high, at the expense of the transportation indicator being average or low, because of the mutually moderate negative influence between them. When translated to a planning decision, this would suggest that creating mixed development in a site would contribute to a higher environmental sustainability score than providing or seeking better transportation linkages. It should be noted that the above planning conclusions are depended not only on relative weights, but also on the relative (normalized) scores achievable (e.g. Table 6.6 and Table 4.4).

Table 6.7: Highest near optimal values for Site domain

Land Use	Infrastructure Efficiency	Transportation	Site Selection	Housing Density	Landscape Design	Microclimate	Score X 100
High	High	Average	High	Low	High	High	44.9
High	High	Average	High	Low	High	Average	43.9
High	High	Average	Average	Low	High	High	43.5
High	High	Average	High	Low	High	Low	42.9
High	High	Low	High	Low	High	High	42.8
High	High	Average	Average	Low	High	Average	42.4
High	High	Average	Low	Low	High	High	42.1
High	Low	High	High	Low	High	High	42.0
High	High	Low	High	Low	High	Average	41.8
High	High	Average	Average	Low	High	Low	41.5

It should be noted that real life planning decisions would depend not only on considerations such as the above but also on cost considerations, which are outside the scope of this work. Furthermore, in situations of economic constraints, it may not be possible to maintain even aspects that are not constrained by negative dependencies at their highest levels. In such cases

aspects that have greater weights would probably be emphasised, in order to increase environmental sustainability in a cost effective manner.

6.5 Conclusions

1. Constraints to achieving the maximum possible sustainability scores derive from negative influences between indicator scores; thee influences can be classified as strongly or moderately negative.
2. Strongly negative influences create a greater number of unlikely indicator level combinations. These subsume the unlikely indicator level combinations generated by moderate negative influences.
3. The Site domain has the most significant inter-aspect negative influences, and its likely maximum sustainability score is clearly reduced thereby.
4. Studying the implications of constraints for sustainability scores can help us in planning decisions. For example, for the Site domain (in Sri Lankan conditions) preserving greater unbuilt areas in a site would contribute to a higher environmental sustainability score than creating greater housing density.
5. The above planning conclusions are dependent not only on relative weights, but also on the relative (normalized) scores achievable.

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Chapter Seven

Conclusions and Recommendations

This chapter presents the conclusions based on the findings of the study from Chapters 3 to 6, and in accordance with the research objectives set out in Chapter one. It also re-iterates the originality of the research. Finally, recommendations are also made. They are proposed both for future research and future practice.

7.1 Conclusions

7.1.1 Chapter three - Weights for Domains and Aspects

1. In the reported survey of construction sector professionals, the direct ranking and analytic hierarchy process (AHP) methods yielded results that were sufficiently similar to give confidence in the weights obtained. The AHP method tended to accentuate differences somewhat across domains.
2. There were no significant differences in weights assigned to the major domains by the three professional groups, i.e. architects, engineers and quantity surveyors. Their disciplinary backgrounds may have influenced the slight differences obtained – for example, architects assigned the highest weight to Site while engineers to Energy efficiency.
3. There was considerable agreement across the above professionals regarding the relative importance of aspects within most of the six domains (an exception being the Materials domain), with 'site selection' aspect being top ranked for the Site domain; 'energy usage' for the Energy efficiency domain; 'water conservation' for the Water efficiency domain; and 'waste reduction' for the Waste & pollution domain.
4. Overall, across all professional groups, the Site was found to be the most important major domain in the Sri Lankan context (with Energy efficiency a close second), whereas Energy efficiency is top ranked in most of the other rating systems worldwide.

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5. While there are similarities in the weights assigned for domains in different sustainability rating systems (e.g. with respect to highly ranked domains), there are also differences that reflect the national context.
6. National statistics on relevant indicators from 9 countries (from which the 9 rating systems originated) were used to demonstrate good correlation between those indicators and the corresponding domain weights for three of the six domains, namely Site, Energy efficiency and Water efficiency. This demonstrates that national contexts have influenced domain weights in rating systems.

7.1.2 Chapter four - Development, Classification and Aggregation of Indicators

1. The subjectivity associated with evaluators using their discretion to allocate points or scores for various aspects of sustainability can be eliminated by using well defined quantitative indicators for all the aspects of sustainability that need to be assessed. Such indicators need to be normalized with respect to benchmarks in order that they can be weighted and summed to obtain a composite score.
2. The greatest contribution to sustainability is from the systems level in a building hierarchy, which is allocated 18 out of 33 indicators and 57% of the total weight; also from the operational stage in the lifecycle, which is allocated 16 of the above 18 indicators and 53% of the total weight. There is thus a high degree of coupling between the systems level and operational stage of a building. This means that even a building not constructed as a 'green' building can be retrofitted to achieve a fairly high sustainability score.
3. Using continuous functions for indicator scores rather than step functions will be better for comparing sustainability features in buildings. This can be contrasted with rating systems approaches that use step functions and require threshold levels of achievement for most if not all aspects, in order for buildings to get rated at various levels.
4. Sustainability assessment schemes can be contextualized by using 'local' benchmarks for indicators. These can be based on averages of indicators from buildings that obtain green certification in a given national context.
5. Accentuating differences in scores for sustainability aspects that are more highly weighted can be achieved through a non linear indicator score function that is defined on the basis of the ratio of the aspect weight to the 'average' weight. The method

proposed increases higher than benchmark scores and reduces lower than benchmark scores for aspects that are weighted more than the 'average' weight. This has the effect of spreading the range of overall sustainability scores.

6. A score of 100% in the proposed basic sustainability assessment scheme implies that all the benchmarks are just met on average. It corresponds (based on our correlation) to 66 points and a gold rating in the LEED rating system, in which scheme a building will obtain 69 points if all the aspects obtain the minimum points allocated.
7. The LEED rating system, based on step functions for aspect scores, gives an unrealistically low score for 'non green' buildings, and does not reflect much of the sustainability content that is nevertheless embedded in them. This justifies the use of continuous functions for indicator scores, if a comparative assessment of sustainability features is desired rather than a rating for 'high achievement' with respect to sustainability.

7.1.3 Chapter five – Dependency between Indicator Scores

1. A very strong positive correlation exists between indicator scores for land use and landscape design aspects and strong positive correlation exists between those for site selection and housing density in the site domain. In the energy efficiency domain strong positive correlations are found between indicator scores for energy use and building envelope performance; lighting efficiency and greenhouse gas emissions; and greenhouse gas emission and renewable energy. In the water efficiency domain a strong positive correlation is found only between the indicator scores for water conservation and water efficient landscaping. In the materials domain there is one very strong positive correlation between the indicator scores for renewable materials and embedded energy and four strong positive correlations between renewable materials and recycled materials; renewable materials and local/ regional materials; recycled materials and embedded energy; and recycled materials and local/ regional materials. There is only one strong positive correlation found in the indoor environmental quality domain, which is between the indicator scores for day light and indoor air quality. There are no strong positive correlations found in between the aspects of the waste and pollution domain.

2. It was possible to identify causal links between aspects within domains (only the Site and Energy efficiency domains were studied), using the correlation coefficients as a guide.
3. A matrix multiplication combined with a summation approach was used to represent and quantify the direct and indirect influences between aspects. In the Site domain, the indicator which influences others highly was found to be that for land use; while the housing density indicator was the one that was most influenced by others. Similarly in the Energy efficiency domain the indicator that most influenced others was found to be that for building envelope performance; while the one that was most influenced by others was found to be the indicator for greenhouse gas emissions.
4. Very high negative R^2 values between the degrees of influencing and being influenced for both Site and Energy efficiency domain aspects show that the results obtained by matrix operations for the degrees of influencing and being influenced are robust and dependable.
5. Low or negligible R^2 values between aspect weights and their degrees of influencing other aspects indicate that the weights reflect the actual environmental impacts made by the aspects much more than their influence on other aspects. This means that aspects weights appear to be independent of their influence on other aspects.

7.1.4 Chapter six – Optimal combination of strategies

1. Constraints to achieving the maximum possible sustainability scores derive from negative influences between indicator scores; these influences can be classified as strongly or moderately negative.
2. Strongly negative influences create a greater number of unlikely indicator level combinations. These subsume the unlikely indicator level combinations generated by moderate negative influences.
3. The Site domain has the most significant inter-aspect negative influences, and its likely maximum sustainability score is clearly reduced thereby.
4. Studying the implications of constraints for sustainability scores can help us in planning decisions. For example, for the Site domain (in Sri Lankan conditions) preserving greater unbuilt areas in a site would contribute to a higher environmental sustainability score than creating greater housing density.

5. The above planning conclusions are depended not only on relative weights, but also on the relative maximum (normalized) scores achievable.

7.2 Overall Summary

Figure 7.1 gives an overall view or 'methodology map' linking the work in this thesis. The rectangular boxes represents input to the study, and the rhombus shaped boxes depict the key outputs from the study.

This study involves generation of both new data and novel concepts and methodologies. It has concentrated on the generation of two main data sets and three main concepts

Where data is concerned, Sri Lankan professionals' input regarding arriving at weights for domains and aspects to determine the environmental sustainability of buildings for Sri Lanka is given in Chapter 3. This is the first survey of this nature in Sri Lanka and those weights were used by the Green Building Council of Sri Lanka (GBCSL) in developing the Green SL rating tool.

Secondly, the sustainability scores achievable for Sri Lankan buildings were established through case studies and given in Chapter 4. Again this was absent for the Sri Lankan context and this data would be useful in decision making and regulation making purposes. It is also suggested in this chapter that these sustainability scores be used to arrive at indicator benchmarks for the local Sri Lankan context.

Where concepts are concerned, establishing the quantitative correlation between domain weights in various rating systems and the national needs and priorities of the countries in which those systems have been developed (Chapter 3) is a novel concept not found in the literature before.

The second major concept presented in this study is alternative methods of arriving at environmental sustainability scores. The study evaluated the applicability of a continuous function approach over the conventional step-function approaches and argues that this is a better way to assess sustainability content in buildings (Chapter 4).

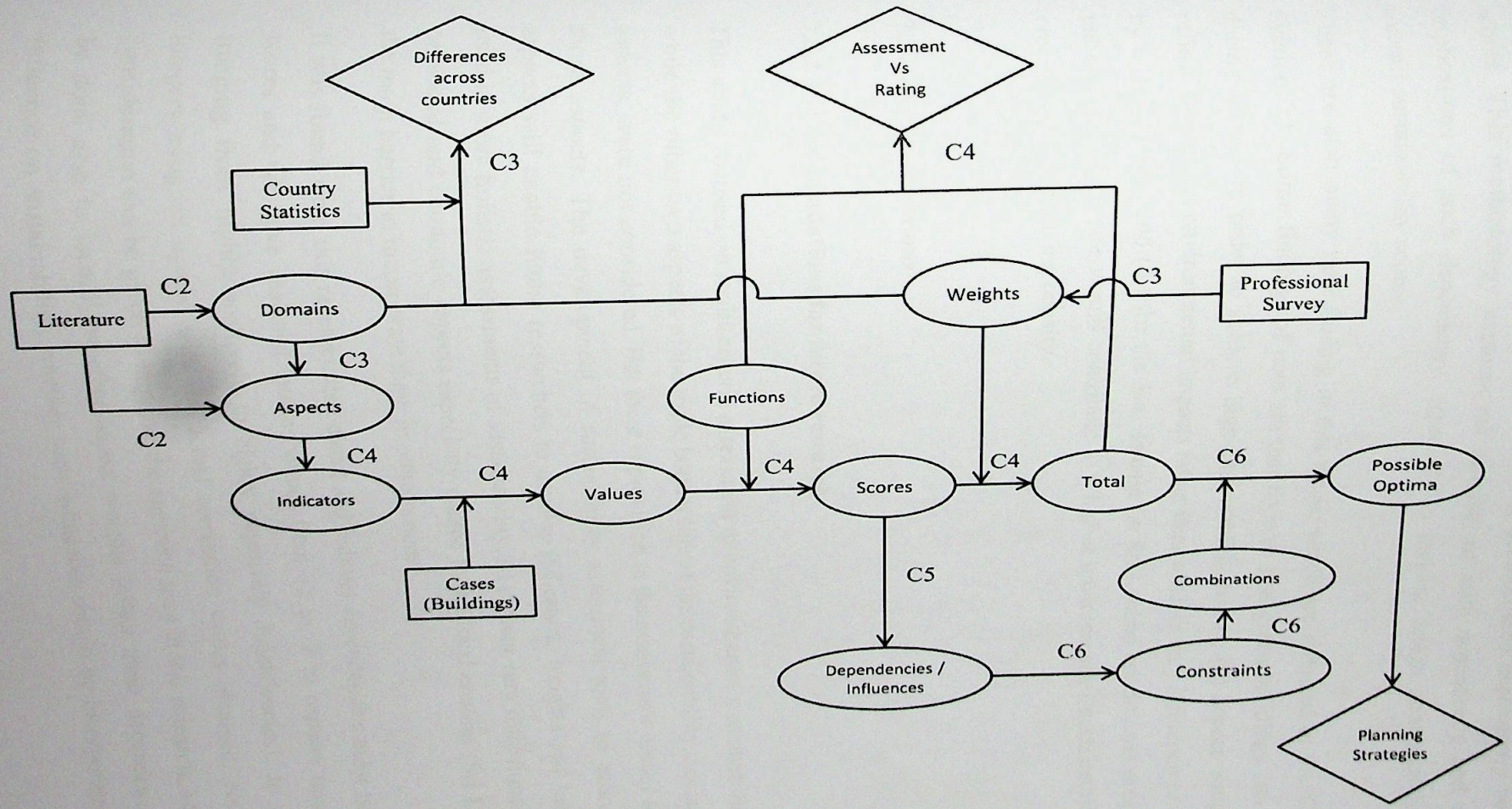

Figure 7.1: Methodology map displaying chapter connectivity

The third concept explored in the study was the demonstrated dependency between aspect scores. This methodology captures the causality of such dependency and considers the implications of such dependency, especially in seeking design strategies for optimizing overall sustainability scores.

There are also many new finding in this thesis, which are reflected in the Conclusions in Section 7.1. Some findings of note are that (i) even non green buildings can be retrofitted during service in order to achieve high sustainability scores; (ii) aspect weights appear to reflect their direct environmental impacts rather than whether they influence or are influenced by other aspects; and (iii) for the Site domain (in Sri Lankan conditions) preserving greater unbuilt areas in a site would contribute to a higher environmental sustainability score than creating greater housing density.

7.3 Recommendations

7.3.1 Recommendations for future research

This study focused on multi-criteria assessment of environmental sustainability of buildings, while the other two aspects of the triple bottom line of the sustainability, social and economic aspects, were not considered. But there is provision in the assessment model to accommodate those aspects. The development of sustainability assessment tools to accommodate those aspects will enable future researchers to develop indicators, weights and benchmarks to be used in more holistic assessments of sustainability. At present very little literature is available on social and economic aspects especially related to the local context (Sri Lanka), which is the main barrier to incorporate them into the system.

It was found from this research that direct and indirect dependencies exist between indicator scores and we have assigned integer values from +2 to -2 to capture those dependencies (ranging from highly positively to highly negatively dependencies). In many cases the integers assigned agreed with the actual correlation values obtained. Nevertheless some consideration can be given to improve the approach used in this research. More work should be done also to identify whether aspect weights reflect these dependencies or just their influence on sustainability; whether such influences should be incorporated to the weights

(and how) is another area that can be considered. In particular dependencies across domains should also be studied as they were not in this study.

There are only a few buildings rated using the local green assessment tool (i.e. GBCSL) to date. From those, this study used ten office buildings for case studies and derived local benchmarks for the selected indicators. Since this research has considered only office buildings it is important to get more case studies and establish benchmarks for other building types as well.

7.3.2 Recommendations for future practice

The application of the proposed assessment model in this study is very useful to identify the environmental sustainability content of any building, irrespective of whether it is a new or existing building. The assessment approach has reduced subjectivity so that the operator can depend on the outcome for decision making.

The final chapter shows the alternative combinations that designers can make use of to optimize the sustainability of the buildings they plan and design. Adoption of such results can aid in the planning process, so that sustainability can be optimized,

Given that Sri Lankan performance is somewhat lower than global benchmarks, it is important to promote the use of Sri Lankan benchmarks for the assessment. It was suggested that using the averages as benchmarks is more relevant in the Sri Lankan national context, and that the resulting higher scores should be used to 'reward' buildings that perform well in a context where the average performance is relatively low. As average performance improves with time, the benchmarks will also become more stringent.

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Appendix 01

List of Aspect Indicators

Domain - Site	Indicator	Reference	R/U	Lifecycle	Hierarchy	Benchmark
Land Use						
Consider the foot print of the building compared to the total land area. Carefully site the building to minimize disruption on existing ecosystems and natural features.	Land Building Ratio = Total un-built area / Total area of the site	LEED	R	Con	Bldg	Institutional = 50% Non-institutional = 25%
Infrastructure Efficiency						
During site selection process, giving preference to sites with pedestrian access to variety of services such as schools, hospitals, shopping malls, post office etc.	Community connectivity = Number of basic services within ½ mile walking distance	LEED	U	Con	Bldg	*10*
Transportation						
Availability of public transportation access to the site and reduce impact from automobile use. Consider availability of rail station or bus stop within walking distance to the development site.	Bus stop proximity = available no. of bus stations within ¼ mile walking distance for more than 2 bus lines	LEED	U	Con	Bldg	1

Site Selection *Avoid the development of inappropriate sites and reduce the environmental impact.*	*Development density* = previously developed site AND with high population density	LEED	U	Con	Bldg	60,000 sqft per acre net (LEED) 1500 people per acre net (GREENSL)
Housing Density Develop sites with higher population density than developing sites with less population density. And provide increased capacity of existing sites with high quality living environment.	Housing density = available no. of housing units per acre	LEED	U	Con	Bldg	10
Landscape Design Design the project site to maintain natural storm water flows by promoting infiltration, minimize impervious surfaces. Maximize vegetated open space area on site.	Open space = Vegetated open area / Total site area	LEED	R	Con	Bldg	0.2
Microclimate Consider Strategies, materials and landscaping techniques that reduce the heat absorption of exterior materials. Maximize shaded hardscape area. Maximize solar reflection from the roof.	Heat island effect (non-roof) = shaded hardscape area / Total hardscape area	LEED	R	Con	Bldg	0.5
	Heat island effect (roof) = Area of roof meeting minimum solar reflection index X SRI of installed roof / Total roof area X required SRI	LEED	R	Con	Bldg	0.75

Domain –Energy Efficiency	Indicator	Reference	R/U	Lifecycle	Hierarchy	Benchmark
Energy Usage Consider the methods and practices which minimize the operational energy of the building.	Operational energy = Energy used in operation Area X % time occupied	Reppe P (editor) 1999	U	Oper	Sys	180 kWh/m2 per annum office buildings (Joseph Iwaro, Abraham Mwasha, 2010)
Building envelope Performance Design the building envelope and systems to minimize thermal discomfort. Consider the Solar Reflection Index(SRI) of the roofing and façade materials	Heat gain/ loss parameter = Total fabric and ventilation heat gain/ loss from the building (W) Total floor area (m^2K)	LEED	U	Oper	Sys	0.8 W/m^2K
Lighting Efficiency Consider the use of energy efficient internal lights for all usable areas of the building	Day light = Daylight illuminated area Total occupied area	Code for Sustainable Homes, 2008	R	Oper	Sys	75%

Green House Gases Emission *Consider the amount of CO_2 emission from energy used for HVAC, hot water and lighting etc..*	CO_2 emissions = Estimated CO_2 emission (in kg) for lighting/HVAC/ hot water etc Area per year	Code for Sustainable Homes, 2008	U	Oper	Sys	63
Renewable Energy Consider maximum use of renewable energy for the operational energy of the building.	Renewable Energy = Total renewable energy used Total energy consumption of the building	LEED	R	Oper	Sys	35%

Domain –Water Efficiency	Indicator	Reference	R/U	Lifecycle	Hierarchy	Benchmark
<u>Water Conservation</u> Reduce potable water demand (below the base line use). Use of water sense certified fixtures and fittings. Use of high –efficiency fixtures and dry fixtures.	Water use reduction = <u>Baseline use (Lit)</u> Aggregate use (Lit)	LEED	R	Oper	Sys	1.25
<u>Water Efficient Landscaping</u> Use of appropriate native or adapted plant material and design the landscape to reduce or eliminate irrigation requirements.	Landscape water efficiency = Total amount of water consumed by <u>the landscape (Lit)</u> Total area of the landscape (m^2)	LEED	U	Oper	Sys	1 Lit/m^2
<u>Sustainable Water Technologies</u> Consider reuse of water and rain water harvesting technologies.	Sustainable water use = <u>Water used sustainable (Lit)</u> Total water consumption (Lit)	Reppe P (editor) 1999	R	Oper	Sys	50%

Domain –Material	Indicator	Reference	R/U	Lifecycle	Hierarchy	Benchmark
Renewable Material Reduce the use and depletion of finite raw materials and long-cycle renewable materials by replacing new with rapidly renewable materials.	Rapidly renewable materials = Value of rapidly renewable materials and products / Total value of building materials	LEED	R	Mat	Mat	5%
Reuse Material Reuse building materials and products to reduce demand for virgin materials and reduce waste, thereby lessening impacts associated with the extraction and processing of virgin resources.	Material reuse = Value of Salvaged, refurbished or reused materials / Total value of the materials used in the building	Environmental Product Declarations, 2008	R	Cons	Comp	5%
Recycle Material Increase demand for building products that incorporate recycled content materials, thereby reducing impacts resulting from extraction and processing of virgin materials.	Recycle rate = Amount recycled in pre-consumer and post-consumer stages(cost) / Total cost of the waste	LEED	R	Cons	Comp	20%

Embedded Energy *Select building materials and components with minimum embedded energy. Consider assembly methods which minimize energy consumption*	Embedded energy = Total embedded energy consumed (GJ) Area of the building (m^2)	Pullen S, 2000	U	Mat	Mat	11 GJ/m^2
Local/Regional Materials Increase demand for building materials and products that are extracted and manufactured within the region.	Regional Materials = value of building materials or products extracted, harvested or recovered and manufactured within 500 miles from project site Total value of materials use for the building	LEED	R	Mat	Mat	10% (LEED) 50% *(GREENSL)*
Carbon Contents Use materials with minimum carbon content	Carbon storage per kg/m^3 or percentage weight	Erasmus and Smail, 1989 Buchanan, 1991	U	Mat	Mat	*50*
Durability Use materials which are compatible with the lifespan of the building and require minimum maintenance.	Life span index = life span of material or component Design life of the building	Reppe P (editor) 1999	R	Mat	Mat	100% (Reppe P)

Domain –Indoor Environmental Quality	Indicator	Reference	R/U	Lifecycle	Hierarchy	Benchmark
Occupant Health & Safety Availability of designated areas for smoking or prohibit smoking on the entire property.	Availability of designated areas for smoking within the property 25feet away from all entries, outdoor air intakes and operable windows	LEED	U	Oper	Sys	1
Thermal Comfort Provide a comfortable thermal environment that promotes occupants productivity and well-being by design and verification.	Number occupants having individual comfort controls Total number of occupants in the building	LEED	R	Oper	Sys	50%
Daylight Provide building occupants with a connection between indoor spaces and the outdoors through the introduction of daylight into the regularly occupied areas of the building.	Area of day lighting zone Total regularly occupied area of the building	LEED	R	Oper	Sys	75%

Visual Quality						
Provide building occupants with a connection between indoor spaces and the outdoors through the introduction of views into the regularly occupied areas of the building.	Availability of direct line of sight to the outdoor via vision glazing in regularly occupied areas Total regularly occupied area of the building	LEED	R	Oper	Sys	90%
Acoustic & Noise Control						
Control the noise levels of the building according to the baseline sound levels. Minimize airborne & structure borne sound levels by proper insulation systems.	Airborne sound insulation in dB	BREEAM	U	Oper	Sys	3 dB
	Impact sound insulation in dB	BREEAM	U	Oper	Sys	3dB
Indoor Air Quality						
Monitor CO_2 concentrations within all habitable areas. Consider minimum outdoor air intake flow (15% min). Minimize concentration of contaminants. Use low emitting materials, composites, adhesives and sealants, paints and coatings for indoors. Control potentially hazardous particulars and chemical pollutants.	Outdoor air intake (m^3/s) Total amount of air circulated within the building (m^3/s)	LEED	R	Oper	Sys	15%

Domain – Waste and pollution	Indicator	Reference	R/U	Lifecycle	Hierarchy	Benchmark
<u>Waste Reduction</u>						
Use building materials and components which generate less waste in manufacturing & assembly.	Material wastage = $\frac{M_A - M_R}{M_A}$ X100 M_A = Quantity of actual materials used by volume M_R = Quantity of materials required by volume	De Silva N, Vithana S B K H, 2008	R	Cons	Comp	10% (De Silva N, Vithana S B K H, 2008)
<u>Waste Management Strategies</u>						
Availability of technology and methods to recycle and/or salvaged non-hazardous construction and demolition debris.	Amount (Tonnes) of materials recycled or reused on site/ off site Total amount of waste generated by the building	LEED	R	Demo	Sys	50%
<u>Waste Water Management</u>						
Specify high efficiency fixtures and dry fixtures to reduce wastewater volumes. Use of onsite mechanical and/or natural wastewater treatment systems.	Amount of waste water treated on site to tertiary standards (Lit) Total amount of waste water generated on site (Lit)	LEED	R	Oper	Sys	50%

Operational Waste						
Facilitate the reduction of waste generated by building occupants. Designate an area for recyclable collection and storage that is appropriately sized and located in a convenient place.	Total amount of waste recycled and composted (Tonnes) Total amount of waste generated from households (Tonnes)	BREEAM	R	Oper	Sys	40%
Flexible Building Plan						
Design buildings for flexible layouts to meet the changing user and functional requirements. Allow provision for renovation and refurbishments.	Interior non-structural elements= Area covered by interior non-structural elements (interior walls, doors, floor coverings, and ceiling systems) Total area of the building	LEED	R	Cons	Sys	50%

Appendix 02

Professional Questionnaire Instrument

Sustainability appraisal in building projects

Please put a ' √ ' in the relevant cage

What is your profession? ☐ Architect ☐ Engineer ☐ Quantity Surveyor

What sector you represent? ☐ Government sector ☐ Private sector

Are you aware of these documents? ☐ LEED ☐ BREEAM

☐ CASBEE ☐ GBTool ☐ Green Globes US

Other (please specify) _____

Have you dealt with sustainable building projects? ☐ Yes ☐ No

How many sustainable building projects that you have engaged? _____

What type of building projects that you have engaged?_____

(e.g.: houses/schools/hotels/hospitals/etc.)

Instructions

Scope Ranking – rank the aspects and sub-aspects given in the list using numerical numbers starting with '1' (most important aspect) and respectively.

Percentage Weight – weight the aspects and sub-aspects using the above ranking as a guide.

For example if there are 4 aspects, an equal weighting would result in 25% for each. But, you can change the weighting up or down from 25% based on the relative rank of the sub-aspects, ensuring that the total percentage is 100%.

Sustainability Aspects List

Site

- Land use - reduce the foot print of the building
- Site selection – minimizing disruption to ecosystem
- Infrastructure efficiency – give pedestrian access to facilities
- Transportation – facilities within easy distance
- Housing density – use areas with already high density
- Microclimate – reduce heat absorption by the building
- Landscape design – infiltration, storm water flow, vegetation

Energy Efficiency

- Energy usage – minimize use of operational energy
- Building envelope performance – minimize thermal discomfort
- Lighting efficiency – use energy efficient lighting
- Green House gases emission – reduce carbon emission from energy use
- Renewable energy – maximize renewable energy use

Water Efficiency

- Water conservation – minimize water usage
- Water efficient Landscaping – reduce irrigation requirements
- Sustainable water technologies – reuse of water, rainwater harvesting

Material

- Local/regional materials – promote local materials usage
- Renewable material – use rapidly renewable materials
- Recycle material – promote recycling
- Reuse material – reuse of materials and components
- Embedded energy – minimize embedded energy
- Carbon content – minimize carbon contents
- Durability – use of building with minimum maintenance and repair

Indoor Environmental Quality

- Occupant health & safety – minimize smoking areas
- Thermal comfort – thermal comfort through natural means
- Daylight – good use of natural light
- Acoustic & noise control – control noise from outside
- Visual quality – external views
- Indoor air quality

Waste & Pollution

- Waste reduction – materials that generate low waste in production
- Waste management strategies – recycling of construction and demolition debris
- Waste water management – reduce wastewater volumes
- Operational waste – reduce and recycle occupant generated waste
- Flexible building plan – reduce probability of obsolescence

Technical content	Scope	Aspect (Scope) Ranking	Percentage Weight
1. Site	Land Use Consider the foot print of the building compared to the total land area. Carefully site the building to minimize disruption on existing ecosystems and natural features.		
	Infrastructure Efficiency During site selection process, giving preference to sites with pedestrian access to variety of services such as schools, hospitals, shopping malls, post office etc.		
	Transportation Availability of public transportation access to the site and reduce impact from automobile use. Consider availability of rail station or bus stop within walking distance to the development site.		
	Site Selection Avoid the development of inappropriate sites and reduce the environmental impact.		
	Housing Density Develop sites with higher population density than developing sites with less population density. And provide increased capacity of existing sites with high quality living environment.		
	Landscape Design Design the project site to maintain natural storm water flows by promoting infiltration, minimize impervious surfaces. Maximize vegetated open space area on site.		
	Microclimate Consider Strategies, materials and landscaping techniques that reduce the heat absorption of exterior materials. Maximize shaded hardscape area. Maximize solar reflection from the roof.		

Note: if equally weighted each will get 14.29%

Technical content	Scope	Aspect (Scope) Ranking	Percentage Weight
2. Energy Efficiency	Energy Usage Consider the methods and practices which minimize the operational energy of the building.		
	Building envelope Performance Design the building envelope and systems to minimize thermal discomfort. Consider the Solar Reflection Index(SRI) of the roofing and façade materials		
	Lighting Efficiency Consider the use of energy efficient internal lights for all usable areas of the building		
	Green House Gases Emission Consider the amount of CO_2 emission from energy used for HVAC, hot water and lighting etc..		
	Renewable Energy Consider maximum use of renewable energy for the operational energy of the building.		

Note: if equally weighted each will get 20%

Technical content	Scope	Aspect (Scope) Ranking	Percentage Weight
3. Water Efficiency	Water Conservation Reduce potable water demand (below the base line use). Use of water sense certified fixtures and fittings. Use of high –efficiency fixtures and dry fixtures.		
	Water Efficient Landscaping Use of appropriate native or adapted plant material and design the landscape to reduce or eliminate irrigation requirements.		
	Sustainable Water Technologies Consider reuse of water and rain water harvesting technologies.		

Note: if equally weighted each will get 33.33%

Technical content		Scope	Aspect (Scope) Ranking	Percentage Weight
4.	**Material**	Renewable Material Reduce the use and depletion of finite raw materials and long-cycle renewable materials by replacing new with rapidly renewable materials.		
		Reuse Material Reuse building materials and products to reduce demand for virgin materials and reduce waste, thereby lessening impacts associated with the extraction and processing of virgin resources.		
		Recycle Material Increase demand for building products that incorporate recycled content materials, thereby reducing impacts resulting from extraction and processing of virgin materials.		
		Embedded Energy Select building materials and components with minimum embedded energy. Consider assembly methods which minimize energy consumption		
		Local/Regional Materials Increase demand for building materials and products that are extracted and manufactured within the region.		
		Carbon Content s Use materials with minimum carbon content		
		Durability Use materials which are compatible with the lifespan of the building and require minimum maintenance.		

Note: if equally weighted each will get 14.29%

Technical content	Scope	Aspect (Scope) Ranking	Percentage Weight
5. Indoor Environmental Quality	Occupant Health & Safety Availability of designed areas for smoking or prohibit smoking on the entire property.		
	Thermal Comfort Provide a comfortable thermal environment that promotes occupants productivity and well-being by design and verification.		
	Daylight Provide building occupants with a connection between indoor spaces and the outdoors through the introduction of daylight into the regularly occupied areas of the building.		
	Visual Quality Provide building occupants with a connection between indoor spaces and the outdoors through the introduction of views into the regularly occupied areas of the building.		
	Acoustic & Noise Control Control the noise levels of the building according to the baseline sound levels. Minimize airborne & structure borne sound levels by proper insulation systems.		
	Indoor Air Quality Monitor CO_2 concentrations within all habitable areas. Consider minimum outdoor air intake flow (15% min). Minimize concentration of contaminants. Use low emitting materials, composites, adhesives and sealants, paints and coatings for indoors. Control potentially hazardous particulars and chemical pollutants.		

Note: if equally weighted each will get 16.67%

Technical content	Scope	Aspect (Scope) Ranking	Percentage Weight
6. Waste & Pollution	Waste Reduction Use building materials and components which generate less waste in manufacturing & assembly.		
	Waste Management Strategies Availability of technology and methods to recycle and/or salvaged non-hazardous construction and demolition debris.		
	Waste Water Management Specify high efficiency fixtures and dry fixtures to reduce wastewater volumes. Use of onsite mechanical and/or natural wastewater treatment systems.		
	Operational Waste Facilitate the reduction of waste generated by building occupants. Designate an area for recyclable collection and storage that is appropriately sized and located in a convenient place.		
	Flexible Building Plan Design buildings for flexible layouts to meet the changing user and functional requirements. Allow provision for renovation and refurbishments.		

Note: if equally weighted each will get 20%

Paired comparison matrix of sustainability aspects

(Please refer next page for instructions)

Site	9	7	5	3	1	3	5	7	9	Energy Efficiency
Site	9	7	5	3	1	3	5	7	9	Water Efficiency
Site	9	7	5	3	1	3	5	7	9	Material
Site	9	7	5	3	1	3	5	7	9	IEQ
Site	9	7	5	3	1	3	5	7	9	Waste & Pollution
Energy Efficiency	9	7	5	3	1	3	5	7	9	Water Efficiency
Energy Efficiency	9	7	5	3	1	3	5	7	9	Material
Energy Efficiency	9	7	5	3	1	3	5	7	9	IEQ
Energy Efficiency	9	7	5	3	1	3	5	7	9	Waste & Pollution
Water Efficiency	9	7	5	3	1	3	5	7	9	Material
Water Efficiency	9	7	5	3	1	3	5	7	9	IEQ
Water Efficiency	9	7	5	3	1	3	5	7	9	Waste & Pollution
Material	9	7	5	3	1	3	5	7	9	IEQ
Material	9	7	5	3	1	3	5	7	9	Waste & Pollution
IEQ	9	7	5	3	1	3	5	7	9	Waste & Pollution

Key:

1 – Both aspects have **Equal** importance

3 – **Slightly High** importance over the other aspect

5 – **Moderate high** importance over the other aspect

7 – **High** importance over the other aspect

9 – **Very high** importance over the other aspect

Sample 01: If aspect **P** has **Moderate high** importance over aspect **Q** it should be represented as;

Aspect **P**	9	7	5	3	1	3	5	7	9	Aspect **Q**

Sample 02: If aspect **Y** has **Slightly High** importance over aspect **X** it should be represented as;

Aspect **X**	9	7	5	3	1	3	5	7	9	Aspect **Y**

Sustainability Aspect	**Aspect Ranking**	**Percentage Weight**
Site		
Energy Efficiency		
Water Efficiency		
Material		
Indoor Environmental Quality		
Waste & Pollution		

Note: if equally weighted each will get 16.67%

Suggestions for additional aspects and/or sub-aspects

Appendix 03

Indicator Scores

Domain / Aspect	Indicator Score											
	Building 1	Building 2	Building 3	Building 4	Building 5	Building 6	Building 7	Building 8	Building 9	Building 10	*Building 11*	*Building 12*
Site												
Land Use	0.215	0.645	0.1875	0.2	0.1	0.0875	0.0875	0.18	0.1125	0.135	*0.34*	*0.26*
Infrastructure Efficiency	13	3	15	8	7	8	20	14	12	9	*12*	*10*
Transportation	3	0.5	1.4	1.2	1.2	1.4	1	1.2	1	1.3	*1*	*1*
Site Selection	1800	1350	2100	1650	2100	1950	1800	2250	1350	1650	*1250*	*1420*
Housing Density	25	4	28	10	20	15	18	18	12	9.5	*12*	*14*
Landscape Design	0.05	0.378	0.12	0.14	0.04	0.03	0.024	0.09	0.164	0.086	*0.05*	*0.06*
Microclimate	0.405	0.65	0.45	0.5	0.25	0.3	0.6	0.4	0.36	0.5	*0.12*	*0.14*
Energy												
Energy Usage	171	150	163	160	170	160	180	145	156.6	140	*230*	*210*
Building envelope Performance	0.608	0.72	0.67	0.7	0.648	0.62	0.76	0.6	0.56	0.8	*1.2*	*1.1*
Lighting Efficiency	0.6	0.9	0.6975	0.915	0.99	1.2	0.7575	0.7875	0.825	0.7875	*0.35*	*0.30*
Green House Gases Emission	60	52	56	60	54	45	54	60	48	59	*73*	*78*
Renewable Energy	0.119	0.1015	0	0	0.0735	0.42	0.119	0	0.0805	0	*0*	*0*
Water												
Water Conservation	1.1	1.65	0.875	1.5	1.375	1.775	1.25	1.5	1.275	1.25	*0.72*	*0.65*
Water Efficient Landscaping	0.83	0.83	0.8	0.95	0.72	0.65	0.75	0.82	0.85	0.73	*1.3*	*1.2*
Sustainable Water Technologies	0.28	0.515	0.1	0.05	0.21	0.15	0	0.115	0	0.17	*0*	*0*
Material												
Renewable Material	0.01	0.08	0.0115	0.014	0.007	0	0.005	0.006	0.0075	0.003	*0.01*	*0.02*
Reuse Material	0	0	0.0105	0	0.005	0.003	0	0.0025	0.001	0.0015	*0*	*0*
Recycle Material	0.15	0.25	0.11	0.06	0.046	0.024	0.022	0.03	0.022	0.016	*0*	*0*
Embedded Energy	9.35	20.13	12.1	8.36	8.8	7.92	12.1	10.45	9.9	11.11	*13.5*	*12.6*
Local/Regional Materials	0.45	0.55	0.325	0.36	0.28	0.35	0.305	0.26	0.35	0.28	*0.35*	*0.30*

Carbon Contents	50	55.5	45	55	52.5	45	42.5	46	41	37.5	52	45
Durability	0.9	1	1.2	1.1	0.9	1	0.8	0.78	1.1	0.92	0.90	0.75
IEQ												
Occupant Health & Safety	1	1	0	1	1	0	1	1	1	1	*1*	*1*
Thermal Comfort	0.3	0.45	0.325	0.35	0.25	0.125	0.25	0.2	0.275	0.225	*0.20*	*0.22*
Daylight	0.63	0.8475	0.675	0.6	0.525	0.825	0.75	0.525	0.6	0.825	*0.1*	*0.17*
Visual Quality	0.549	0.999	0.9	0.72	0.585	0.63	0.9	0.765	0.504	0.702	*0.20*	*0.28*
Acoustic & Noise Control	3.51	4.5	3.3	2.7	3.15	2.7	2.4	3.3	2.61	3.15	*2*	*2.1*
Indoor Air Quality	0.1305	0.1695	0.165	0.12	0.135	0.165	0.168	0.1275	0.1305	0.1725	*0.14*	*0.12*
Waste												
Waste Reduction	0.12	0.2	0.09	0.132	0.112	0.153	0.124	0.115	0.092	0.11	*0.05*	*0.08*
Waste Management Strategies	0.35	0.54	0.51	0.56	0.425	0.46	0.51	0.42	0.565	0.47	*0.30*	*0.35*
Waste Water Management	0.14	0.55	0.17	0.21	0.375	0.4	0.425	0.45	0.325	0.115	*0.10*	*0.21*
Operational Waste	0.3	0.6	0.448	0.26	0.42	0.44	0.34	0.464	0.344	0.448	*0.20*	*0.25*
Flexible Building Plan	0.52	0.65	0.55	0.425	0.45	0.575	0.525	0.48	0.38	0.53	*0.12*	*0.22*

Appendix 04

Normalised Indicator Values

Domain / Aspect	Normalized Indicator (Value/ Global Benchmark)											
	Building 1	Building 2	Building 3	Building 4	Building 5	Building 6	Building 7	Building 8	Building 9	Building 10	*Building 11*	*Building 12*
Site												
Land Use	0.86	2.58	0.75	0.80	0.40	0.35	0.35	0.72	0.45	0.54	*1.36*	*1.04*
Infrastructure Efficiency	1.30	0.30	1.50	0.80	0.70	0.80	2.00	1.40	1.20	0.90	*1.20*	*1.00*
Transportation	3.00	0.50	1.40	1.20	1.20	1.40	1.00	1.20	1.00	1.30	*1.00*	*1.00*
Site Selection	1.20	0.90	1.40	1.10	1.40	1.30	1.20	1.50	0.90	1.10	*0.83*	*0.95*
Housing Density	2.50	0.40	2.80	1.00	2.00	1.50	1.80	1.80	1.20	0.95	*1.20*	*1.40*
Landscape Design	0.25	1.89	0.60	0.70	0.20	0.15	0.12	0.45	0.82	0.43	*0.25*	*0.30*
Microclimate	0.81	1.30	0.90	1.00	0.50	0.60	1.20	0.80	0.72	1.00	*0.24*	*0.28*
Energy												
Energy Usage	1.05	1.20	1.10	1.13	1.06	1.13	1.00	1.24	1.15	1.29	*0.78*	*0.86*
Building envelope Performance	1.32	1.11	1.19	1.14	1.23	1.29	1.05	1.33	1.43	1.00	*0.67*	*0.73*
Lighting Efficiency	0.80	1.20	0.93	1.22	1.32	1.60	1.01	1.05	1.10	1.05	*0.47*	*0.40*
Green House Gases Emission	1.05	1.21	1.13	1.05	1.17	1.40	1.17	1.05	1.31	1.07	*0.86*	*0.81*
Renewable Energy	0.34	0.29	0.00	0.00	0.21	1.20	0.34	0.00	0.23	0.00	*0.00*	*0.00*
Water												
Water Conservation	0.88	1.32	0.70	1.20	1.10	1.42	1.00	1.20	1.02	1.00	*0.58*	*0.52*
Water Efficient Landscaping	1.20	1.20	1.25	1.05	1.39	1.54	1.33	1.22	1.18	1.37	*0.77*	*0.83*
Sustainable Water Technologies	0.56	1.03	0.20	0.10	0.42	0.30	0.00	0.23	0.00	0.34	*0.00*	*0.00*
Material												
Renewable Material	0.20	1.60	0.23	0.28	0.14	0.00	0.10	0.12	0.15	0.06	*0.20*	*0.40*
Reuse Material	0.00	0.00	0.21	0.00	0.10	0.06	0.00	0.05	0.02	0.03	*0.00*	*0.00*
Recycle Material	0.75	1.25	0.55	0.30	0.23	0.12	0.11	0.15	0.11	0.08	*0.00*	*0.00*
Embedded Energy	1.18	0.55	0.91	1.32	1.25	1.39	0.91	1.05	1.11	0.99	*0.81*	*0.87*

Local/Regional Materials	0.90	1.10	0.65	0.72	0.56	0.70	0.61	0.52	0.70	0.56	*0.70*	*0.60*
Carbon Contents	1.00	1.11	0.90	1.10	1.05	0.90	0.85	0.92	0.82	0.75	*1.04*	*0.90*
Durability	0.90	1.00	1.20	1.10	0.90	1.00	0.80	0.78	1.10	0.92	*0.90*	*0.75*
IEQ												
Occupant Health & Safety	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	*1.00*	*1.00*
Thermal Comfort	0.60	0.90	0.65	0.70	0.50	0.25	0.50	0.40	0.55	0.45	*0.40*	*0.44*
Daylight	0.84	1.13	0.90	0.80	0.70	1.10	1.00	0.70	0.80	1.10	*0.13*	*0.23*
Visual Quality	0.61	1.11	1.00	0.80	0.65	0.70	1.00	0.85	0.56	0.78	*0.22*	*0.31*
Acoustic & Noise Control	1.17	1.50	1.10	0.90	1.05	0.90	0.80	1.10	0.87	1.05	*0.67*	*0.70*
Indoor Air Quality	0.87	1.13	1.10	0.80	0.90	1.10	1.12	0.85	0.87	1.15	*0.93*	*0.80*
Waste												
Waste Reduction	1.20	2.00	0.90	1.32	1.12	1.53	1.24	1.15	0.92	1.10	*0.50*	*0.80*
Waste Management Strategies	0.70	1.08	1.02	1.12	0.85	0.92	1.02	0.84	1.13	0.94	*0.60*	*0.70*
Waste Water Management	0.28	1.10	0.34	0.42	0.75	0.80	0.85	0.90	0.65	0.23	*0.20*	*0.42*
Operational Waste	0.75	1.50	1.12	0.65	1.05	1.10	0.85	1.16	0.86	1.12	*0.50*	*0.63*
Flexible Building Plan	1.04	1.30	1.10	0.85	0.90	1.15	1.05	0.96	0.76	1.06	*0.24*	*0.44*

Domain / Aspect	Normalized Indicator Score (Value/ Local Average)											
	Building 1	Building 2	Building 3	Building 4	Building 5	Building 6	Building 7	Building 8	Building 9	Building 10	*Building 11*	*Building 12*
Site												
Land Use	1.10	3.31	0.96	1.03	0.51	0.45	0.45	0.92	0.58	0.69	*1.74*	*1.33*
Infrastructure Efficiency	1.19	0.28	1.38	0.73	0.64	0.73	1.83	1.28	1.10	0.83	*1.10*	*0.92*
Transportation	2.27	0.38	1.06	0.91	0.91	1.06	0.76	0.91	0.76	0.98	*0.76*	*0.76*
Site Selection	1.00	0.75	1.17	0.92	1.17	1.08	1.00	1.25	0.75	0.92	*0.69*	*0.79*
Housing Density	1.57	0.25	1.76	0.63	1.25	0.94	1.13	1.13	0.75	0.60	*0.75*	*0.88*
Landscape Design	0.45	3.37	1.07	1.25	0.36	0.27	0.21	0.80	1.46	0.77	*0.45*	*0.53*
Microclimate	0.92	1.47	1.02	1.13	0.57	0.68	1.36	0.91	0.82	1.13	*0.27*	*0.32*
Energy												
Energy Usage	0.93	1.06	0.98	1.00	0.94	1.00	0.89	1.10	1.02	1.14	*0.69*	*0.76*
Building envelope Performance	1.10	0.93	1.00	0.96	1.03	1.08	0.88	1.11	1.19	0.84	*0.56*	*0.61*
Lighting Efficiency	0.71	1.06	0.82	1.08	1.17	1.42	0.90	0.93	0.98	0.93	*0.41*	*0.35*
Green House Gases Emission	0.91	1.05	0.98	0.91	1.01	1.22	1.01	0.91	1.14	0.93	*0.75*	*0.70*
Renewable Energy	1.30	1.11	0.00	0.00	0.80	4.60	1.30	0.00	0.88	0.00	*0.00*	*0.00*
Water												
Water Conservation	0.81	1.22	0.65	1.11	1.01	1.31	0.92	1.11	0.94	0.92	*0.53*	*0.48*
Water Efficient Landscaping	0.96	0.96	0.99	0.83	1.10	1.22	1.06	0.97	0.93	1.09	*0.61*	*0.66*
Sustainable Water Technologies	1.76	3.24	0.63	0.31	1.32	0.94	0.00	0.72	0.00	1.07	*0.00*	*0.00*
Material												
Renewable Material	0.69	5.56	0.80	0.97	0.49	0.00	0.35	0.42	0.52	0.21	*0.69*	*1.39*
Reuse Material	0.00	0.00	4.47	0.00	2.13	1.28	0.00	1.06	0.43	0.64	*0.00*	*0.00*
Recycle Material	2.05	3.42	1.51	0.82	0.63	0.33	0.30	0.41	0.30	0.22	*0.00*	*0.00*
Embedded Energy	1.18	0.55	0.91	1.32	1.25	1.39	0.91	1.05	1.11	0.99	*0.82*	*0.87*

Local/Regional Materials	1.28	1.57	0.93	1.03	0.80	1.00	0.87	0.74	1.00	0.80	*1.00*	*0.85*
Carbon Contents	1.06	1.18	0.96	1.17	1.12	0.96	0.90	0.98	0.87	0.80	*1.11*	*0.96*
Durability	0.93	1.03	1.24	1.13	0.93	1.03	0.82	0.80	1.13	0.95	*0.93*	*0.77*
IEQ												
Occupant Health & Safety	1.25	1.25	0.00	1.25	1.25	0.00	1.25	1.25	1.25	1.25	*1.25*	*1.25*
Thermal Comfort	1.09	1.64	1.18	1.27	0.91	0.45	0.91	0.73	1.00	0.82	*0.73*	*0.80*
Daylight	0.93	1.25	0.99	0.88	0.77	1.21	1.10	0.77	0.88	1.21	*0.15*	*0.25*
Visual Quality	0.76	1.38	1.24	0.99	0.81	0.87	1.24	1.05	0.69	0.97	*0.28*	*0.39*
Acoustic & Noise Control	1.12	1.44	1.05	0.86	1.01	0.86	0.77	1.05	0.83	1.01	*0.64*	*0.67*
Indoor Air Quality	0.88	1.14	1.11	0.81	0.91	1.11	1.13	0.86	0.88	1.16	*0.94*	*0.81*
Waste												
Waste Reduction	0.96	1.60	0.72	1.06	0.90	1.23	0.99	0.92	0.74	0.88	*0.40*	*0.64*
Waste Management Strategies	0.73	1.12	1.06	1.16	0.88	0.96	1.06	0.87	1.17	0.98	*0.62*	*0.73*
Waste Water Management	0.44	1.74	0.54	0.66	1.19	1.27	1.34	1.42	1.03	0.36	*0.32*	*0.66*
Operational Waste	0.74	1.48	1.10	0.64	1.03	1.08	0.84	1.14	0.85	1.10	*0.49*	*0.62*
Flexible Building Plan	1.02	1.28	1.08	0.84	0.88	1.13	1.03	0.94	0.75	1.04	*0.24*	*0.43*

Appendix 05

Correlation among Aspects

LIBRARY / UOM
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AQ - SECTION
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		Site							Energy Efficiency					Water Efficiency			Material							IEQ						Waste	
		Land Use	Infrastructure Efficiency	Transportation	Site Selection	Housing Density	Landscape Design	Microclimate	Energy Usage	Building envelope Performance	Lighting Efficiency	Green House Gases Emission	Renewable Energy	Water Conservation	Water Efficient Landscaping	Sustainable Water Technologies	Renewable Material	Reuse Material	Recycle Material	Embedded Energy	Local/Regional Materials	Carbon Contents	Durability	Occupant Health & Safety	Thermal Comfort	Daylight	Visual Quality	Acoustic & Noise Control	Indoor Air Quality	Waste Reduction	Waste Management Strategies
Site	Land Use	1.00	-0.55	-0.28	-0.46	-0.47	0.91	0.59	0.74	0.76	-0.06	-0.02	-0.13	0.27	0.58	0.83	0.98	-0.21	0.90	0.87	0.83	0.58	0.15	0.18	0.79	0.35	0.56	0.88	0.20	0.75	0.22
	Infrastructure Efficiency		1.00	0.26	0.36	0.62	-0.55	0.07	-0.66	-0.39	-0.58	-0.37	-0.16	-0.60	-0.70	-0.66	-0.55	0.14	-0.40	-0.25	-0.46	-0.53	-0.26	-0.07	-0.30	-0.23	0.07	-0.52	0.00	-0.60	-0.13
	Transportation			1.00	0.27	0.62	-0.51	-0.34	-0.44	-0.52	-0.44	-0.12	0.11	-0.42	-0.38	0.02	-0.41	-0.01	0.06	-0.48	0.07	-0.01	-0.12	-0.07	-0.19	-0.23	-0.50	-0.02	-0.31	-0.31	-0.74
	Site Selection				1.00	0.72	-0.64	-0.49	-0.17	-0.26	0.02	0.02	0.01	-0.15	-0.26	-0.23	-0.52	0.60	-0.33	-0.44	-0.61	-0.04	-0.31	-0.38	-0.53	-0.42	-0.01	-0.15	-0.12	-0.36	-0.59
	Housing Density					1.00	-0.62	-0.42	-0.49	-0.35	-0.42	-0.24	-0.04	-0.67	-0.65	-0.28	-0.52	0.62	-0.12	-0.41	-0.33	-0.12	-0.03	-0.40	-0.26	-0.44	-0.16	-0.18	-0.14	-0.60	-0.56
	Landscape Design						1.00	0.56	0.64	0.79	0.00	-0.02	-0.22	0.25	0.48	0.60	0.92	-0.18	0.73	0.82	0.72	0.42	0.37	0.19	0.79	0.29	0.48	0.70	0.14	0.59	0.54
	Microclimate							1.00	0.32	0.48	-0.36	-0.26	-0.31	-0.03	0.33	0.26	0.60	-0.37	0.47	0.75	0.44	0.09	-0.03	0.28	0.62	0.53	0.79	0.33	0.44	0.46	0.45
Energy Efficiency	Energy Usage								1.00	0.82	0.55	0.57	0.37	0.68	0.78	0.66	0.75	-0.04	0.59	0.59	0.59	0.54	0.18	-0.27	0.35	0.51	0.54	0.58	0.36	0.89	0.25
	Building envelope Performance									1.00	0.20	0.35	0.07	0.25	0.40	0.50	0.77	0.23	0.64	0.76	0.55	0.28	0.47	-0.40	0.53	0.52	0.71	0.60	0.50	0.60	0.50
	Lighting Efficiency										1.00	0.78	0.65	0.80	0.55	0.06	0.03	-0.01	-0.22	-0.17	-0.05	0.20	0.10	-0.32	-0.34	0.22	-0.14	-0.18	0.11	0.44	0.20
	Green House Gases Emission											1.00	0.82	0.64	0.32	0.07	-0.03	0.05	-0.10	-0.15	0.11	-0.05	0.23	-0.66	-0.42	0.49	-0.08	-0.12	0.30	0.43	0.08
	Renewable Energy												1.00	0.53	0.18	0.11	-0.08	-0.12	-0.06	-0.18	0.21	-0.03	-0.05	-0.50	-0.47	0.44	-0.22	-0.18	0.29	0.42	-0.16
Water Efficiency	Water Conservation													1.00	0.78	0.29	0.31	-0.45	0.01	0.09	0.21	0.34	-0.21	0.06	-0.16	0.24	0.01	0.09	-0.02	0.73	0.13
	Water Efficient Landscaping														1.00	0.50	0.60	-0.43	0.39	0.33	0.47	0.73	-0.04	0.19	0.36	0.26	0.32	0.34	-0.01	0.85	0.24
	Sustainable Water Technologies															1.00	0.79	-0.14	0.84	0.66	0.74	0.54	-0.08	0.12	0.50	0.37	0.29	0.92	0.26	0.72	-0.24
Material	Renewable Material																1.00	-0.22	0.87	0.90	0.82	0.58	0.16	0.19	0.80	0.38	0.59	0.81	0.25	0.77	0.33
	Reuse Material																	1.00	-0.06	-0.11	-0.37	-0.12	0.43	-0.70	-0.12	-0.18	0.14	0.03	0.20	-0.44	-0.06
	Recycle Material																		1.00	0.74	0.89	0.63	0.22	0.04	0.81	0.27	0.46	0.87	0.16	0.61	0.01
	Embedded Energy																			1.00	0.63	0.23	0.03	0.15	0.69	0.50	0.76	0.74	0.52	0.61	0.34
	Local/Regional Materials																				1.00	0.56	0.26	0.08	0.71	0.40	0.25	0.66	0.12	0.72	0.14
	Carbon Contents																					1.00	0.11	0.17	0.59	-0.23	0.17	0.49	-0.37	0.56	-0.01
	Durability																						1.00	-0.50	0.40	0.08	0.01	0.01	0.02	-0.11	0.58
IEQ	Occupant Health & Safety																							1.00	0.30	-0.30	-0.13	0.12	-0.41	0.05	-0.03
	Thermal Comfort																								1.00	0.07	0.48	0.61	-0.02	0.37	0.42
	Daylight																									1.00	0.45	0.22	0.87	0.57	0.24
	Visual Quality																										1.00	0.42	0.58	0.45	0.37
	Acoustic & Noise Control																											1.00	0.19	0.55	-0.18
	Indoor Air Quality																												1.00	0.32	0.18
Waste & pollution	Waste Reduction																													1.00	0.14
	Waste Management Strategies																														1.00
	Waste Water Management																														
	Operational Waste																														
	Flexible Building Plan																														